DEVELOPMENTS IN SANDWICH CONSTRUCTION

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by

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D E C L A R A T I O N

None of the material contained in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institution of learning.

S. Tajbakhsh

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ABSTRACT

The research is divided into two parts. In the first part the structural behaviour of sandwich beams using timber-based facings and foamed plastic cores was studied. Various available theories were examined and the most appropriate theory for this type of panel was identified. In an extensive test programme the relevant properties of the constituent materials were measured and the data used in the proposed theory of structural behaviour to predict beam deflections and core and facing stresses. Corresponding sandwich beam tests were carried out on the range of skin/core combinations and the theoretical and experimental behaviours were compared. Good agreement was confirmed within the range of span/depth ratios investigated, confirming the applicability of the theory for semi-thick timber-based facings. A variety of timber based facings were investigated and those most suitable for sandwich construction were identified.

This type of panel construction has many advantages but lacks the benefit of good fire resistance. The required fire resistance could be provided by a suitable core material.

Part two of the research concentrated on the development of a new core material which was intended to have good structural properties at reasonable density, and to have adequate fire resistance free from the production of

smoke and toxic fumes. Coated paper honeycombs were chosen for the study. The properties of the constituent materials were investigated in detail and then the structural properties of the developed cores were measured using methods drawn from national and international standards. One particular coating combination proved to be effective in terms of stiffness, fire resistance, freedom from micro cracking and strength retention at high temperature. This was based on a mixture of sodium silicate and ball clay. Cores were tested both with cells empty (to be blocked by intumescence) and with cells filled (e.g. with lightweight filler). In the best of the developed cores, shear stiffness and transverse stiffness were much higher than in normal core materials. On the basis of the test programme, panels can be designed to give a fire resistance defined by insulation of up to two hours.

CHAPTER 1
GENERAL INTRODUCTION AND
REVIEW OF RELATED STUDIES

CHAPTER 1

1.1 HISTORICAL REVIEW

The first broad scale application of structures built on the sandwich principle dates back to world war two where extensive use was made of Birch facing material laminated to balsa wood core in the de Havilland "Mosquito" bomber[1]. Later in the war, drastic increases in air speeds and a concomitant requirement for aerodynamically smoother surfaces added interest. Finally, the sharp growth after 1945 in the size of both commercial and military planes spurred the efforts to reduce airframe weight and intensified the work on sandwich materials. Today, sandwich panels in aircraft use glass or carbon-fibre composite skins separated by aluminium or paper-resin honeycombs or by rigid polymer foams, giving a panel with enormous specific bending stiffness and strength. Most recently a diffusion-bonded titanium honeycomb core has been developed for the components of jet engine ducts and casing where it provides significant weight reductions compared with solid titanium[2].

In building construction the use of sandwich panels is not new : Le Maison du peuple at Clichy, by Jean Prouve completed in 1939 is an early example. Prouve used a spring to separate the steel skins to achieve a light weight rigid component.

During the second world war, a factory-made sandwich

material composed of asbestos-cement board facing on laminated vegetable fibreboard core was applied extensively to defence and military housing in the United States[3]. More recently, cladding panels have been manufactured using a variety of materials. Facings have utilised metal sheeting, particularly steel and aluminium, plastics, plywood, or a variety of compressed fibreboards and various cement-based sheathing boards. There has also been some application for deeply profiled sheathing as facing. The main contrast with earlier sandwich applications is that facings are much thicker and, in many cases, composed of semi-brittle or less ductile materials. In most applications the core material also serves as thermal insulation. Polystyrene slab or rigid urethane foam materials are commonly used. Metal honeycomb core was used in the early applications of sandwich construction which provided strong yet light structural forms.

In lengthwise compression, applicable in stressed skin aircraft design, the core resisted local rippling allowing instability to be assessed using the overall sandwich stiffness. In flexure, the high strength membrane facings were maintained at a large lever arm providing efficient restraint against bending. Metal honeycomb is light but particularly stiff. The modern rigid foams have a similar density but shear modulus in the region of one hundred times smaller. The structural

response of the honeycomb is fortuitously close to the analytical assumption of weak longitudinal stiffness and transverse incompressibility. Modern materials also provide light construction and have the added advantage of excellent thermal insulation properties. However, there have been lagging interest and slower progress in the building industry. Composite cladding panels only became available commercially in the 1970s, when the 1973 energy crisis emphasised the need to conserve fuel. Thus the thermal performance of the building envelop became much more important. The Sainsbury centre designed by Foster association[4] in 1977 incorporated one of the first rigid plastic foamed core and aluminium skin insulated composite cladding panels.

Sandwich panels are being increasingly used as external wall and roof cladding because they are energy efficient, lightweight, and can be easily handled and rapidly erected. However, since they often consist of a thick structural core of flammable material and thin facings, it may be difficult to predict the risk to life that may result from their involvement in fire.

1.2 DEFINITION

Sandwich structural members are made up of two stiff flat or corrugated skins separated by a thick layer of much weaker and lower density material. The skins or face materials are usually made up of high strength, stiff materials such as steel, aluminium, plywood, or fibre-reinforced composite; the cores are are made up of polymeric foams or aluminium or paper-resin honeycombs which are bonded to the faces (see fig 1.1). The core must be stiff enough to keep the faces at the required distance apart and it must also be stiff enough in shear so that when the panel is bent the faces do not slide over each other.

1.3 DESIGN ADVANTAGES

Sandwich panels are now extensively used in building construction. They owe their success to the following properties :

1.   Good strength to weight ratio, i.e.,more strength for less weight of the materials involved in it's construction.

2.   Optimum heat insulation values and assembly with no thermal bridges.

3.   Their good sound insulation compared to homogeneous wall or roof elements of the same weight.

4.   Installation unaffected by weather conditions;

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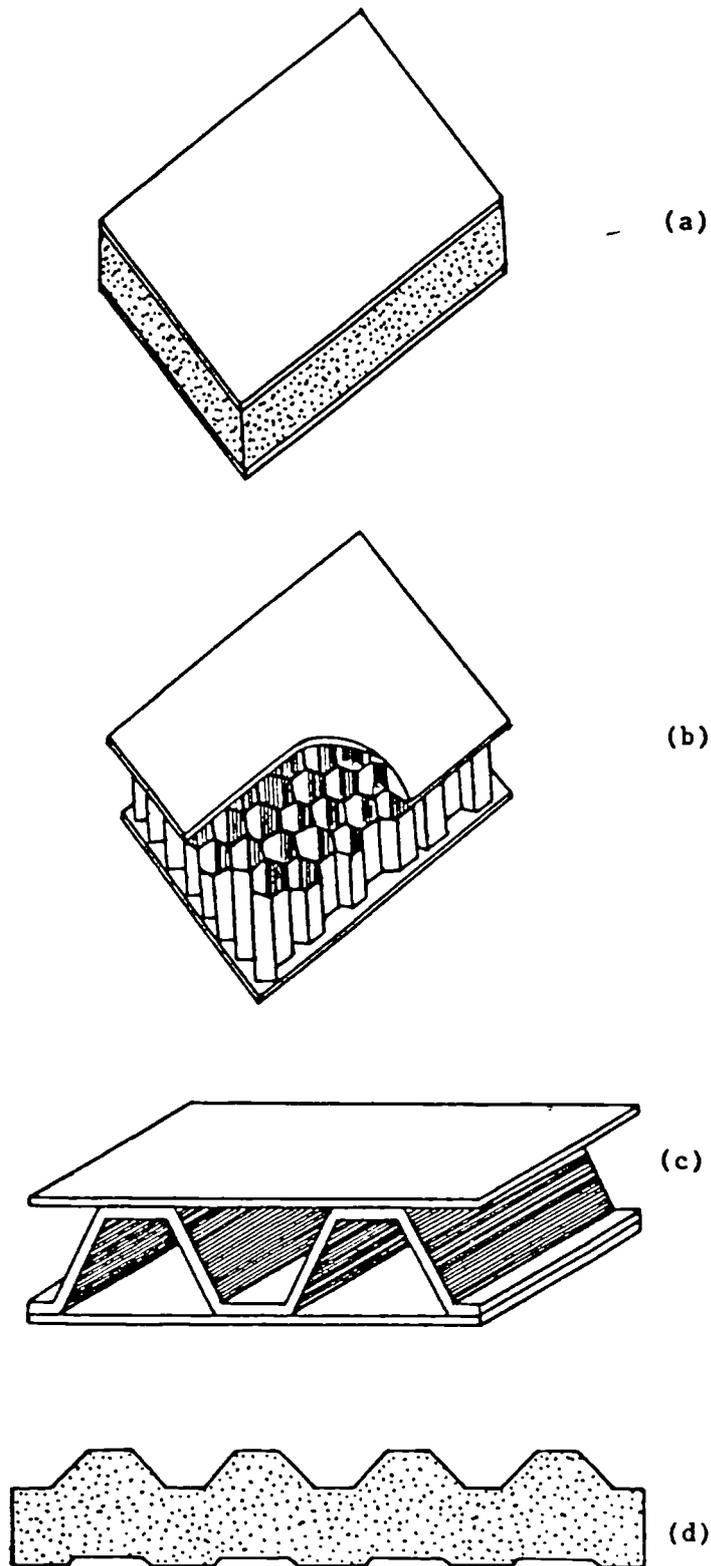
Figure 1.1 Sandwich panels with (a) rigid foam core

(b) honeycomb core   (c) corrugated core

(d) profiled facings

rapid construction and ease of handling and assembly.

5.   Provision for dismantling and re-erecting at any time; provision for extensions.

1.4 DESIGN LIMITATIONS

Sandwich panels are not without their problems and have less good properties. Their disadvantages are summarised in the following :

Sandwich panels using a plasic rigid foam core do not reach a notable fire resistance time. Here, resistibility to fire is defined as the ability of a building component:

a)_   to resist the passage of fire through a wall or roof for a specified time.

b)_   to avoid temperatures in excess of 140° C above ambient temperature to occur on the unexposed side.

C)_   to maintain it's loadbearing capacity in the case of loadbearing panels and not to collapse in the case of non loadbearing panels.

d)_   not to evolve combustible gasses.

Other limitations inherent in modern day sandwich panels containing plastic cores are:

1.   Ozone depletion by trichlorofluoromethane (CFC) blowing agent used in the foaming

process of some rigid plastic materials.

2. Creeping behaviour under permanent load with roof panels.

3. Temperature loading due to the high thermal insulation provided by the foam plastic.

4. Delamination (blistering) of metal face from the core due to sun exposure in areas with poor adhesion between core and the heated face. The risk can be minimised by light-coloured face surfaces and good quality control.

1.5 REVIEW OF RELATED STUDIES

<u>1.5.1 SANDWICH BEAMS.</u> During the early part of this
century advances were made by Timoshenko[5] in
structural mechanics. These were discussed in several
books published in the 1930,s. His book on `Theory of
Elasticity' defines the more advanced analytical methods
of this period, and provide an appropriate foundation
for the understanding of modern structural analysis. Two
distinct approaches to the solution of complex
engineering problem have been evolved. The first
involves the direct application of equilibrium
equations. This method may be applied to the
determination of stresses, by employing generalised
equilibrium and compatibility equations used in
conjunction with a particular stress function.
Alternatively, the overall response may be built up in
specific manner by considering the equilibrium of small
elements of the structure and defining internal
compatibility by relating strain components between
different elements. This leads to the formation of
equilibrium equations by explaining forces in terms of
displacements. The second means of dealing with
particularly the more complex problems is the use of
variational methods. In this case equilibrium conditions
are expressed in terms of stationary energy principles
or virtual work equations. In general, solutions rely on
the definition of assumed displacement fields expressed

usually in terms of polynomial or fourier series. Both methods give exact solution for the simplest problems. For more complex cases, the direct equilibrium/compatibility approach relies on the prescription of simplifying assumptions to make the solution more manageable. The latter variation methods allow a rigorous solution to complex problems, but are in a sense approximate in nature on account of the specification of an initially assumed displacement shape.

Figure 2.3 (page 40) shows a cross-section through a symmetrical sandwich beam, useful for defining terminology and describing sandwich action. The facing thicknesses t are attached to a core thickness C giving an overall sandwich thickness h. The distance between the two facing centrelines is defined by the dimension d. Thin face sandwich action refers to the situation where the facings have no internal stiffness. In this case sandwich response arises from membrane forces in the facings acting as a couple providing bending resistance about the overall sandwich centreline, accompanied by shear deformation within the core. Thick face action describes the situation were internal stiffness of the facings bending about their own axes contribute to the overall sandwich stiffness. In flexurally thin faced beams however, the facing thickness may be large enough to affect the deflection

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of the core in shear. The term very thin face is required to describe the situation where facing thickness is so small as to have little effect on core distortions.

The initial work on sandwich beams was carried out at the United States Forest Products Laboratory in 1940's. March and Smith[6] evaluated the total central deflection of a simply supported sandwich beam with thin flat faces. The deflection at the centre of a simple beam carrying a single load P was evaluated as:

$$\Delta = \frac{WL^3}{48D} + \frac{WL}{4AG} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(1.1)$$

The total deflection was shown to be composed of two parts, the first being the contribution of ordinary bending displacement, the second due to shear strain in the core. The parameter D in the equation (1.1) refers to the flexural rigidity (EI) of the sandwich as a whole. The parameter A reflects the shear action in the core and is the net core area. The term AG describes the core shear rigidity.

Norris et al[7] approached the analysis in a different way, using a direct engineering equilibrium approach. This was successfully applied to include thick face action giving a deflection equation of the form

$$\Delta = \frac{WL^3}{48D} + \frac{WL}{4GA}(1-\frac{If}{I})^2(1-\psi) \qquad \ldots\ldots\ldots(1.2)$$

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the first term in brackets represents the alteration to
the average shear stress in the core imposed by the
bending stiffness of the facing. The function ϕ
represents the reduction in beam flexibility resulting
from the extra thickness of the facings bending about
their own axes in reaction to core shear displacements.
Norris presented a general solution method applied to
beams with three or four point loading with overhangs.
The thick face equations are, however, complex in
application and later authors Kuenzi[8,9](1951), Howard[10]
(1962), and Doherty et al[11] (1965) based their studies
on performance testing of sandwich beams and comparison
with the March and Smith equation.

There was another requirement _ to be able to assess
overall sandwich response properties by testing
sandwich beams themselves. This was a more complex
process than the testing of ordinary beams. Apart from
the application of thick face action , at least two
measurements were required in each test in order to
separate the independent bending and shearing
displacement components. Kuenzi applied the differential
equation of flexure for thin faced beams to the central
portion of 4-point loaded beams, and used displacements
measured at two different locations to determine the
response parameters. Howard made use of a 5 point load
test, again using two measurement for assessment of
stiffness. Doherty et al used a range of beam tests of

different spans, the results being presented in two
different formats to evaluate separate property
components. With reference to the March equation (1.2)
a graph of Δ/WL^2 against $1/L^2$ separated out the shear
stiffness in like manner. Comparison with small scale
material property tests showed reasonable agreement for
thin aluminium skins, and poor agreement for thick
asbestos cement skins.

Allen[12] applied himself directly to the problem of
testing beams with predominantly thick faces. He adopted
a Doherty et al approach of multiple testing but
discussed fully the implications of thick face action in
relation to a new theory of analysis. The Allen theory
is presented fully in a book[13] (1969) devoted to the
bending and buckling analysis of sandwich beams and
plates and further development in a later paper[14] (1973).
Adams and Wienstien[15] (1975) developed the Norris and
Allen approach, producing an analysis which included the
contribution from core bending in the solution. The
format of the analysis also provided direct insight into
the nature of core and face interface bond stresses.
Ogorkiewicz[16,17,18,19] and others (1967-73) used the
March theory to underpin several programs on the testing
of sandwich beams utilising new plastic materials for
skins and cores. Farkas and Jarmai[20] (1982) used Allen's
theory to predict the response of very thick faced
sandwiches composed of aluminium I beams or box sections

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with thin rubber cores.

Other researchers have applied the engineering equilibrium approach to sandwich beam analysis formats. Plantema[21] (1966) developed equations for sandwich beams with thick facings in a similar format to Norris and Allen. Hartsock[22] (1966) initially presented a thin face equation similar to March considering shear deformation, acting simply over the net core area. However his book[23] (1969) contain a detailed analysis of thick faced beams which was extended to include the condition of thermal warp due to temperature difference between the facings. Hartsock and Chong[24] (1977) presented an experimental study of sandwich beams with a combination of formed and flat faces subjected to flexural loading and compared their results with the theoretical work reported previously by Hartsock[23]. Later Chong and others[25,26] examined the effect of temperature on sandwich panels used as walls in buildings and studied the stresses and deflection arising in this case. The test results were compared to calculated theoretical values and the analysis was extended to include indeterminate beams of more than one span. Drysdal and others et al[27] (1979) propounded a method for the analysis of thick skin and weak core sandwich beam-columns. The authors developed expressions for different type of loading to assist the design of practical sandwich elements for buildings. O'Connor[28,29]

1985,1988 discussed the analysis of sandwich panels on the basis of Allen's formulations for sandwich beams with thick faces. The author considered responses within the regions of the concentrated load and established the critical span concept where the effect of the point load disappeared at an identified distance away from the point load.

Stamm and Witte[30] (1974) presented formulations to assist the design of sandwich elements for building construction. Since this work is not available in English, Davies[31] (1986) has represented the basic equations and the most important solutions. The Stamm and Witte method is used to predict the behaviour of the sandwich beams described in chapter 5. In order to check the accuracy of the calculations, the results of the sandwich beams tested as part of the program (see chapter 5) are compared with the calculated results in chapter 6.

The basic equations and solution for point loading are repeated here in chapter 2. The solution of point loading is modified for the case of four point loading.

1.5.2 MECHANICAL PROPERTIES OF HONEYCOMB CORES

Man made paper, metal and ceramic honeycombs are now available as standard products. Paper and metal ones are used for the cores of sandwich panels in everything from cheap doors to advanced aerospace components and ceramics for high-temperature processing (e.g. catalyst carriers). If honeycombs are to be used as cores in sandwich panels it is important to understand their mechanics and since honeycombs have a regular geometry their deformation can be analysed to give equations to describe their mechanical properties. Honeycombs have two different sets of properties, in-plane and out-of-plane. The in-plane stiffness and strength (X_1-X_2 direction in fig. 1.2) are the lowest because the stress in X_1-X_2 plane makes the cell walls bend. The out-of-plane strength and stiffness (in X_3 direction) are much larger because the stress in X_3 direction will result in axial extension or compression of the cell wall. It is the out-of-plane properties of honeycomb which are needed for the design of the honeycomb core in sandwich panels.

The calculation of the out-of-plane shear modulus of developed honeycombs is re-presented in chapter two and the accuracy of the analysis is demonstrated by comparing the results with the experimental data.
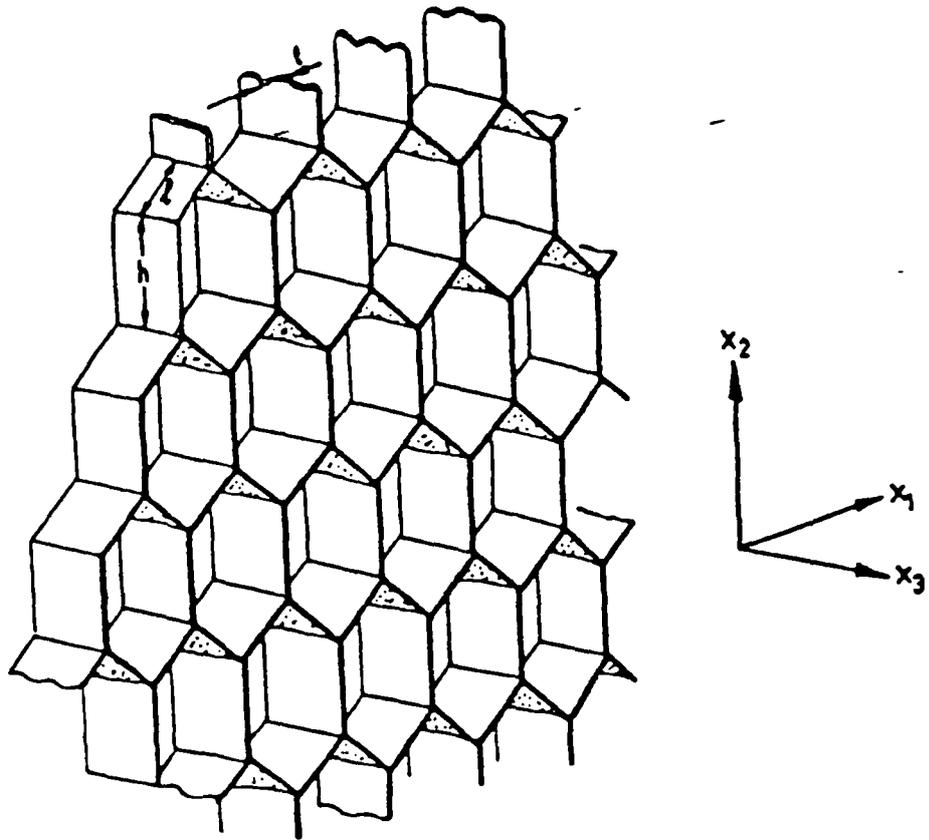
Figure 1.2 A honeycomb with hexagonal cells. The in-plane properties are those relating to loads applied in the X_1-X_2 plane. Responses to loads applied to the faces parallel to X_3 are referred to as the out-of-plane properties.

1.5.2.1 THE CALCULATION OF HONEYCOMB SHEAR MODULUS

Kelsey and others[32] (1958) obtained expressions for the

upper and lower limits to the shear modulus (G_c) of

honeycomb sandwich cores made up of foil by application

of unit displacement and unit load methods in

conjunction with simplifying assumptions as to stress

and strain systems in the core. In this work the shear

modulus is expressed by the equation

$$G_c = K_{11} = \frac{K_{12}^2}{K_{22}} \qquad \qquad \dots\dots\dots(1.3)$$

Where the symbols K denote stiffness's which are

functions of the core geometry and material and

subscripts 1 and 2 refer to two mutually, perpendicular

directions. The term K_{12}^2/K_{22} takes into account shear

displacements which are not in line with the applied

force.

Kelsey and others[32] used two methods to calculate the

stiffness quantities necessary to determine G_c. The

first method yields a lower limit solution for G_c and

can be explained as assuming a sandwich having faces of

zero bending stiffness. The second method yields an

upper limit solution for G_c and can be explained as

assuming a sandwich having rigid faces in bending.

Chang and Ebcioglu[33] (1961) presented an analytical

theory for the effect of cell geometry on the shear

modulus. They analysed the core shear modulus in

different directions to include the effect of the core
cell angle (α) and the aspect ratio (h/l) (see fig 2.9)
of the core cell walls making use of the unit
displacement method from equilibrium considerations.
Their method was in parallel with Kelsey and others[32]
except that Chang and Ebcioglu neglected the shear
displacements which where not in line with the applied
shear force since these displacements are generally
small. Equation (1.3) therefore simplified to the
following form

$$G_c = K_{11} \qquad \qquad \ldots\ldots\ldots (1.4)$$

Penzien and Didriksson[34] (1964) examined the problem of
predicting the effective shear modulus of honeycomb core
materials and included in the analysis the effects
resulting from boundary conditions which prevent warpage
of the cell. They showed that these warpage constraints
have little effect on the shear modulus except when the
ratio of core cell length to it's lateral dimension
becomes relatively small.

Gibson and Ashby[35] (1988) simplified the method used by
Kelsey and formulated upper and lower bounds for the two
shear moduli and if the two coincide, then the solution
is exact.

The method used by Gibson and Ashby is re-presented in
section 2.5.2 and the shear modulus of the developed
honeycomb cores described in chapter 7 are calculated

using this method. The results of the analysis are compared with the experimental work in chapter 8.

1.5.3 DEVELOPMENT OF FIRE RESISTANT PLASTIC

RIGID FOAMED CORE

Plastic rigid foams are being increasingly used in cores of sandwich construction. They owe their success to their low thermal conductivity, high ratio of strength to weight and low moisture absorption. However, being organic materials, they can burn. When they are heated, smoke and toxic gasses can be evolved during smouldering and at some initiating temperature depending on the oxygen supply, they can undergo flaming combustion which result in new and sometimes dangerous degradation products.

Considerable work has been done in trying to reduce the ignitablity and to improve the fire resistance capacity of foams. Polystyrene was discovered in 1839, but it was not developed commercially until 1930 when much activity in developing foamed polystyrene started in several countries : for example, extrusion of foamed polystyrene in Sweden in 1931; Dow chemical Co. also developed independently styrofoam in the US; BASF in Germany investigated many techniques in the 1930s and during the 1939-45 war and in the 1950s introduced a process using expanded polystyrene granules containing a solvent blowing agent.

Madorsky[36] (1959) stated that polystyrene will volatize at about 300° c and the amount and rate of volatization is greatly influenced by the actual temperature of

degradation. Madorsky[37] (1962) later found that with polystyrene heated to a higher temperature (about $370^{\circ}C$) a different degradation mechanism predominates which greatly influences the gaseous products. Polystyrene foam will soften at 100° c and dripping occurs at the temperatures associated with combustion. Attempts have been made to eliminate dripping of polystyrene foam by Linderman[38] (1969) by incorporating glass fibre , but this tends to reduce the fire rating according to some methods of evaluation because the polystyrene no longer flows away from the flames. Briggs[39] (1984) stated that this melting-back mechanism can provide a useful safety control since it delays ignition, particularly if heat has to pass through poor conducting facings (e.g. plaster, concrete). Melting back leads to rapid failure in fire resistance tests (e.g. BS 476, part 22 etc.) since no direct link is maintained between the exposed face and the molten surface of the foam. Polystyrene foam can cause molten drips (especially in ceiling applications) and with some formulation these drips burn. However many polystyrene foams now contain brominated fire retardants which delay ignition of the molten polystyrene.

In 1982 Imperial Chemical industries PLC[40] claimed to have developed a fire-resistant expanded polystyrene. This was achieved by coating the expanded polystyrene bead with a non-flammable material such as silicate or a

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layer mineral. The fire performance of such products was reported to be greatly improved compared with conventional expanded polystyrene products. The modified polystyrene does not melt or drip prior to and/or during burning, and whilst the polystyrene may burn out, there remains an inorganic structure of a foam-like appearance.

However the desirable physical properties of conventional expanded polystyrene such as their toughness and light weight were reported to be adversely affected.

In 1945, at the end of the war, B.I.O.S. investigating teams visiting the German chemical industry discovered that in 1937 Dr Otto Bayer Igfarben industries) had made an elastomet by reacting isocyanates with various compounds containing hydroxy groups such as polyesters and polyethers. Since this discovery, the chemistry of polyurethane (PUR) has been developed to the stage where polyurethanes can be formulated from hard to soft solids to low density flexible and rigid foams. PUR rigid foams in the form of laminates for the construction industry have made a worthwhile contribution to the growth of rigid foam products for several years. Efficient processes have been developed for the continuous manufacture of laminates consisting of a layer of rigid foam sandwich between flexible or rigid facings. The use of laminates by the construction industry throughout the

world represents the major outlet for PUR rigid foam. Foamed plastics are, however, regarded as a fire hazard and the need to improve the fire performance of both rigid and flexible PUR foams has been accepted.

Reich and Levi[41] (1967) point out that various degradation reactions are likely to occur when PUR foams are heated, the dissociation being firstly to isocynate and alcohol with side reaction due to further degradation of the isocynate, and then interaction between the isocynate and some of its degradation products and oxidation if air is present. Concerning the polyol component of PUR, Saunders[42] (1967) pointed out that polyester segments have lower heats of combustion than polyether segments, and are more suitable for producing thermally stable PUR. Nicholas and Gmitter[43] (1965) reported an apparently higher melting point (mechanical stability up to 200° c) by fire forming a cyclic trimmer of toluene disocyanate, which is termed an isocyanurate, to produce a foam but did not give any data on thermal stability at higher temperature.

Polyisocyanurate (PIR) foams were developed in 1968 with the following advantages over conventional rigid PUR foam :

1_   Higher operating temperature.

2_   improved surface spread of flame resistance.

3_   reduced ignitablity.

4_   less smoke development on burning.

5_ improved fire resistance in composites

compared to conventional urethane foams.

The improved performance of PIR foams in resistance to proposed torch and fire resistance tests is due to the formation of a Carbonaceous fibrillar network as a facsimile of the original foam structure. Once formed this char is destroyed only slowly and it act as a flame and heat barrier.

Phenolic foam were first produced in about 1945 and it was in the late 1960s and 1970s that they were evaluated in those countries where it had been recognised that the fire resistance of PUR rigid foams needed improvement.

Phenol foam has superior dimensional stability at high temperature when compared with the other commercially available rigid foams. A research conducted by the Building Research Station in 1968 qualitatively identified this rigid foam as being highly resistant to ignition with good fire and high temperature characteristics but poor physical and mechanical properties. A detailed study by Jeffreys[44] (1963) on the thermal degradation of many phenolic foams indicate that the unsubstitued phenol formadehyde was the most stable. Later work by Learmonth and Osborn[45] (1968) showed that this stability was also associated with highest yield char. The fact that phenolic foams have great tendency to char was an attraction. At this time, however, phenolic foams had some disadvantages compared to other

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rigid foams namely : difficulty in processing, low
mechanical strength, friability and relative poor
insulation properties. However, BP have made successful
advances to overcome some of these problems by
increasing the number of closed cells to 90 % plus and
producing a very fine cell structure[46] .

1.5.4 SIMULATED FIRE TESTS ON SANDWICH PANELS

Early simulated fire tests on sandwich panels were conducted by Kaplan[47], et al. (1965) on roof deck assemblies. Rigid plastic foam was sandwiched between a metal face and a bituminous membrane in a full scale structure about 30 x 7m, and a standard exposure fire maintained at one end. The test was not strictly concerned with sandwich panels and the main purpose was to check whether the plastic foam would limit leakage of molten bitumen. The system was found to be acceptable for many applications except for large roof areas of industrial building where an additional layer of inorganic board was required between the metal face and the plastic foam.

Gross[48] (1967) conducted full scale burn out tests on sandwich panels with aluminium skins and polystyrene core. The panels were included as curtain walls to multi -story concrete housing units in order to obtain information about the fire protective features of new construction. Matters such as structural performance, fire involvement of fuel load, and radiation and temperature level reached were investigated. In one test the sandwich panel tested reached a temperature of 450 c in 33 min. prior to falling out. Toxic gases were measured but were not associated solely with the panels but also with the particleboard flooring and timber cribs used to simulate furniture. No particular hazards

were associated with sandwich panels except that slow propagation occurred in the polystyrene core of one of the tests.

During 1970 several manufacturers sponsored full scale fire tests at the Joint Fire Research Organisation[49]. Different panel systems were used for cladding three single-storey steel framed buildings. Two of the systems included foamed polyurethane cored panels with steel skins. One of the later systems was constructed with and without an air gap in the cavity between the steel faces. Flame spread occurred in the panels only where there was an air cavity. Results on smoke and toxic gas measurement indicated that there was no additional hazard associated with sandwich panels compared to an acceptable lining system of steel cladding, mineral wool insulation, air gap and an internal lining of treated organic fibre insulating board.

A similar test was conducted in Australia during 1970 sponsored by the Plastic Institute of Australia[50]. A sandwich panelled house was compared to similar timber framed house. Structural performance, smoke and toxic gases were monitored and indicated that the panelled house did not present a greater hazard.

Studies at the Underwriters Laboratories[51] (1969), were conducted to relate performance of cellular plastics in actual fires to test data on the materials involved. Over a period of 10 years, they considered 97 cellular

plastics fires out of which 34 of these fires were in buildings other than warehouses and manufacturing plants. Only two of these involved sandwich panels and both had internal skins of plywood. The cellular plastics involved in other fires were mostly unprotected and were ignited by welding or electrical faults. Insufficient information was available to relate the properties of foams, as determined by tests, to performance in fire. However as the result of these studies it was suspected that test data had little relation to what happened in the actual fires.

This work led to the sponsorship of a full-scale fire test known as the corner wall test, at the Factory Mutual Research[52] (1973). Various types of insulating wall and roof construction built on a large scale were tested using a timber crib ignition. The object of the tests was to determine the fire characteristics of full-scale buildings according to type of cellular plastics insulation and method of construction, with and without additional sprinklers. Both sandwich panels and spray-on foams were studied. The result of the tests indicated that polyurethane foam and steel skins systems performed satisfactorily as walls for storage of noncombustibles without the aid of sprinklers. A similar polystyrene system were found to require sprinkler aid.

EicKner[53] (1975), examined wood frame systems under load and reported that plywood-faced panels with polyurethane

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or Polyisocyanurate cores failed in 3 to 6 minutes. However, the extra protection of 12 mm plasterboard or intumescent mastic on the fire-exposed side provided a further 20 minutes of fire endurance.

Ashton[54] (1976), reported that expanded polystyrene used in cores of sandwich panels had virtually no influence on the stability of the panels. Tests demonstrated that 30 minutes stability could be obtained with certain timber frame and plasterboard facing systems and 60 minutes stability with certain steel and sheet-steel facing systems.

Other work by "Imperial Chemical Industries",[55] indicated that panels with polyurethane cores could retain integrity in model fire resistance test up to 120 minutes depending on the nature of the skin. Metal skins failed from as early as 13 minutes; 12 mm plasterboard on each face lasted about 40 minutes and systems with asbestos insulation board on both faces lasted 120 minutes. In these tests the polyurethane degraded and produced large amount of smoke, but the degradation had little influence upon the fire resistance of the system

Dowling[56] (1981), examined sandwich panel systems containing cores of cellular plastics. The systems examined all had either polystyrene or polyurethane foam cores with variety of facing materials (e.g. Asbestos/cellulose/cement sheet, plywood board and

galvanised steel), representing both cold-room and modular housing systems. Eleven sandwich panels were exposed for 10 minutes in a small furnace that modelled the Australian standard fire resistance test (As 1530 part 4. 1975). The authors reported that polystyrene used in cores of sandwich panels had no influence upon the dimensional stability of the panel. Polyurethane foam cores burnt wherever exposed but, in unexposed areas, degraded to a stable char remaining in place and retaining some insulation and mechanical value. Behaviour of the different types of facing varied considerably. The cellulosic facings offered little protection to the foam core. When they were exposed to the furnace they were rapidly consumed and allowed complete combustion of the foamed core. Asbestos/cellulose/cement facings warped, and when prevented from warping, cracked. The galvanised steel facings warped and exposed the foam core.

In nearly all the above studies, hardly any attention has been given to the insulation performance of sandwich panels in the fire situation (i.e. the ability to avoid temperatures in excess of $140^{\circ}C$ above ambient temperature on the unexposed face for the required time). They were all concerned with the integrity of the panels under investigation and their contributions to fire and smoke.

1.6 THE BEHAVIOUR OF TIMBER FACE FACING

At this point it may be appropriate to digress a moment to point out the characteristics of wood as a construction material.

The character, orientation, and arrangements of wood fibres makes wood an anisotropic material. For all practical purposes, however, it may be treated as orthotropic, with three principal axes of symmetry, the longitudinal, the radial, and the tangential. The assumption of three structural axes result in a variable galaxy of properties :

> Three Young's modulis : varying by 150 to 1,
>
> Three shear moduli varying by 20 to 1,
>
> Six Poison's ratios varying by 40 to 1 and,
>
> Nine strength properties varying with grain direction (3 tension, 3 compression, and 3 shear).

The stiffness and strength are greatest in the axial direction, that is, parallel to the trunk of the tree; in the radial and tangential direction they are less by a factor of 1/2 to 1/20 .

The concept of wood as an orthotropic material with three principal axes of symmetry, and its widely different properties along and across the grain, involves a complicated mathematical problem in structural analysis.

Thus an already complicated material is employed to form

an even more complicated material from the point of view of mathematical treatment.

1.7 FIRE RESISTANT SANDWICH CORE

Conventional sandwich panels with rigid plastic foam cores are being increasingly used as external wall and roof cladding for buildings. The panels often employ rigid plastic foam cores of polyurethane (PUR), polyisocyanurate (PIR), expanded or extruded polystyrene and steel faces. Since plastic foam materials are combustible, the steel-plastic foam sandwich elements are in principle also to be classed as combustible according to the requirements of for instance, building supervision of the Federal Republic of Germany[57].

Fire resistant sandwich panels are available made with mineral wool cores but the incorporation of the mineral wool core for sandwich panels will result in increasing weight and cost of the panel. The mineral wool slabs are cut into strips of panel thickness perpendicularly to fibre direction in order to increase the tensile and compression strengths. Fire tests conducted at the University of Salford on sandwich panels with mineral wool core and aluminium alloy faces revealed that shrinkage of the strips caused opening up each joint in a V notch shape through which the heat was able to penetrate.

The use of CFC blowing agent, which is used in the

foaming process of some rigid plastic materials, will soon be forbidden, since CFC'S are considered to contribute largely to the destruction of the ozone shield. In Germany the use of CFC blowing agent will no longer be permitted after the end of 1994[58]. It was concluded that a novel core material was needed. The requirements for this new material were good fire resistance, adequate structural performance and an acceptable low density.

One such core material is based on a honeycomb construction. The structural requirement can be obtained via the honeycomb and fire resistance requirements can be obtained by filling the cells with non-combustible insulating material.

There is very limited published work in this area of research concerning fire resistant honeycomb sandwich panels, in particular, the development of a honeycomb core panel with good insulation properties at elevated temperature. Some research development has been carried out concerning honeycomb composite materials for high heat flux encountered in many aerospace applications. For example, at the nose cap of a glide re-entry vehicle, temperatures are expected to approach $2760^\circ C$. The combination of metal honeycomb and ceramic is an example of this type of composite where a metal honeycomb is embedded in a ceramic body . The function of the metal honeycomb is not to serve a structural

requirement. It is to control the thermal shock properties by preventing the propagation of cracks through the ceramic phase and providing some flexibility to the overall structure.

Considerable success has been achieved in this manner. Both ballistic missile nose cones and rocket engine parts have been successfully fabricated and tested using material systems of this type[59].

Burnett[60] (1960) has reported that, in addition to the oxide filled honeycomb structures, nitrides and carbides have been successfully fabricated into similar structures. A further development of this type of composite structure has been reported by Vogan and Trumbull[59] (1964). These structures were basically chemically bonded zirconia incorporating a novel metal honeycomb. Excellent thermal shock resistance for operation at $1300^\circ C$ was obtained by selecting the proper honeycomb cell size.

The best system studied was reported to be a partially crushed honeycomb structure in which the honeycomb is bonded to desired backing material and partially filled with a fibrous insulating material. The remainder of the structure was then filled with an alumina mix which was pressed into place and cured at $420^\circ C$. A 12.7mm thick composite of this material was found to produce a temperature gradient of $760^\circ C$ when the hot face temperature was measured to be $1650^\circ C$.

CHAPTER 2
SANDWICH BEAM THEORY AND
CALCULATION OF HONEYCOMB
CORE SHEAR MODULUS

CHAPTER 2

2.1 INTRODUCTION TO SANDWICH BEAM THEORY

Sandwich panels may be classified into two types for design purposes. The first is those with thin flat or lightly profiled types as shown in fig 2.1a and 2.1b, and the second is those in which one or both faces are thick or heavily profiled (fig.2.2a and 2.2b). The former type are used mainly for walls and the latter may be used for both walls and roofs in building construction.

For design purposes, it is necessary to consider panels with flat or lightly profiled faces separately from those with thick or profiled faces.

The structural analysis of sandwich beams with thin flat facings has been investigated as early as the 1940's at the United States Forest Products Laboratory. Two different approaches were evolved. The first one was based on equilibrium consideration and internal and external compatibility requirements. The second approach adopted variational methods where the equilibrium statement was defined in terms of stationary energy principles in order to reduce the governing system of partial differential equations to a corresponding system of ordinary differential equations.

The research and development of sandwich beams with thick or profiled facings for the building industry were only introduced in the early 1970's . Early work

(a)
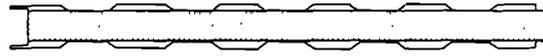
(b)

Figure 2.1 (a) Panel with flat thin faces

(b) Panel with light profiled faces
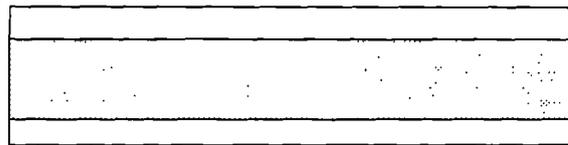
(a)

(b)

Figure 2.2 (a) Panel with flat thick faces

(b) Panel with profiled faces

was carried out by Hartsock[61] and Allen[62,63]. They presented methods for calculating deflection and stresses in simply supported sandwich panels with thick or formed faces. Allen[62] derived more general equations for beam columns subjected to combined transverse and edge loads using energy method. Stamm and Witte[30] and Davies[31,64] developed solutions for sandwich beam columns making use of equilibrium analysis.

In this chapter the analysis of sandwich beam with thin flat faces using Allen's approach [13] is re-presented. Then the analysis of sandwich beam with thick face having different thickness and elastic modulus using Stamm and Witte[30] approach for point loading is re-presented and the solution is modified for four point loading.

2.1.1 GENERAL ASSUMPTIONS

The stresses and deflections in a beam are found using bending theory. The theory is based on the following assumptions:

1.   The faces and the core are linearly elastic.

2.   There is adequate adhesion between the core and the faces.

3.   The shear   stress distribution is constant over the depth of the core.

4.   Deflections are small.

5.   The core is too weak to provide significant

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contribution to the flexural rigidity of the sandwich.

6.   There is no deformation of the core in the direction perpendicular to the core.

2.1.2   ANALYSIS OF A SANDWICH BEAM WITH THIN FLAT FACES : ALLEN'S THEORY[12]

The overall flexural rigidity D of a sandwich beam (see fig. 2.3) is the sum of the flexural rigidity of the two separate parts, namely the faces and the core, measured about the centroidal axis of the entire cross-section thus :

$$D = E_f \frac{bt^3}{6} + E_f \frac{btd^2}{2} + E_c \frac{bc^3}{12} \quad \ldots\ldots\ldots(2.1)$$

where

E_f is the Young's modulus of faces.

b   is the width of the beam.

t   is the face thickness.

d   is the distance between the centre lines of the opposite faces.

c   is the core thickness.

The first two terms represent the stiffness of the faces associated with bending about the centroidal axes of the entire sandwich cc, of these, the first term represent the local stiffness of the faces, bending separately about their own centroidal axes. The third term represents the bending stiffness of the core.
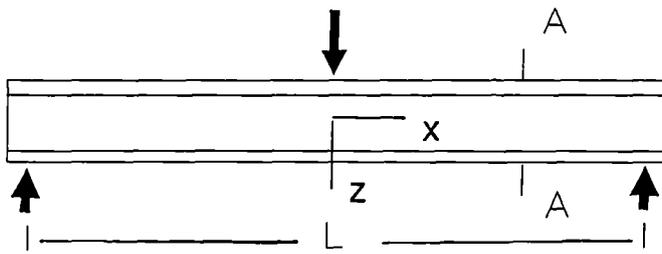
(a)
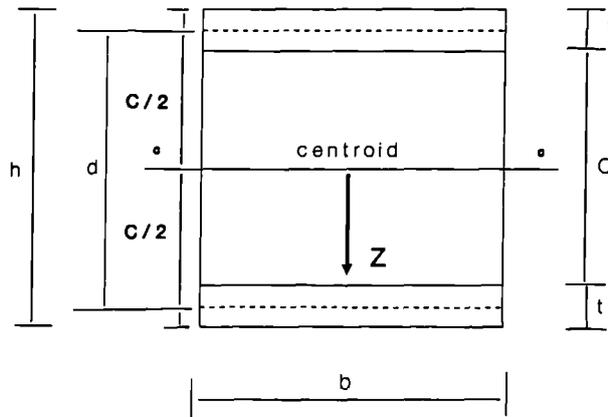
(b)

Figure 2.3 (a) Sandwich beam (b) Cross section A-A

In sandwich beams with thin flat faces the flexural rigidity of the faces is very small in which case the second moment of area is negligible. The bending stiffness of the core amount to less than 1% of the second term and may consequently be neglected. The overall flexural rigidity is reduced to following :

$$D = \frac{E_f.b.t.d^2}{2} \qquad \dots\dots\dots(2.2)$$

The distribution of shear stress τ throughout section of a homogeneous beam has been modified to take account of the moduli of elasticity of different elements of the cross-section :

$$\tau = \frac{Q}{D.b} \Sigma(S\ E) \qquad \dots\dots\dots(2.3)$$

Where

Q   is the shear force.

$\Sigma(S\ E)$ is the sum of the products of first moment   of area (s) and   modulus of   elasticity (E) of the different component of the cross-section.

The shear stress at level Z in the core of the sandwich in fig. 2.3 is therefore :

$$\tau = \frac{Q}{D} \left[E_f \frac{t.d}{2} + \frac{E_c}{2} \left(\frac{c^2}{2} - z^2\right) \right] \dots\dots\dots(2.4)$$

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The shear stress in the faces and complete shear stress distribution across the depth of the sandwich is illustrated in fig. 2.4a.

For a very weak core it is permissible to write $E_c = 0$ in the equation (2.4); the shear stress in the core is then given by :

$$\tau = \frac{Q}{D} \cdot E_f \cdot \frac{t.d}{2} \qquad \dots\dots\dots (2.5)$$

In the case of sandwich beam with flat faces equation (2.5) is reduced to the simplest form :

$$\tau = \frac{Q}{b.d} \qquad \dots\dots\dots (2.6)$$

This Shear stress in the core is associated with a shear strain given by :

$$\gamma = \frac{Q}{G.b.d} \qquad \dots\dots\dots (2.7)$$

where

G is the core shear modulus.

Like shear stress it is constant through out the depth of the core. These shear strains produce a new kind of deformation (W_2) illustrated in fig. 2.5c. The points a,b c ...... which lie on the centre line of the faces are are moved in the vertical direction only by an amount W_2. Therefore, the average direct stress in the faces are independent of shearing displacement. This additional displacement caused by shear strain is added

41
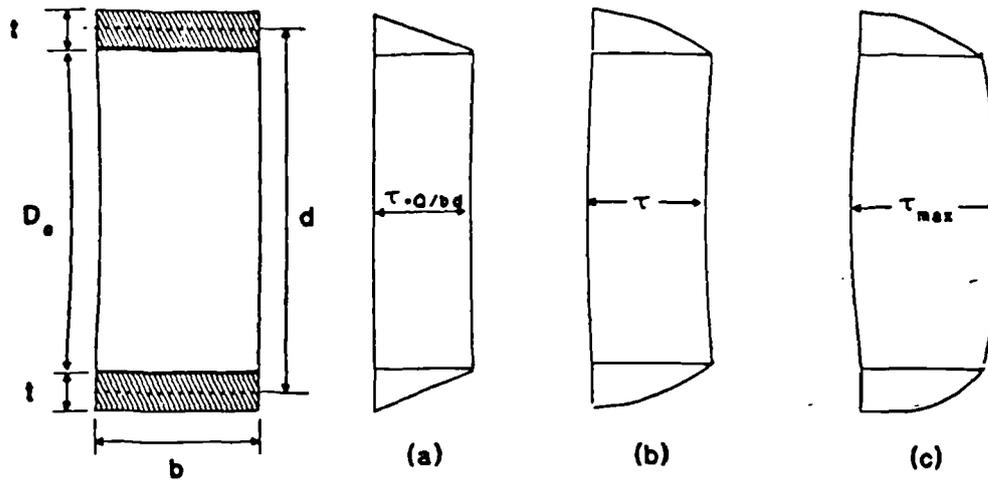
Figure 2.4 Shear stress distribution in sandwich beam.

(a) Effect of weak core, neglecting the local bending
stiffness of the faces.

(b) Effect of weak core.

(c) True shear stress distribution.
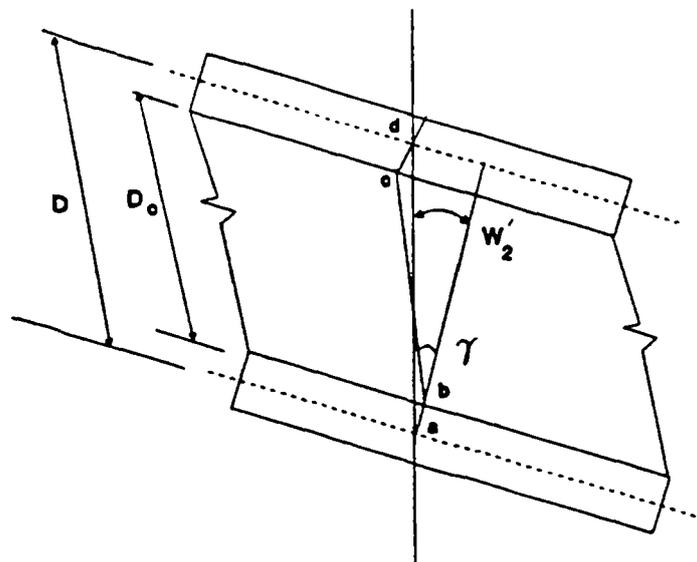
Figure 2.5 Shear deformation of a sandwich beam with thick faces.

to the ordinary bending deflection, to give a total displacement of :

$$\Delta = \Delta_1 + \Delta_2 = \frac{WL^3}{48D} + \frac{WL}{4AG} \qquad \ldots\ldots\ldots (2.8)$$

where

W is point load.

L is the span of the beam.

Δ_1 is centeral bending deflection

Δ_2 is central shear deflection

$A = bd^2/c$

2.1.3 ANALYSIS OF SANDWICH BEAM WITH THICK FACES

STAMM'S AND WITTE'S THEORY

The general principal of Allen's approach to the analysis of simply supported sandwich beam with thin flat faces are initially presented. In this section analysis of a simply supported sandwich panel with thick faces of different thickness and modulus are re-presented using the Stamm and Witte approach. As this work is not available in English, Davies[30] has presented the basic equations and most important solutions which are re-produced here. The solution for a simply supported panel with point load any where on the span is presented and later the solution for a simply supported sandwich panel with four point loading is derived.

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2.1.3.1 GENERAL PRINCIPLES

The behaviour of a thick faced sandwich panel refers to the situation where the local bending rigidity of the facings contributes significantly to the overall sandwich stiffness. The contribution of the thick face has two separate components.

Figure 2.6 shows the relevant stress resultant and deformation associated with a typical sandwich element under the effect of applied an load. The relationships between the stress resultants and deformations are :

$$\left.\begin{array}{l} M_1 = B_1\ W^{II} \\[2mm] M_2 = -B_2\ W^{II} \\[2mm] M_S = B_S(W_1{}^{II}) \end{array}\right\} \qquad \dots\dots\dots(2.10)$$

where

M_1, M_2 are the bending moments in the upper and lower faces, respectively.

B_1, B_2 are the flexural rigidities of the upper and lower faces, respectively.

M_S is the bending moment in sandwich part of the cross section.

B_S is the flexural rigidity of the sandwich part of cross section.

W is the total deflection

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$$Q_s = A\ G_{eff}$$
$$Q_1 = B_1\ W'''$$
$$Q_2 = -B_2\ W'''$$

........(2.11)

where

Q_1, Q_2 are the shear forces in the upper and lower faces, respectively.

Q_s is the shear force in the sandwich part cross section.

G_{eff} is the effective shear modulus of core;= $G_{nom} \cdot D/D_c$.

$A = B \cdot D_c$

Since the stress resultants in the two faces are proportional to the same deformation, it is suitable to treat them together, thus,

$$M_D = M_1 + M_2$$
$$M = M_D + M_s$$

........(2.12)

$$Q_D = Q_1 + Q_2$$
$$Q = Q_D + Q_s$$

........(2.13)

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(a) stress resultants   (b) deformation element
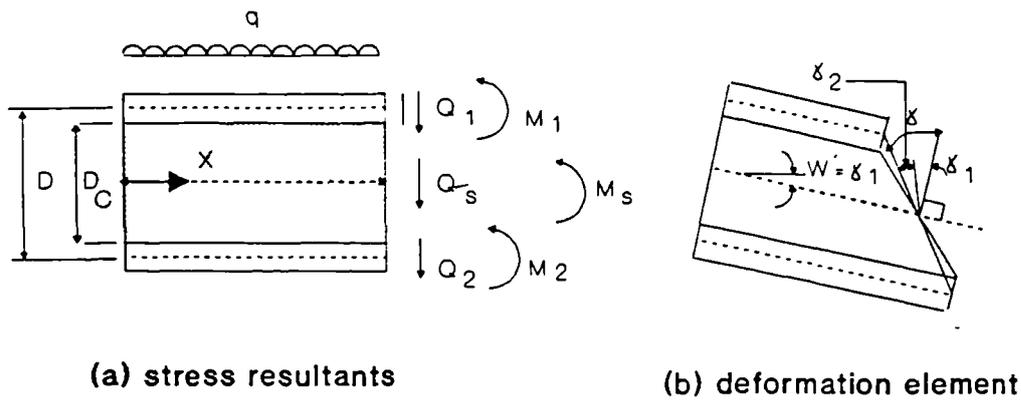
Figure 2.6 Forces and deformations in a typical sandwich element

$$B_D = B_1 + B_2$$
$$B = B_D + B_s$$

$$\dots\dots(2.14)$$

where –

M_D is the total moment in faces.

M is total bending moment in the panel.

B_D is the total flexural rigidity of the faces.

B is the total flexural rigidity of the panel.

Q_D is the total shear force in the faces.

Q is the total shear force in the element

The total moment M and shear force Q may be found using equations (2.10) and (2.11), thus,

$$Q = A \cdot G_{eff} \ \gamma - B_D \cdot W^{III}$$
$$M = B_s(\gamma' + \theta) - B \cdot W^{II}$$

$$\dots\dots(2.15)$$

Excluding γ and noting that $Q_1 = -q$, a fourth order differential equation in W is obtained.

$$W^{IV} - (\frac{\lambda}{L})^2 W^{II} = (\frac{\lambda}{L})^2 \frac{M}{B} + \frac{1+\alpha}{\alpha} \frac{q}{B}$$
$$- (\frac{\lambda}{L})^2 \frac{Q}{1+\alpha}$$

$$\dots(2.16)$$

Where :

$$\alpha = \frac{B_D}{B_s}$$

$$B = \frac{B_s}{A.G_{eff}\ L^2}$$

$$\lambda^2 = \frac{1+\alpha}{\alpha.\beta}$$

...(2.17)

similarly, excluding W from (2.15)

$$\gamma^{II} - \frac{(\lambda)^2}{L}\gamma = \frac{1}{B}\ \beta\ \lambda^2\ Q \qquad ....(2.18)$$

For statically determinate systems, the general solutions of (2.16) and (2.18) are :

$$W = C_1\ \cosh\ \frac{\lambda X}{L}\ +C_2\ \sinh\ \frac{\lambda X}{L}\ +C_3+C_4 X+W_p$$

$$\gamma = D_1\ \cosh\ \frac{\lambda X}{L}\ +\ D_2\ \sinh\ \frac{\lambda X}{L}\ +\ \gamma_p$$

...(2.19)

Where W_p and γ_p are particular integrals which depend on the loading etc. As these solution must satisfy (2.15) it follows that

$$D_1 = (1+\alpha)\ \frac{\lambda}{L}\ C_2$$

$$D_2 = (1+\alpha)\ \frac{\lambda}{L}\ C_1$$

...(2.20)

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Stamm and Witte gave the solution of the above equations
for simply supported panels subject to :

    (a)   uniformly distributed load.

    (b)   point load.

    (c)   uniform temperature   difference between
            faces.

The solution for a simply supported panel with a point
load is re-presented in the following section and later
it is used to derive the solution for simply supported
sandwich panel with four point loading.

2.1.4.2 SIMPLY SUPPORTED BEAM WITH POINT LOAD P

Stamm and Witte[30] presented the following work as
solution for the simply supported beam under point load.
Figure 2.7 shows a simply supported beam with transverse
load P at a position given by X = e. i.e. ϵ = e/l
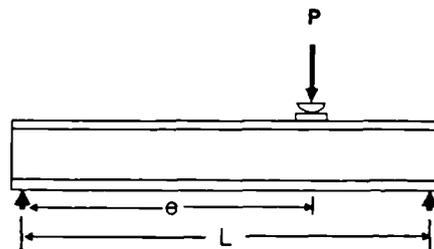
Figure 2.7

The bending moment and shearing force are determined by

$$M = \frac{P}{L}(L-e)x - P(X-e)^{o}$$
$$Q = \frac{P}{L}(L-e) - P(x-e)^{o}$$

..........(2.21)

The particular integrals in equation (2.19) are then

$$W_p = \frac{P}{6BL} \left[-(L-e)X^3 + L(x-e)^3 \right] - \frac{PL}{B\lambda^2}$$

$$\left[(L-e)X + \frac{L}{\alpha}\left(X-e - \frac{\sinh\lambda(X-e)/L}{\lambda/L}\right) \right]$$

$$(X-e)^0 \Bigg] \qquad\qquad ..(2.22)$$

$$Y_p = \frac{\beta PL}{B} \left[L-e-L(1-\cosh\frac{\lambda(x-e)}{L}(X-e)^0 \right]$$

using index 1 valid for $0 \ll \xi \ll \epsilon$ and index 2 for

$\epsilon \leq \xi \leq 1$

$$W_1 = \frac{PL^3}{B} \left[\frac{1}{6}(1-\epsilon)\,\xi\,(2\epsilon-\epsilon^2-\xi^2) + \frac{1}{\alpha\lambda^2} \right.$$

$$\left. (1-\epsilon) - \frac{1}{\alpha\lambda^3}\frac{\sinh\lambda(1-\epsilon)}{\sinh\epsilon\,\lambda}\sinh\lambda\xi \right]$$

$$\qquad\qquad (2.23)$$

$$W_2 = \frac{PL^3}{B} \left[\frac{1}{6}\,\epsilon\,(1-\xi)(-\epsilon^2+2\xi-\xi^2) + \frac{1}{\alpha\lambda^2} \right.$$

$$\left. \epsilon(1-\xi) - \frac{1}{\alpha\lambda^3}\frac{\sinh\lambda\,\epsilon}{\sinh\lambda}\sinh\lambda(1-\xi) \right]$$

$$Y_1 = \frac{PL^3}{B}\,\beta\left[1-\epsilon + \frac{\sinh\lambda(1-\epsilon)}{\sinh\lambda}\cosh\lambda\xi \right]$$

$$\qquad\qquad (2.24)$$

$$Y_2 = \frac{PL^2}{B}\,\beta\left[-\epsilon + \frac{\sinh\lambda\,\epsilon}{\sinh\lambda}\cosh\lambda(1-\xi) \right]$$

$$M_{S1} = PL \frac{1}{1+\alpha} \left[(1-\epsilon) \left\{ - \frac{\sinh \lambda (1-\epsilon)}{\sinh \lambda} \sinh \lambda \xi \right] \right.$$

$$M_{S2} = PL \frac{1}{1+\alpha} \left[\epsilon (1-\xi) - \frac{\sinh \lambda \epsilon}{\sinh \lambda} \sinh (1-\xi) \right] \right\} \quad (2.25)$$

$$M_{D1} = PL \frac{\alpha}{1+\alpha} \left[(1-\epsilon) \left\{ + \frac{\sinh \lambda (1-\epsilon)}{\alpha \lambda \sinh \lambda} \sinh \lambda \xi \right] \right.$$

$$M_{D2} = PL \frac{\alpha}{1+\alpha} \left[\epsilon (1+\xi) + \frac{\sinh \lambda \epsilon}{\alpha \lambda \sinh \lambda} \sinh \lambda (1-\xi) \right] \right\} \quad (2.26)$$

$$Q_{S1} = P \frac{1}{1+\alpha} \left[1-\epsilon - \frac{\sinh \lambda (1-\epsilon)}{\sinh \lambda} \cosh \lambda \xi \right. $$

$$Q_{S2} = P \frac{1}{1+\alpha} \left[-\epsilon + \frac{\sinh \lambda \epsilon}{\sinh \lambda} \cosh \lambda (1-\xi) \right] \right\} \quad (2.27)$$

$$Q_{D1} = P \frac{\alpha}{1+\alpha} \left[1-\epsilon + \frac{\sinh \lambda (1-\epsilon)}{\alpha \sinh \lambda} \cosh \lambda \xi \right. $$

$$Q_{D2} = P \frac{\alpha}{1+\alpha} \left[-\epsilon - \frac{\sinh \lambda \epsilon}{\alpha \sinh \lambda} \cosh \lambda (1-\xi) \right] \right\} \quad (2.28)$$

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2.1.3.3 SIMPLY SUPPORTED BEAM WITH FOUR POINT LOAD

The solution for single point loading presented in section 2.1.4.2 has been modified to suit a 4 point loading arrangement. For the 4-point load case, the calculation segments required to be assessed twice, each with opposite loads.

A Computer program was written to process the repetitive deflection and bending and shear stress calculations given in the above equations using a computer incorporating FORTRAN as the programming language.

By solving these equations twice, taking at first the left hand point load into consideration then the right hand point load and adding them. A solution for a four point loaded beam is achieved. The problem is illustrated diagrammatically in fig. 2.8.

The program calculates the stresses for each element of the sandwich beam at any given cross-section together with the deflection of the beam at any cross section. The computer program is presented in the Appendix A together with a typical output.
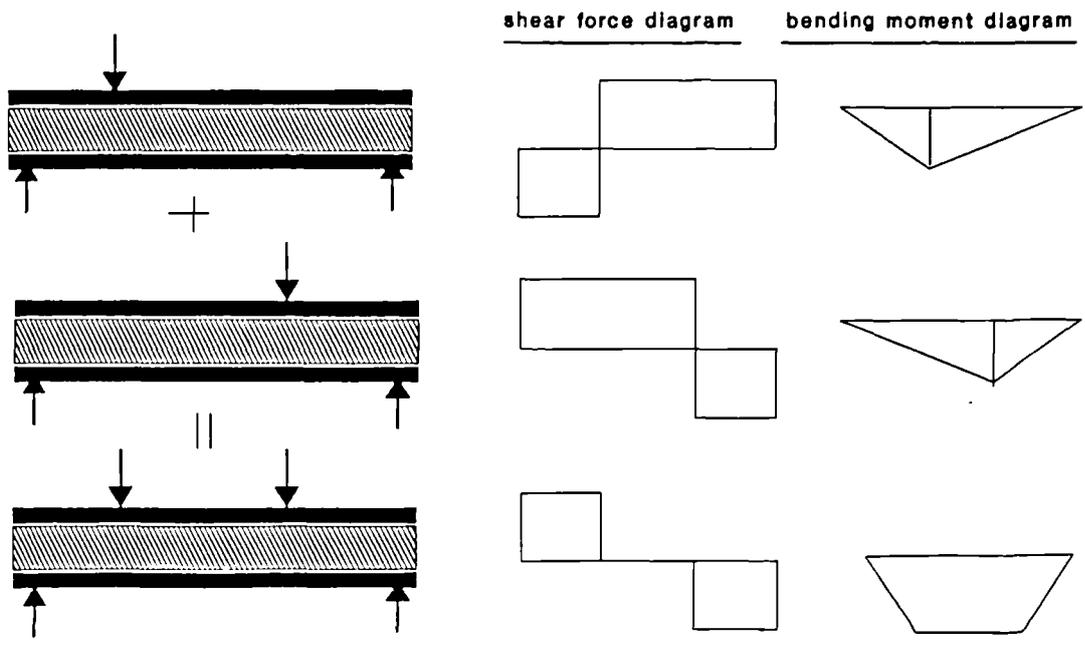
Figure 2.8 Diagramatic presentation of 4-point loading solution

2.2 CALCULATING THE SHEAR MODULUS OF

THE DEVELOPED HONEYCOMB CORE

2.2.1 INTRODUCTION

A Honeycomb is a two dimensional array of polygons which pack to fill a plane area like the hexagonal cells of the bees hive. Honeycombs are often used as cores in sandwich panels in applications where weight-saving is critical: in aircraft, in space vehicles, in portable structures and in sports equipment. The function of the honeycomb core here is to carry normal load and shear loads in planes containing the axes of the hexagonal prisms (the X3 direction as shown in fig. 1.2). In such a honeycomb construction, the shape and size of the cells and the thickness of the cell walls can be varied. A change in any of these may be expected to change the strength of the honeycomb.

The aim of this particular work was to present expression to relate the shear modulus of the honeycomb core under investigation to it's cell geometry. In order to demonstrate the accuracy of the analysis, the results of the calculations are compared with experimental work performed on the developed honeycomb core sandwich beams described in chapter 8.

The honeycomb-type structures used in this study were made by sodium silicate, or clay based sodium silicate-impregnated paper as described in chapter 6.

2.2.2 CALCULATION OF SHEAR MODULUS

The distribution of stress in a honeycomb is not simple, according to Kelsey[65] ,Chang and Ebcioglue[66] and Penzein and Didriksson[67], each cell suffers a non_uniform deformation due to the constraint imposed on it by it's neighbours and that the initial plane of the honeycomb may not remain plane. Exact calculation of the shear modulus is only possible by using numerical methods. Gibson and Ashby[35] derived upper and lower bounds for the honeycomb shear modulus by simplifying the method used by Kelsey et al[65].This was done by calculating the strain energy associated, first with a strain distribution which allows compatible deformation and second, with a stress distribution which satisfies equilibrium. The solution is exact if the two coincide and if not, the true solution lies between them. Gibson and Ashby[35] made use of the theorems of minimum potential energy and of minimum complementary energy to obtain upper and lower bounds for the shear modulus. The first theorem gives an upper bound shear modulus. It states that the strain energy calculated from any postulated set of displacements which are compatible with external boundary conditions and with themselves attains an absolute minimum when the displacements of the body are those of the equilibrium configuration. Gibson and Ashby derived expressions for the upper bound shear modulus by considering a uniform shear
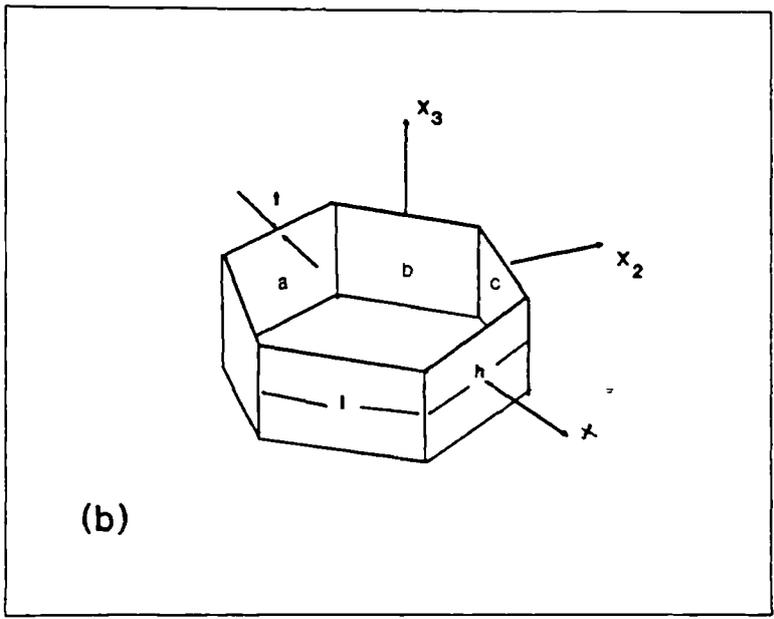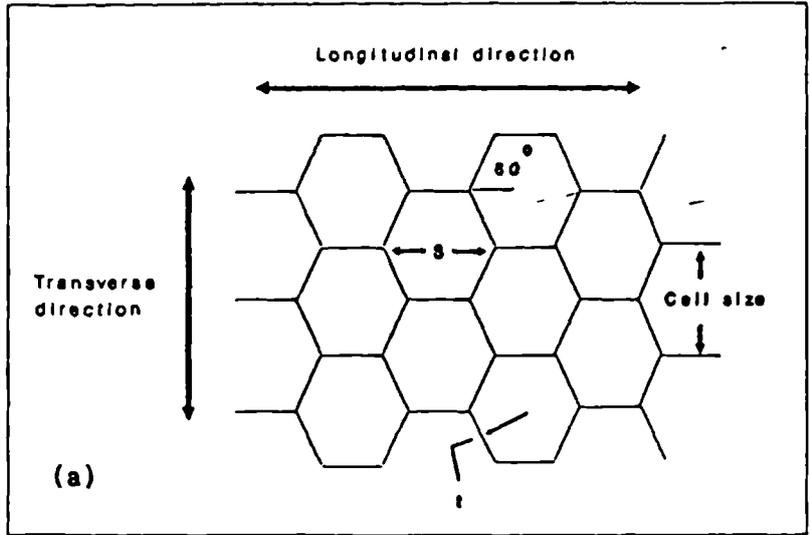
Figure 2.9 (a) The geometric form of a honeycomb with hexagonal cell, (b) one cell, showing the walls a, b and c.

γ_{13}, caused by a shear stress τ_{13} acting on the face normal to X_3 in the X1 direction of a unit-cell which repeats exactly to build up the entire honeycomb. The elastic strain energy is stored in the shear displacement in the cell wall. The shear strain in the cell walls a,b and c (fig. 2.7b) are

$$
\left.
\begin{array}{l}
\gamma_a = 0 \\[6pt]
\gamma_b = \gamma_{13}\cos\theta \\[6pt]
\gamma_c = \gamma_{13}\cos\theta
\end{array}
\right\} \qquad \dots\dots\dots(2.29)
$$

The authors expressed the theorem as an inequality and gave the following form for shear in X_1 direction

$$
\frac{1}{2}\, G_{13}\, \gamma^2_{13}\, V \ll \frac{1}{2}\, \Sigma_i (G_s\, \gamma_i^2\, V_i) \qquad \dots\dots(2.30)
$$

where
G_s = the shear modulus of the cell wall material.

γ_i = the shear strain in the three cell walls.

The summation of the shear strain in the cell walls is carried out over the three cell walls a,b, and c of volumes V_a, V_b and V_c. Evaluating the sum gives:

$$\frac{G_{13}}{G_s} \ll \frac{\cos \theta}{(h/l+\sin\theta)} (\frac{t}{l}) \qquad \ldots\ldots\ldots\ldots(2.31)$$

where

θ   is the core cell angle.

t   is the cell wall thickness.

h,l   are the core cell dimensions   as shown in
fig. 2.9b.

The calculation can be repeated for shear γ_{23} in the X_2 direction. The shear strains in walls a, b, and c will be

$$\left.\begin{array}{l} \gamma_a = \gamma_{23} \\ \gamma_b = \gamma_{23}\sin\theta \\ \gamma_c = \gamma_{23}\,\sin\theta \end{array}\right] \qquad \ldots\ldots\ldots\ldots(2.32)$$

and

$$\frac{G_{23}}{G_s} \leq \frac{1}{2} \frac{h/l+2\sin^2\theta}{(h/l+\sin\theta)\cos\theta} (\frac{t}{l}) \ldots\ldots\ldots(2.33)$$

The lower bound shear modulus was found by the authors using the principle of minimum complementary energy which states that among the stress distributions that satisfy equilibrium at each point and are in equilibrium with the external loads, the strain energy is a minimum for the exact stress distribution. For shear in the X_1 direction the authors expressed the shear modulus as an inequality

$$\frac{1}{2} \quad \frac{\tau^2_{13}}{G_{13}} \quad V \quad \ll \quad \frac{1}{2} \quad \Sigma_i \quad (\quad \frac{\tau^2_i}{G_s} \quad V_i \quad) \quad \ldots\ldots (2.34)$$

Loading the honeycomb in X_1 direction will result in an external stress τ_{13} which induce a set of shear stresses τ_a , τ_b and τ_c in the walls a,b and c respectively. By symmetry the shear stress in the wall b is equal to that in the wall c, and as the wall a is loaded in bending it carries no significant load (i.e. $\tau_a = 0$). Equilibrium requires that

$$2\tau_{13} \quad 1(h+1.sin\theta)cos\theta \quad = \quad 2\tau_b \quad tl.cos\theta \quad \ldots\ldots (2.35)$$

Combining equation (2.34)) with equilibrium equation (2.35) will give a lower bound for shear modulus:

$$\frac{G_{13}}{G_s} \quad \gg \quad \frac{cos\theta}{(h/1+sin\theta)} \quad (\frac{t}{1}) \quad \ldots\ldots (2.36)$$

Equations (2.31) and (2.36) show that the upper bound and lower bound shear modulus are identical indicating that the result is exact.

For a regular honeycomb h = 1 and θ = 30. Therefore expression for shear modulus of a regular hexagons is reduces to the following form:

$$\frac{G_{13}}{G_s} = 0.557 \quad (\frac{t}{1}) \quad \ldots\ldots (2.37)$$

If the honeycomb is loaded in X_2 direction, the external shear stress τ_{23} will induce a set of shear stresses τ_a, τ_b and τ_c in the walls a, b and c. Symmetry again require the shear stresses in the walls b and c to be equal (i.e. $\tau_b = \tau_c$).

Equilibrium in X_3 direction means that

$$\tau_a = \tau_b + \tau_c = 2\tau_b$$

Equilibrium in X_3 direction with external stresses gives

$$2\tau_{23}l(h+l.\sin\theta)\cos\theta = 2\tau_b \; tl \; \sin\theta + \tau_a th \quad \ldots (2.38)$$

so that $\qquad \tau_b = \tau_{23} \cos\theta \; \dfrac{l}{t}$ $\qquad\qquad \ldots\ldots\ldots(2.39)$

An expression for shear modulus in X_2 direction can be obtained by combining the inequality equation (eqn 2.34) with equations (2.38) and (2.39) as :

$$\frac{G_{23}}{G_s} \geq \frac{h/l+\sin\theta}{(1+2h/l)\cos\theta} \left(\frac{t}{l}\right) \qquad \ldots\ldots\ldots(2.40)$$

As equations (2.33) and (2.40) shows, the upper and lower bound shear modulus do not coincide for shear stress in the X_2 direction. But the bounds do coincide for a regular hexagons and both equations (2.33) and (2.40) will be reduced to the following form

$$\frac{G_{23}}{G_s} = 0.577 \left(\frac{t}{l}\right) \qquad\qquad \ldots\ldots\ldots(2.41)$$

The expression for the shear modulus of a regular honeycomb with shear stress in X_1 direction is identical with shear stress in X_2 direction (eqn (2.37) and (2.41)) indicating that regular hexagonal honeycombs are isotropic in the X_1-X_2 plane.

The shear modulus of the developed honeycomb core found from the tests are compared with shear modulis found by the calculations discussed above in chapter 8. Throughout the calculations honeycomb cores are considered to be irregular hexagons. Use was made of equations (2.31) and (2.37) for calculation of shear modulus in X_3 direction.

CHAPTER 3
TEST TO DETERMINE MATERIAL
PROPERTIES

CHAPTER 3

TESTS TO DETERMINE MATERIAL PROPERTIES

3.1 INTRODUCTION

The physical properties of materials used in the construction of sandwich panels are important for two purposes :

1_   For determination of certain parameters which
          must be known before design calculations.

2_   For quality control.

For the purpose of design analysis, only the former is concerned here. However, some of the test procedures may be identical for both purposes with different interpretations.

The physical properties of the material required for the design of sandwich panels are:_

   Core material :

                 shear modulus

                 shear strength

                 tensile modulus of elasticity

                 tensile strength

                 compression modulus of elasticity

                 compression strength

                 tensile bond to face material

                 creep factor

   Face material :

                 modulus of elasticity

yield strength

wrinkling stress.

The above face material applies to homogeneous materials and when the face material is none homogeneous such as timber the required properties will be as follows :

Timber facing :

modulus of elasticity in bending

modulus of rupture.

In this chapter description of the different standard test methods for rigid foam core material are presented, followed by previous work on shear properties, and finally the authors experimental work on physical properties of extruded and expanded polystyrene core will be discussed.

Discussion of tests to determine the properties of the face materials are presented in chapter 5.

3.2 NOTATION

A_O Initial cross section area   in compression test.

b Width of beam.

C Core thickness.

E_S Young's modulus of face material.

F Area of the specimen glued to the four steel plates in hinged shear test.

F_m, F_{10} Loads at cell structure collapse and 10% deformation respectively in compression test.

G_e Weight of sandwich beam.

G_C Core shear modulus.

h_O Initial height in compression test.

I Total moment of inertia of sandwich beam.

L Total beam span

Q_e Applied load in dynamic test.

T Complete duration of back and front vibration in seconds

W_S Deflection due to shear.

W_b Deflection due to bending.

X_m, X_O Defection of cell structure collapse and 10% deformation respectively in compression test.

τ Core shear stress.

δ Shear strain.

σ_m Compression stress at collapse of the cell

structure.

σ_{10} Compression stress at 10% deformation.

3.3 CORE PROPERTIES

In the design of sandwich panels the choice of suitable core materials is of particular importance. The low density core must be stiff enough in compression and shear in the plane perpendicular to the face to keep the faces fixed at given distance apart and to ensure that the faces and core act as a composite section under loading.

The mechanical properties of rigid plastic foams are dependent on the apparent density, the cell structure and the manufacturing process. Figure 3.1 shows the tensile strength, compression strength and shear strength as a function of the apparent density of rigid polyurethane foam[68]. The cell structure also has a very significant influence on the properties. The cell structure can be described as a skeleton and walls, supporting the construction of the foam. Therefore, it is important that for each foamed core the physical properties should be determined before the structural analysis is carried out.

The properties of most common rigid plastic core materials are listed in table 3.1. extracted from a paper by Stemmann[58] presented in a symposium on sandwich panels held at the University of Salford[69].

Strength (N/mm**2)

0.8
┤ A tensile strength
    B Compressive strength
0.6 ┤ C Shear strength
    ─
0.4

0.2

0

A

B

C

20   30   40   50   60   70
Density (kg/m**3)
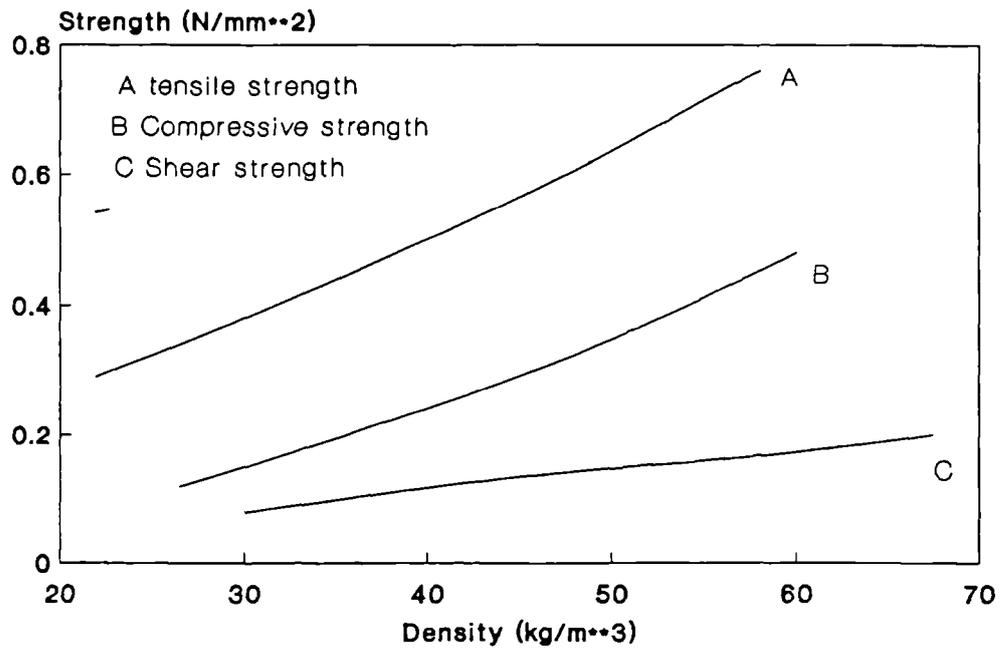
Figure 3.1 Typical relationships between
        STRENGH   and   density   of
rigiu polyurethane foam

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Table 3.1 Typical Material Properties of Rigid Plastic Foams Used in Sandwich Panels (at 20° C)

Property	Unit	Polystyrene		Phenolic	Polyurethane/ Polyisocyanurate
		Expanded	Extruded		
density	Kg/m³	20 - 50	25 - 55	35 - 60	35 - 55
tensile strength	N/mm²	0.15 - 0.6	0.2- 0.6	0.2 - 0.3	0.1 - 0.5
shear strength	N/mm²	0.1 - 0.4	0.2 - 1	0.1 - 0.3	0.1 - 0.3
compression strength	N/mm²	0.1 - 0.6	0.2 - 0.8	0.2 - 0.6	0.1 - 0.3
modulus of elasticity	N/mm²	4 - 20	16	--	2.5 - 8
shear modulus	N/mm²	2 - 8	15	—	2 - 4
thermal conductivity	W/(mK⁹)	0.032 - 0.04	0.025 -0.035	0.020 - 0.035	0.020 - 0.030
water vapour diffusion factor (μ) (air=1)		40 - 100	80 - 250	10 - 40	50 - 100
water absoption	vol.%	2 - 5	0.5 - 2	2 - 10	2 - 4
thermal dimension stability	°C	75 - 85	75 - 90	120	90/110

3.3.1 SHEAR TEST METHODS

There are number of test methods available to determine the shear strength and shear modulus of the foamed core of a sandwich construction. In the following test methods given in four international standards (BSI, DIN, ISO and ASTM) are described.

3.3.1.1 LAP SHEAR TEST ACCORDING TO BSI 4370,[69] DIN 5342[70] AND ISO 1922[71]

The methods described in BSI 4370[70] DIN 5342[71] and ISO 1922[72] determine shear strength parallel to the plane of the sandwich or core and shear modulus associated with strain in a plane normal to the facings.

According to the above standards[70,71,72,],test pieces 250 mm long, 50 mm wide and 25 mm thick are glued to metal supports through which the forces are transmitted. The metal supports are held between two fixing devices, one of these devices being fixed and the other moveable. The line of loading should pass through the centre line of the specimen (fig.3.2). After appropriate conditioning, five test pieces must rupture at a test speed of 1 mm per minute without separating from the metal supports. The core shear stress τ can be determined using:

$$\tau = \frac{P}{(L\ b)} \qquad \ldots\ldots\ldots (3.1)$$

and the shear strain which is the relative movement of

cross
section
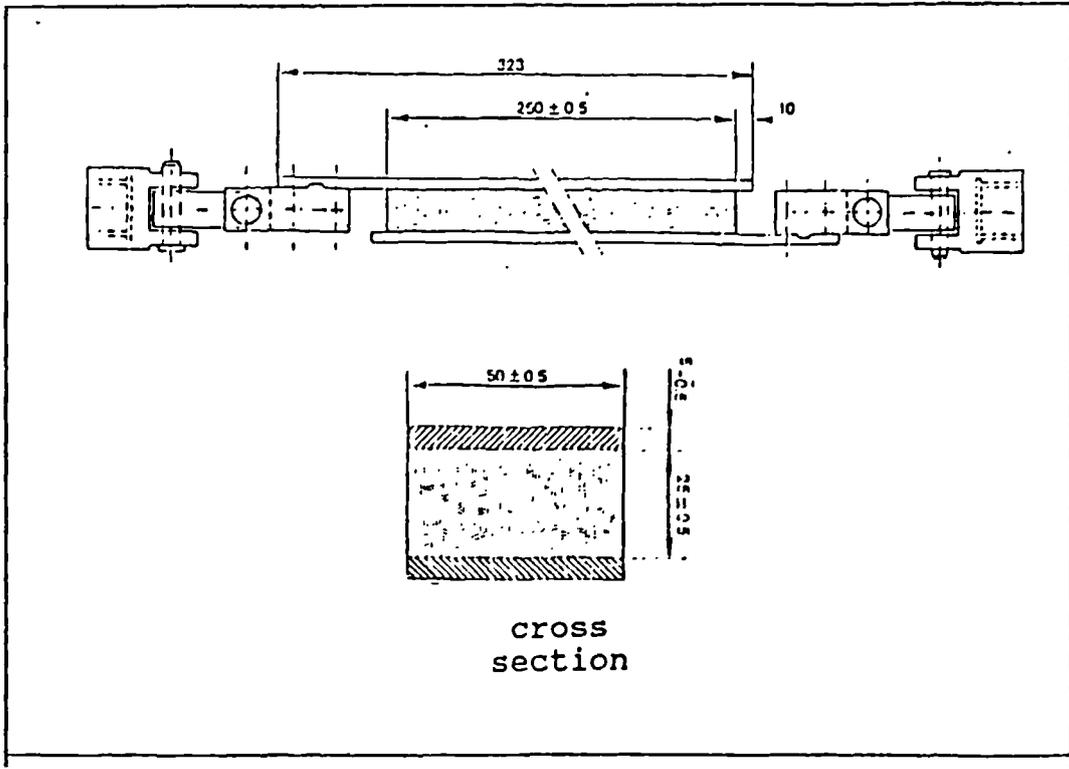
Figure 3.2. Lap shear test to BSI 4370, DIN 5342 and ISO 1922.

tension
test

compression
test
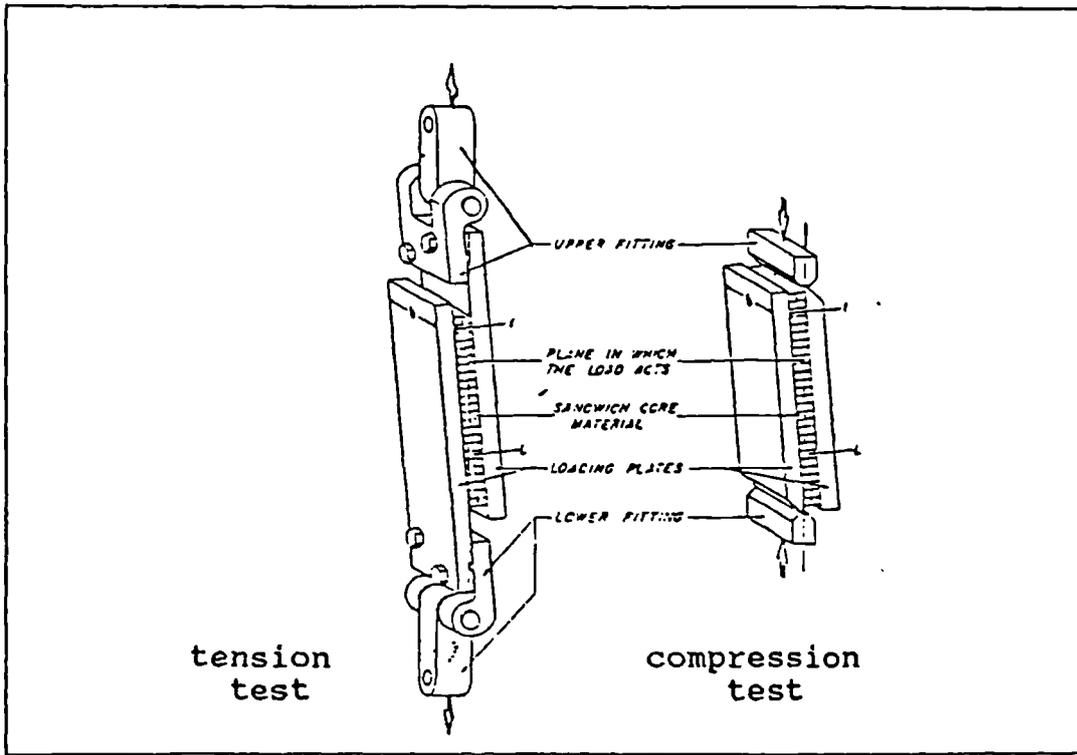
Figure 3.3. Lap shear test to ASTM C273-61

the two metal supports divided by the thickness of the core C may be written as :

$$\gamma = \frac{\delta_c}{C} \qquad \ldots\ldots\ldots(3.2)$$

The shear modulus can now be obtained from the following:

$$G_c = \frac{\tau}{\gamma} \qquad \ldots\ldots\ldots(3.3)$$

where

δ_c is the movement of one loading plate with respect to the other.

3.3.1.2 LAP SHEAR TEST ACCORDING TO ASTM C273-61[73]

The test method described in ASTM C273[73] provides information on the load-deflection behaviour of the sandwich construction or cores when loaded in shear parallel to the plane of the facing. The arrangement of the apparatus and test specimens for shear test and alternative method of applying the load in tension and compression are shown in fig. 3.3. According to the above standard, not less than five test specimens having a thickness equal to the thickness of the sandwich, a width not less than twice the thickness, and a length not less than 12 times the thickness shall be rigidly supported by means of steel plates bonded to the facings or core. The load is applied to the end of rigid plates

in compression or tension at a rate of movement such that the maximum load will occur within 3 to 6 minutes (0.13 mm / min. per 24.5 mm of specimen length). The load is applied through a spherical bearing block or a universal joint with the line of loading passing through the corners of the steel plates. Shear stress and shear strain can be calculated using the equations presented in section 3.3.1.

3.3.2 REVIEW OF OTHER WORK ON THE SHEAR PROPERTIES OF FOAMED CORE.

Various researchers previously quoted (section 1.5.1) have used tests on sandwich beams to obtain core shear modulus properties. Kuenzi[74], Doherty[75] et al and Allen[76] have described 3-point load tests while Howard[77] detailed a 5-point load test. All methods however, are based on the thin face sandwich beam theory and become inaccurate in cases where thick face action plays a dominant role in sandwich behaviour. This is particularly apparent in the paper by Doherty[75] et al, where results of sandwich beam tests were compared with those of standard shear tests. Allen[78] tackled the thick face problem to some extent. However, although the analysis of thick face action was sufficiently developed, the complex nature of the response made it difficult to accurately determine the core shear modulus values directly from simple tests on sandwich beams.

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Clapper[78] (1960) reviewed methods of shear and torsion testing of many materials. Raville[80] (1960) described a dynamic method based on forced flexural vibration of simply supported beams. Odell[81] (1965) used the dynamic response of beams supporting a large lumped mass to determine elastic and shear moduli.

Basu[82] (1976) determined the shear modulus of some continuously foamed material by four alternative methods and obtained the results shown in figure 3.4. The following tests methods were described by him.

3.3.2.1 FOUR-POINT TEST

A simply supported sandwich beam was subjected to a four point loading in which the two concentrated loads was applied at one third of span. The deformation of the beam consisted of two components, bending W_b and shear W_s. The shear deformation was calculated by subtracting the bending deflection from the total mid span deflection. The shear modulus was calculated from :

$$G_c = \frac{M}{[W_s \, b \, (h + t)]} \qquad \dots\dots\dots(3.4)$$

$$\tau = Q \, [\, b(h + t)] \qquad \dots\dots\dots(3.5)$$

$$\delta = \frac{3 \, W_s}{L} \qquad \dots\dots\dots(3.6)$$

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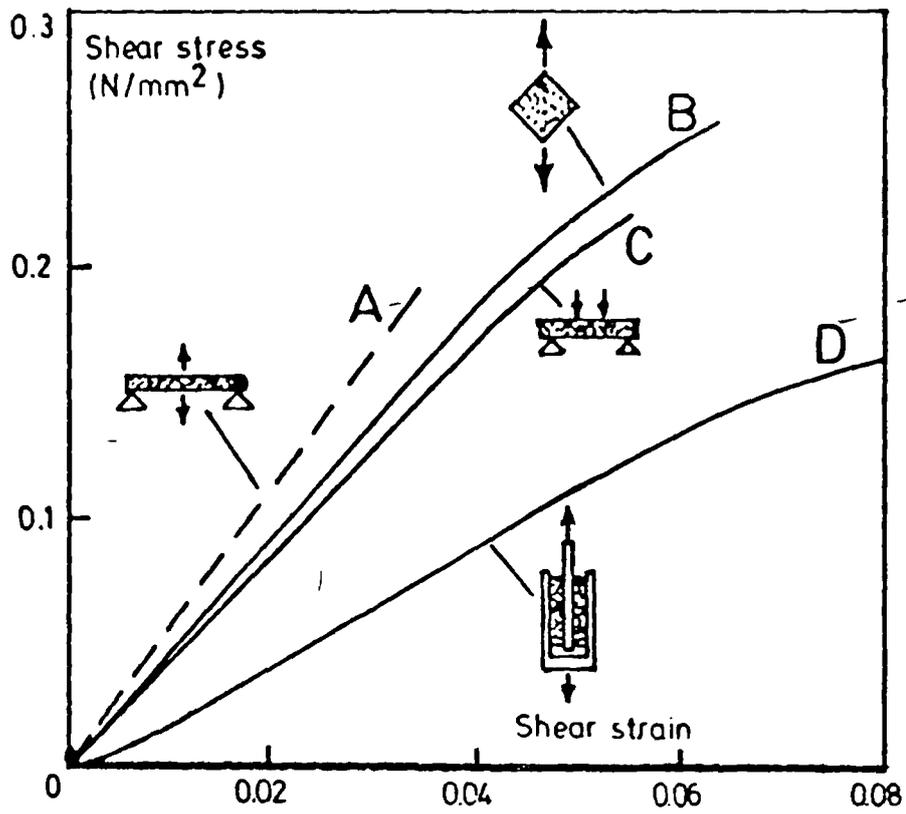
Figure 3.4 Results obtained by Basu from alternative tests to
determine the shear modulus of the core material

where

$$Wb = \frac{M\ L^2}{9.39\ E_s\ I}$$

$$Ws = W - W_b$$

$$I = 2\ b\ t\ [\ \frac{h+t}{2}\ ]^2$$

3.3.2.2 DYNAMIC TEST ON A SIMPLY SUPPORTED BEAM

Basu used this method to determine the shear modulus of the foam core from the relationship between the rigidity of the core and the inherent frequency of a sandwich beam. A sandwich beam was bonded in it's middle with a swinging single weight. With the aid of an inductive displacement transducers fixed to the beam, the displacement of the beam was measured, and by means of a pen the path of the swing was recorded until it was fully damped. Then the following relationship was used for shear modulus calculation.

$$G_c = \frac{1}{4\ bh\ [g/((Q_e + \alpha G_E)\ W_1^2) - W_b]} \qquad \ldots\ldots(3.7)$$

where

$$\alpha = \frac{17+336\ \beta+\ 1680\ \beta^2}{35(1+12\ \beta)^2} \qquad \ldots\ldots\ldots(3.8)$$

$$\beta = \frac{E_s\ I}{G_E\ b\ h\ l^2} \qquad \ldots\ldots\ldots(3.9)$$

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$$W_1 = \frac{2\pi}{T} \qquad\qquad ....(3.10)$$

3.3.2.3 TEST WITH A JOINED SQUARE

A square sample was glued to four stiff steel plates which were connected to hinges at four corners with sides equal to thickness of the sandwich. The steel plates containing the foam sample were pulled at the upper and lower joints by applying a tensile load as shown in fig. 3.5. The diagonal displacement u in the direction of pull dependent on the pulling force P is measured up to failure of the core. The shear properties were then calculated as follows :

$$\delta = \frac{\sqrt{2}\ U}{L} \qquad\qquad ....(3.11)$$

$$\tau = \frac{P}{\sqrt{2}\ F} \qquad\qquad ....(3.12)$$

This method was suggested by Basu[82] and Allen[12] as a particularly good determination of the shear properties. Later Basu results were verified by Hakmi[83].

Note: an alternative method as described in ASTM is by applying compression load at the upper and lower corners of the square and the four
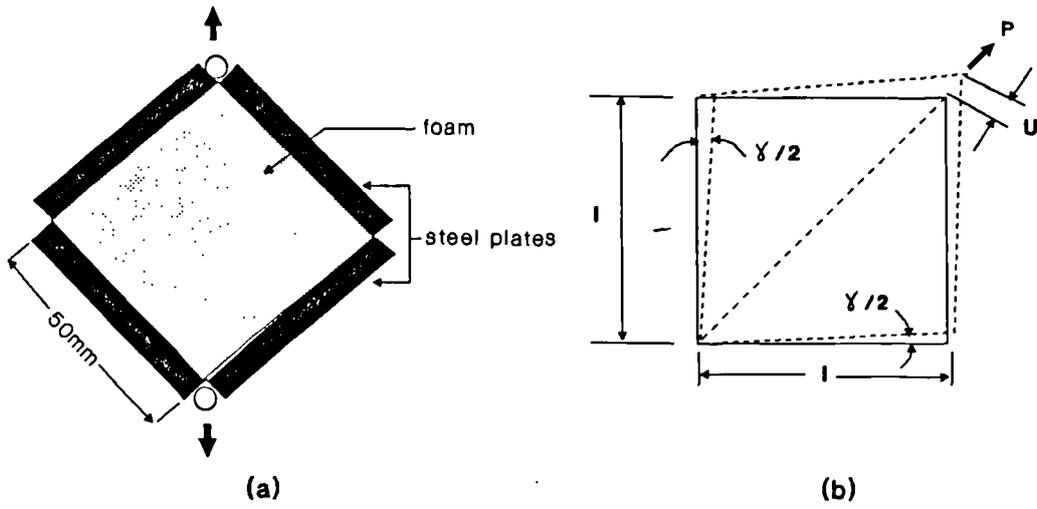
Figure 3.5. (a) Joined square shear test (b) diagonal displacement in direction of the pull
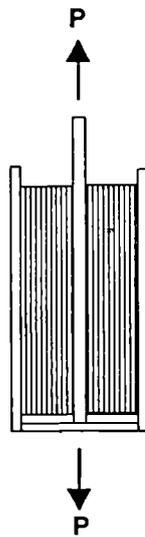
Figure 3.6. Double shear test

rigid   steel   are   bonded   to   the   specimen

without being hinged where they meet.

3.3.2.4 DOUBLE BLOCK TEST

In this test method two identical specimens were bonded

between three stiff steel plates and pulled apart in the

length wise direction. The shear test apparatus used for

this method is described in fig. 3.6. The relative

displacement between the surface layers in relation to

the tensile load P were measured from which the shear

properties were calculated as follows :

$$\tau = \frac{P}{2\ b\ L} \qquad \dots\dots(3.13)$$

$$\delta = \frac{U}{h} \qquad \dots\dots(3.14)$$

3.4 STANDARD COMPRESSION TESTS

The purpose of the compression test is to assess the

strength and deformation properties of the sandwich core

in compression.

The compression properties are, usually, determined for

design purposes in the direction normal to plane of the

facing as the core would be placed in structural

sandwich construction.

In the following, compression tests will be discussed

according to four international standards.

3.4.1 COMPRESSION TEST ACCORDING TO ASTM 365[84]

This standard describes a test procedure for determining compression properties of sandwich constructions. Test specimens shall be core or sandwich construction and shall be of square or circular with a cross-section area not exceeding 10000 mm^2 and not less than 625 mm^2 the height should be 100-200 mm but not grater than four times the width or diameter of the specimen should be cut so that the loaded ends will be parallel to each other and perpendicular to the sides of the specimen.

The load should be applied through a spherical loading block at rate of 0.003 cm / min. per unit height of the core.

3.4.2 COMPRESSION TEST ACCORDING TO ISO 844[85]

DIN 53421[86]AND BSI 4370[70].

These international standards describes methods of determining :

a) the compression strength and corresponding relative deformation.

b) the compressive stress at 10% relative deformation of rigid cellular plastics.

Five test specimen are required with an edge 50 mm long and thickness 50 mm or the thickness of the core provided that the minimum thickness is 10 mm. The test rig shall be between two flat hardened steel plates,

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between which the specimen is crushed. The compression
load is applied using a universal testing machine or
compression machine at constant speed of displacement of
10% per minute relative to height of the specimen. The
compressive stress at collapse of the cell structure
and at 10% deformation are given by :

$$\sigma_m = \frac{F_m}{A_o} \qquad \dots\dots\dots(3.15)$$

$$\sigma_{10} = \frac{F_{10}}{A_{10}} \qquad \dots\dots\dots(3.16)$$

where

F_m = maximum force.

A_o = the initial cross - section area (mm^2).

3.5 STANDARD TENSILE TEST METHODS

3.5.1 TENSILE TEST ACCORDING TO ISO 1926[87]

AND DIN 5430[88]

These standards gives details of the test for the
determination of the tensile strength of the core
material. Test specimen shall be of dumb-bell shape and
tensile load is applied by means of simple clamps. The
test specimens often fracture prematurely in the area
of transition between the wide end section and the gauge
length and if more than two such failures occur out of
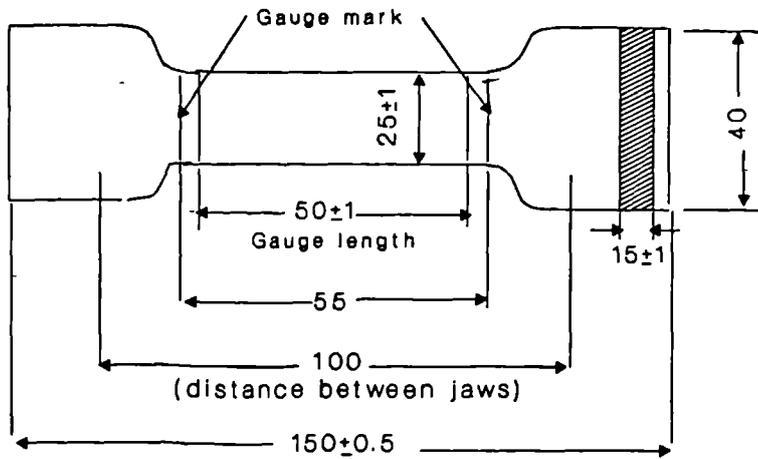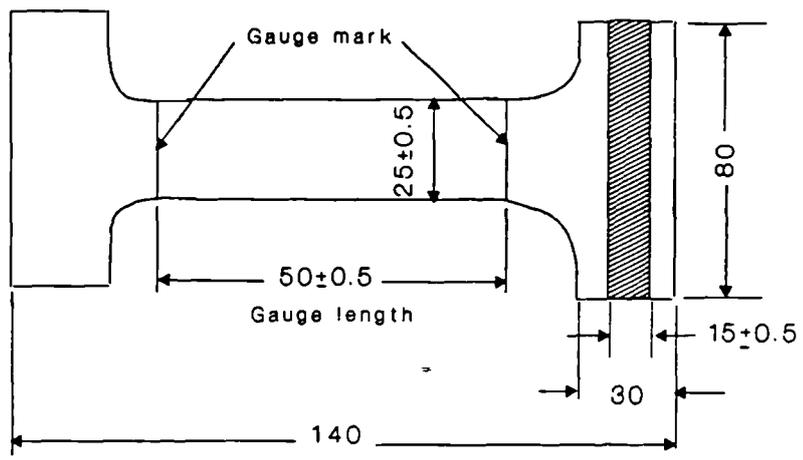
Figure 3.7 Different dumbells for tensile test to DIN 430 and ISO 1926

seven tests, a dumb-bell of different shape must be used (see fig. 3.7). The ends of these specimens are glued to metal plates which transmit the force from the test machine to the foam test piece. Maximum tensile stress can be obtain by dividing the maximum force applied by the original cross-section of the test piece. Tensile stress at rupture is given by dividing the maximum force applied at the moment of rupture by the cross-section.

DIN 53292[89] gives details of a tensile test perpendicular to the facing for sandwich construction. This test, unlike the tensile tests described above, serves primary to check the adhesion of the facing to the core. According to this standard five elements 50 mm x 50mm x thickness of the sandwich panel are glued to metal blocks, and tensile force are transmitted via these blocks free of moment. The arrangement of the apparatus and test specimen is shown in fig. 3.8.

3.5.2 TENSILE TEST ACCORDING TO BSI 4370[70].

This standard describes test methods for determining the tensile strength of core material by stretching the specimen at a speed of 10 mm/min. to breaking point.

The dimension of the specimen having a thickness of 12.5 mm is shown in fig. 3.9a. If the thickness of the specimen is greater than 12.5mm, a larger specimen shall be used having the dimension shown in fig. 3.9b. The
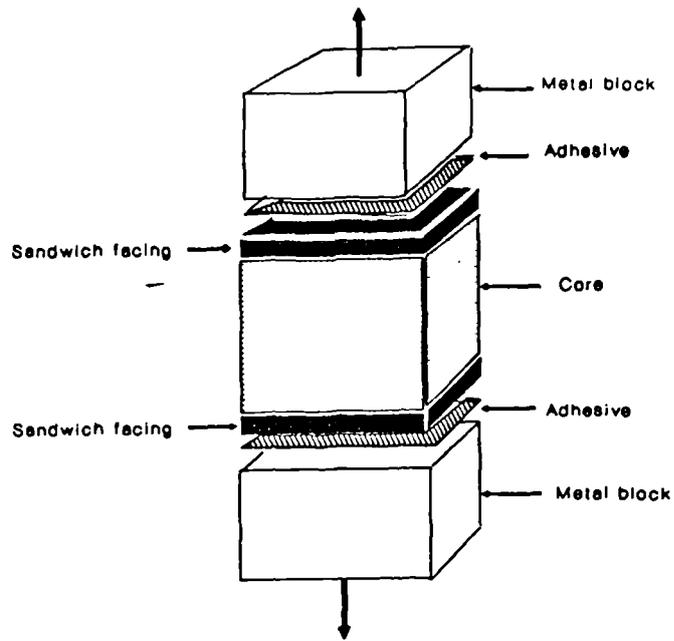
Figure 3.8   Tensile test to DIN 53292
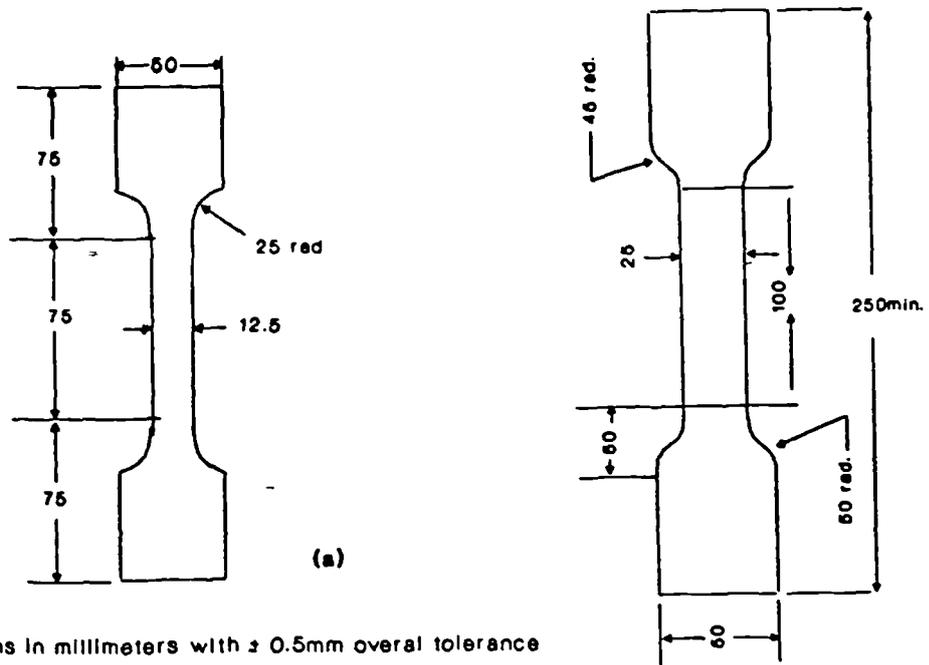
All dimensions In millimeters with ± 0.5mm overal tolerance

Figure 3.9 The dimension of the test specimen to BSI 4370

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tensile force is applied through the longitudinal axis of the test specimen through special holder, which shall be fixed in the testing machine. The tensile strength of the specimen is calculated using the following expression :

$$f_t = \frac{W}{B\ D} \qquad \ldots\ldots\ldots(3.17)$$

where

f_t = tensile strength.

W = maximum force.

B = width of the specimen.

D = thickness of the specimen.

3.5.3 TENSILE TEST ACCORDING TO ASTM C297[90]

This test method covers the procedure for determining the tensile strength flatwise of the core or the facing -to-core bond of a sandwich assembly. Five square specimens of thickness equal to the thickness of the sandwich with a minimum facing area of 635 mm^2 are bonded between heavy metal loading blocks which are pulled apart in a testing machine at a rate of 0.06 in/min. per inch of specimen thickness.

The flatwise tensile strength is then given by :

$$f_t = \frac{W}{B\ D} \qquad \ldots\ldots\ldots(3.18)$$

3.6 DISCUSSION ON DESCRIBED TEST METHODS

3.6.1 DISCUSSION ON SHEAR TEST METHODS

The four international standards describing the lap shear method assume a state of uniform shear stress along the entire length of the specimen and that the steel plates move parallel to each other. They agree on the dimension of the specimen, the number of specimen to be tested and rate of loading. However, the main difference between DIN, BSI, ISO and ASTM is in the orientation of the axis of loading to the axis of symmetry of the specimen.

In the ASTM the line of loading passes through the opposite corners of the two steel plates while the other standard the line of loading passes through the centre line of the specimen.

A comparison of all the results from the four testing method by Basu[82] revealed that: the lapped arrangement showed the lowest value of the shear modulus. Basu blames this firstly on the assumed state of uniform shear and he stated that the shear stress distribution is not constant and the shear stresses are different at the ends and in the middle of the specimen. Secondly, the stress distribution along the plane of loading is not pure shear. The dynamic method gives the highest value of shear modulus because of the very short duration of the vibration. The four square hinge method gives the actual shear properties of the core because,

for small values of stress, the specimen is in pure shear. The shear modulus found from the simply supported test with four - point loading only differ slightly from those obtained by joined sqare test method.

It is recommended that the lap shear test should be used solely as a quality control test and the joined square shear test or the beam with four point loading are suitable for determination of shear properties of rigid foamed core.

3.6.2 DISCUSSION ON COMPRESSION TEST METHODS

The four standards are similar to each other and the common points between them could be summarised in the following :

1.   The recommended cross-section in between 625 mm^2 and 100 mm^2 .

2.   A minimum of five specimen should be tested.

3.   The loaded ends should be parallel to each other and perpendicular to the sides of the specimen.

4.   The test permit the   calculation   of compression strength and of the compressive stress at a given compression.

3.6.3 DISCUSSION ON TENSILE TEST METHODS

The method described in ISO 1926[87], DIN 5430[88] and BSI 4370[70] describe a test method for determining the tensile strength of core material. The method described in ISO and DIN are similar to each other, Whereas the method described in BSI is not in agreement with them. The difference between them can be summarised in the following :

1.   The size of the test specimen shall have the dimension given in fig. 3.7 or depending on the plane of failure whereas in the BSI method the choice of specimen dimension depend on the thickness of the test specimen.

2.   The specimens are pulled by means of simple clamps as described in DIN and ISO but in BSI the specimen is placed in the holders which is fixed in the testing machine.

The test method described in DIN 53292[89] and ASTM C297[90] is for the determination of the strength in tension flatwise of the core, or of the bond between the core and facing of an assembled sandwich construction. The two standards are similar to each other in terms of specimen dimension, method of applying the load and fixing to the test rig.

The determination of the modulus of elasticity is not mentioned in the standards quoted. The distance

travelled by the movable grips is too imprecise a quantity to be used in calculating the modulus of elasticity. This requires additional sensitive strain gauges which are mounted on the specimen without interfering with the test and monitor the true deformation in the direction of the tensile stress and perpendicular to it.

3.7 AUTHOR'S EXPERIMENTS TO DETERMINE
CORE PROPERTIES.

The low density core material must be stiff enough in compression and shear in the plane perpendicular to the faces to keep the faces apart at a correct distance and to resist relative shear movement.

The mechanical properties of rigid foam core materials are density, temperature, humidity, and method of manufacture dependent. It is therefore essential, from the structural point of view, to determine the compression and shear strength by means of tests.

In the following, the author's experimental work related to the determination of the shear and compression properties of extruded polystyrene foam core will be discussed. In particular the determination of the core shear modulus was needed for the analysis of simply supported sandwich beams described in chapter 5.

3.7.1 JOINED SQUARE SHEAR TEST

To induce pure shear in a specimen of core material , a square core specimen was bonded to four rigid steel plates as illustrated in fig. No. 3.5. Five test specimens (50 x 50 x 50 mm^2) were cut from sheets of identical expanded and extruded polystyrene used as core material for beams described in section 5.2.1. The specimens were glued to four steel plates using Apaloo[91] (polyurethane based adhesive) and the test specimens were loaded in compression through two small bars as shown in fig. 3.5.

The load deformation curve was plotted for each specimen using the autographic recorder of testing machine.

The core shear stress and the core shear strain was calculated using the *following equations* :

$$\tau = \frac{P}{a\ c\ \sqrt{2}} \qquad \dots\dots\dots(3.19)$$

$$\delta = \frac{2\ \delta_c}{a\ \sqrt{2}} \qquad \dots\dots\dots(3.20)$$

The core shear modulus was determined by :

$$G_c = \frac{\tau}{\delta} = \frac{P}{2c\ \delta_c}$$

$$G_c = \frac{P}{\delta_c}\ \frac{1}{2c} \qquad \dots\dots\dots(3.21)$$

where
δ_C is the vertical movement of the specimen corner.

a./2 is the diagonal distance between the corners of the test piece.

P/δ_C is the slope of the initial linear portion of load deflection curve.

The result of the tests are listed in table (B1) in the appendix B.

3.7.2   COMPRESSION TEST

The compression test on rigid foams is described in DIN 53421[86],ISO 844[85] and ASTM 365[84] for tests on sandwich construction.

Five square test specimens (50 x 50 x 50 mm) were cut from a sheet of EXP polestyrene foam used as cores of the sandwich beams described in chapter 5.

The specimen were placed at the centre of the two parallel plates of the compression testing machine and compressive load was applied normal to the plane of facing, as the core would be placed in a sandwich construction.

The load deformation curve was plotted for each specimen using the autographic recorder of testing machine.

The compressive elastic modulus was calculated as follows :

$$E_c = \frac{P \; t}{A \; d} \qquad\qquad \ldots\ldots\ldots(3.22)$$

The compressive strength was calculated by dividing the maximum load at the moment the cell structure started to collapse by the initial cross-section of the specimen. The result of the tests are listed in table (B2) in the appendix B.

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CHAPTER 4
TIMBER-BASED FACING MATERIAL

CHAPTER 4

TIMBER-BASED FACING MATERIALS

4.1 INTRODUCTION

Timber is the most ancient, but still the most widely used, structural material in the world. The use of timber in building ships and furniture is as old as the Pyramids. During the sixteen century the demand in Europe for stout oaks for shipbuilding was so great that the population of suitable trees was depleted. Today the world production of wood is roughly the same as that of iron and steel: roughly 10^9 tonnes per year. Much of the total production is used structurally: for I beams; joists, flooring and supports which bear load.

There is also an increase in use of timber in structural sandwich panels. Timber-based materials such as plywood/ or particleboard are bonded to plastic rigid foam. This results in efficient rigid building panels.

The use of timber-based material for sandwich panel facings is not new. An early example is the design of the Mosquito bomber by De Haviland during the world war II. Birch plywood facings with a lightweight balsa wood core were employed.

In 1959 Markwardt and Wood[92] conducted experimental work on timber-faced sandwich panels with paper honeycomb core. They stated that sandwich panels with timber based-material with honeycomb core can be satisfactorily used for housing. The panels under

investigation were found to have much more than the minimum strength and stiffness necessary to meet the general requirement usually applied to such construction.

Due to the rapid increase in the use of timber-based material for sandwich panel facings and since the first part of this research concerned the behaviour of sandwich beams with timber-based facings it was decided to conduct an investigation into timber based material suitable for sandwich facings.
In this chapter methods of test for plywood and particleboards are reviewed and also some examples of the timber based materials suitable for sandwich panel construction are discussed.

4.2   PLYWOOD

Plywood is made up of veneers or plies glued together with adjacent plies having their grain generally at right angles to each other. The adhesive penetrates the surface of the wood, modifying it's properties so that there are composite bands of material stiffer than the wood itself at the junction of the veneers. Most commercial plywoods are of balanced construction, with an odd numbers of veneers arranged symmetrically with regard to thickness and species, although more than one species may occur in the make-up. By altering veneer thickness, ply orientation and species, plywood has demonstrated considerable versatility in being useful for a wide variety of industrial and residential construction market areas.

Although a very small part by the weight of the final product, the adhesive is extremely influential in determining the use to which any plywood may be put. This is not so much from structural considerations as it is the wood properties which determine the strength properties. The adhesive's strongest influence relates to the ability of the plywood to with stand degrees of weathering without loss of glue-line adhesion (i.e. delamination). Those adhesives of WBP (water and boil proof) type as defined in BS 1203[93] `synthetic resin adhesives (phenolic and aminoplastic) for plywood ' are accepted as capable of providing a bond in plywood which

is highly resistant to weather, micro-organisms, water, steam and heat. Other adhesive types, BR (boil-resistant), MR (moisture-resistant) and INI (interior) are progressively less resistant.

4.2.1 Theories of Plywood Bending

The distribution of stress in plywood is more complicated than that in solid timber. This is due to the fact that in a plywood beam those layers of plywood having their grain parallel to span have different bending properties from the adjacent veneers. The modulus of elasticity of plywood parallel to the grain is often 15 to 20 times greater than that in the direction at right angle to the grain. Thus the stress is by no means is proportional to the distance from the neutral axes (see fig. 4.1.).
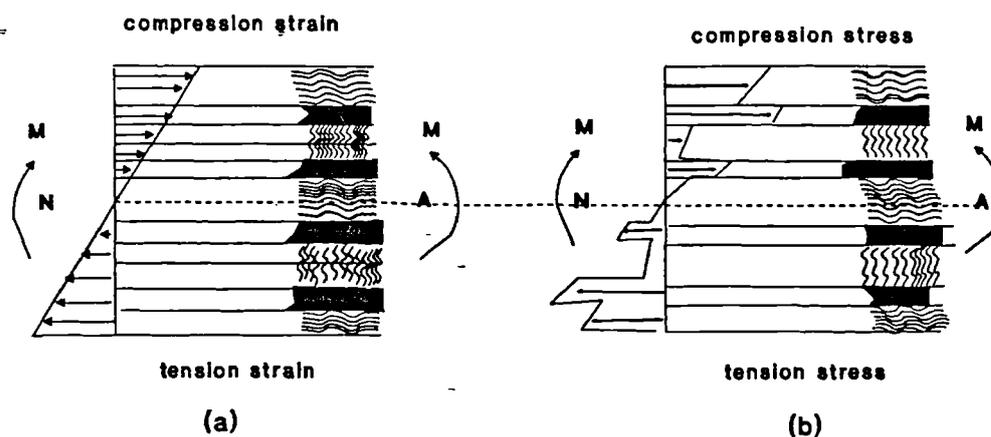
Figure 4.1. Stress and strain distribution across a plywood strip subjected to bending

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4.2.2 Elastic Strain Theory

The total stiffness of the plywood equals the summation of the stiffness of the individual plies.

$$E_p I' = \Sigma EI \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

where E_p = equivalant elastic modulus for plywood

E = elastic modulus of each element

I' = second moment of area of the full cross section.

I = second moment of area of each element

Curry[94] and Armstrong[95], working on the ultimate strength of plywood, adopted an elastics bending theory which assumes that in the case of bending with no shear, plane section remain plane and the stress is proportional to strain, both on tension and compression side of the neutral axis.

$$M = f\Sigma EI/EY = fI'/Y \; . \; EP/E \qquad \ldots\ldots\ldots\ldots (2)$$

Where f = stress in the most outer fiber of the outer ply with its grain parallel to the span.

E = elastic modulus of this element, and

Y = the distance between the outer face and the neutral axis.

Since the perpendicular to-the-span plies contribute little to the strength in bending, a simplification may be made by ignoring their effects and the effect of the

glue layers.

$$M = I_1/Y \qquad \ldots\ldots\ldots\ldots(3)$$

where I_1 = 2nd moment of area of plies having their grain parallel to the span

Curry[94] has found that this would lead to a considerable error in the case of 3-ply construction with the face grain perpendicular to the span.

The procedure of Douglas Fir Plywood Manufacturing Association[96] is to increase the value of M by 50% in this case, and by 15% in all other constructions.

The assumptions stated are not unreasonable within the limit of proportionality of the material, although stress is rarely proportional to strain for wood in compression, and consequently there will be a slight movement of the neutral axis. However, it is only applicable where the shear deformation are not great, as in beams with large span-depth ratio or regions of low shear such as the central portion of a uniformly loaded beam.

4.2.3 Geometrical Properties of Plywood

As a first stage in calculating the stress in plywood caused by a given load, the geometrical properties must be known.

In the following the standard procedure for calculating the moment of inertia and section modulus of plywood are described.

4.2.3.1 Moment of Inertia

Provided a balanced construction is adopted the moment of inertia of the equivalent solid wood about the centre line is:

$$I = BD^3/12$$

Lee[97] (1957) developed the following expressions for plywood, ignoring the plies with their grain perpendicular to the grain of the face veneer.
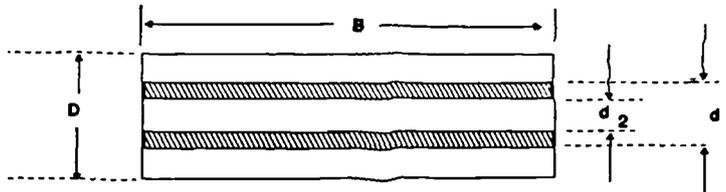
I_1 (parallel) $= B/12$ $(D^3 - d_1^3 + d_2^3)$

or $D^3 - d_1^3 + d_2^3$ per ft. width of board

I_2 (perpendicular) $= d_1^3 - d_2^3$ per ft. width of board

4.2.3.2 Section Modulus

Lee[97] described that the section modulus is the I value divided by the distance from the neutral axis, or section of zero bending stress, to the outer face of outermost effective ply.

Thus Z_1 (parallel) $= 2I_1/D$

and Z_2 (perpendicular) $= 2I_2/d_1$

4.2.4 METHOD OF TEST FOR CLEAR PLYWOOD

The British standard 4512[98] has been prepared to cover the method of testing clear plywood and is based on the United Nations FAO standard, also ASTM D805-63.

This British standard has been prepared to cover methods of testing clear plywood, defined as that manufactured from veneers containing no strength reducing defects. The methods defined in this standard are not generally suitable for commercial plywood but may be used with reservations on this material. Commercial plywood in practice is seldom completely free from imperfections, and even if manufactured to the appropriate specification, may contain defects comparable in size with certain dimensions of the specimens described in BS 4512 : 1969 and if commercial plywood is to be used for structural design purposes, then the test specimens should contain strength reducing characteristics of sufficient number and appropriately located to ensure that the results give a satisfactory estimate of the strength of the plywood when used as a structural component.

This British standard covers procedures for measuring the mechanical properties of plywood. Methods are described for determining the following properties:

Static bending, compression, tension, panel shear, modulus of rigidity, rolling shear, panel impact, moisture content, and density.

Test of the glue in plywood are covered in British standard 1203[93].

4.2.5 RECOMMENDATION FOR THE USE OF PLYWOOD

BS 5268 part 2[99], gives recommendations for the use of sanded and unsanded plywoods subject to the quality control procedures of the following:

American Plywood Association (APA)

British Standard Institution (BSI)

Council of Forest Industries of British Columbia (COFI)

Technical research Centre of Finland (VTT)

The National Swedish Testing Institute (Statens Provninigsanstalt)

BS 5268 Part 2[99] gives the section properties of plywoods, and these are based on the minimum thickness presented by the relevant product standard and are applicable to both dry and wet exposure conditions. The standard also covers the grade stress applicable to plywoods having the identification marks listed in the standard.

In the following two of the most common plywoods are discussed and compared.

4.2.6 CANADIAN COFI EXTERIOR PLYWOOD

The Canadian COFI exterior plywood is manufactured by the council of forest industries of British Colombia. The capacity of COFI's plywood sector exceeds 2 million cubic meters per year. It supplies 80% of Canada's needs and the balance of production is exported world wide. Canadian COFI Exterior plywood is an engineering panel built up of plies balanced with regard to thickness about the central ply or panel centrelines. The thickness and orientation of the plies determine the structural performance of the panel. The veneers are united under high temperature and pressure with thermosetting phenol formaldehyde glue that is completely water proof, making the plywood suitable for use under conditions of exposure to moisture.

COFI Exterior plywood is manufactured in two two types, Douglas Fir (DFP) and Canadian Softwood (CSP), and in a number of grades. Names of regular grades are based on the quality of the veneer used for the face and back of the panel. The three qualities of the veneer are designated by the letters A (the highest grade), B, and C (the lowest grades). The manufacturer, using these grades of veneer in various combinations, can produce panels for a variety of uses (see table 4.1).

4.2.6.1 PANEL SIZES AND THICKNESSES

COFI Exterior square-edge plywood panels are manufactured in panel sizes of 1200mm by 2400mm and 1220mm by 2440mm. The thickness of the regular grades of COFI Exterior plywood ranges from 6mm to 31.5mm.

4.2.6.2 PROPERTIES OF COFI

EXTERIOR PLYWOOD

The species permitted in faces, backs and inner piles of DFP and CSP are listed in table 4.2. The section properties for standard construction of regular grades of COFI Exterior DFP and CSP are given in tables 4.3 and 4.4.

The grade stresses for standard construction of regular grades of COFI exterior Douglas Fir plywood and softwood plywood are given in tables 4.5 to 4.7 for dry service conditions. For wet service condition (i.e. where the plywood will have a moisture content in excess of 18%), the modification factors given in table 4.8 must be used.

Table 4.1 Regular grades of COFI Exterior plywood%

Grade	Veneer Grades			Characteristics	Typical Applications
	Face	Inner Plies	Back		
good two sides	A	C	A	Sanded. Best appearance both faces. may contain neat wood paches, inlays or synthetic patching material.	Furniture cabinet doors. partitions, shelving concrete forms, opaque paint finishes.
good one side	A	C	C	Sanded. Best appearance one side only. May contain neat wood patches, inlays or synthetic patching material.	Where appearance of one exposed surface is important.
select-tight face	B	C	C	Unsanded. Permissible surface openings filled.	Underlayment and combined subfloor and underlayment
select	B	C	C	Unsanded. uniform surface with minor open splits.	
sheathing	C	C	C	Unsanded. Face may contain limitedsize knots.	Roof, wall and floor sheathing.
high density overlaid	B	C	B	Smooth resin-fiber overlaid surface. Further finishing not required.	Bins, tanks, boats, furniture, signs.
medium density overlaid	C'	C	C	Smooth resin-fiber overlaid surface. Best paint baes.	Siding, soffits, paneling.
CONFIFORM CONFIFORM SP.	A	C	A	Douglas Fir panels specially constructed to provide improved and premium strength and stiffness.	for premium perfomance applications. Particularly in wet service conditionc.
	A	C	C		
CONFIFORM PLUS. CONFIFORM SP PLUS.	B	C	C	Special construction Douglas Fir with exceptional stifness and strength.	
	C	C	C		

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Table 4.2 Selected British Columbia species used in COFI Exterior plywood%.

COFI Exterior Douglas Fir plywood		COFI Exterior Canadian Softwood plywood	
Faces and Backs	Inner Plies	Faces and Backs	Inner Plies
Douglas Fir	Douglas Fir Western Hemlock True Fir Sitka Spruce Westren white Spruce western Larch Western White Pine Ponderosa Pine Lodgepole Pine	Western Hemlock True Fir Sitka Spruce Western White Spruce Lodgepole Pine Western Larch	Douglas Fir Western Hemlock True Fir Sitka Spruce Western White Spruce Western Larch Western White Pine Ponderosa Pine Lodgepole Pine

Table 4.3 Section properties for standard construction of regular grades of unsanded COPI Exterior Douglus Fir plywood and COPI Exterior Canadian soft plywood%.

Nominal thickness (mm)	Number of plies	Section properties for a 1m width				Approximate weight per unit area (Kg/m²)
		Minimum thickness width	Area (10^3 mm³)	Section Modulus (10^3 mm³)	Second moment of area (10^3 mm³)	
7.5	3	7.0	7.0	8.17	28.6	4.4
9.5	3	9.0	9.0	13.5	60.7	5.5
12.5	3,4 and 5	12.0	12.0	24.0	144.0	7.2
15.5	5	15.0	15.0	37.5	281.0	8.9
18.5	5,6 and 7	18.0	18.0	54.0	486.0	11.0
20.5	5,6 and 7	20.0	20.0	67.0	667.0	12.0
22.5	6,7 and 9	22.0	22.0	81.0	887.0	13.0
25.5	7 and 9	25.0	25.0	104.0	1300	15.0
28.5	9	28.0	28.0	131.0	1830	16.0
31.5	9 and 11	31.0	31.0	160.0	2480	18.0

table 4.4 Section properties for construction of *regular* grades of sanded COFI Exterior Douglas Fir plywood%.

Normal thickness (mm)	Number of plies	Minimum thickness width (mm)	Section properties for 1 m			Approximate weight per unit area (Kg/m²)
			Area (10³ mm²)	Section modulus (10³ mm³)	second moment of area (10³ mm⁴)	
6	3	5.5	5.5	5.04	13.9	3.4
8	3	7.5	7.5	9.38	35.2	4.7
11	3, 4 and 6	10.5	10.5	18.4	96.5	6.3
14	5	13.5	13.5	30.4	205	8.0
17	5, 6 and 7	16.5	16.5	45.4	374	9.7
19	5, 6 and 7	18.5	18.5	57.0	528	10.8

Table 4.5 Dry grade stress and moduli for unsanded COFI Exterior Canadian softwood plywood%.
(Sheathing, select and select tight face grades)

Type and direction of stress and modulus (N/mm²)	Nominal thickness and number of plies (in parentheses)										
	7.5 (3)	9.5 (3)	12.5 (3)	12.5 (4)	12.5 (5)	15.5 (5)	18.5 (5)	18.5 (5)	18.5 (6)	18.5 (7)	20.5 (5)
Extreme fiber in bending											
Face grain parallel to span	7.69	7.16	7.66	6.99	7.45	6.49	5.79	6.78	6.37	5.91	
Face grain perpendicular to span	2.28	2.25	2.26	3.45	3.39	3.14	3.83	3.33	3.36	4.33	
Tension											
Parallel to span	3.40	2.69	3.35	2.55	2.88	2.74	3.48	3.11	3.04		
Pependicular to span	2.01	1.97	1.98	2.88	2.34	1.90	2.26	1.61	2.32	2.60	
Compression											
Parallel to span	5.67	4.47	5.57	4.23	4.80	3.92	3.71	4.70	4.17	4.09	
Perpendicular to span	2.57	2.51	2.52	3.67	2.97	2.42	2.88	2.04	2.96	3.31	
Panel shear											
Parallel to span	1.43	1.15	0.93	1.23	1.46	1.21	0.99	1.24	1.41	0.9	
Perpendicular to span											
Rolling shear in plain of plies											
Face and Back	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	
Modulus of elasticity in bending											
Face grain parallel to span	7600	7100	7600	6900	6950	6100	5400	6350	5950	5550	
Face grain perpendicular to span	650	600	600	1400	1950	1750	2450	2100	1950	2900	
Modulus of elasticity in tension and compression											
Parallel to span	6550	5200	6450	4900	5850	4750	5800	5200	5100		
Perpendicular to span	3400	3350	4900	4000	3250	3850	2750	3950	4450	2500	
Shear modulus (for panel shear)											
Paralle and perpendicular to face grain	450	450	450	450	450	450	450	450	450	450	450

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Table 4.6 Dry grade stress and moduli for sanded COFI Exterior Douglas Fir Plywood[96].
(Sheathing, select and select tight face grades)

Type and direction of stress and modulus (N/mm²)	Nominal thickness and number of plies (in parentheses)									
	7.5 (3)	9.5 (3)	12.5 (3)	12.5 (4)	12.5 (5)	15.5 (5)	18.5 (5)	18.5 (6)	18.5 (7)	20.5 (5)
Extreme fiber in bending										
Face grain parallel to span	11.6	10.7	11.5	9.39	11.1	9.72	8.63	8.73	9.26	8.78
Face grain perpendicular to span	2.78	2.76	2.77	3.71	3.67	3.41	4.14	3.58	3.61	4.61
Tension										
Parallel to span	5.13	4.05	5.06	3.09	4.77	3.89	3.60	3.97	3.97	3.92
Pependicular to span	2.14	2.11	2.12	2.95	2.47	2.01	2.39	1.70	2.45	2.74
Compression										
Parallel to span	7.99	6.31	7.84	4.82	6.54	5.32	5.00	5.56	5.56	5.47
Perpendicular to span	3.22	3.15	3.17	4.45	3.72	3.03	3.61	2.56	3.70	4.13
Rolling shear in plain of plies										
Face and Back	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Panel shear										
Parallel to span	1.82	1.45	1.19	1.46	1.73	1.43	1.18	1.40	1.62	1.07
Perpendicular to span										
Modulus of elasticity in bending										
Face grain parallel to span	12350	11450	12300	10050	11200	9800	8700	8800	9350	8650
Face grain perpendicular to span	850	800	850	1600	2350	2150	2900	2500	2550	3400
Modulus of elasticity in tension and compression										
Parallel to span	10550	8350	10400	6530	8500	6900	6450	7150	7050	6900
Perpendicular to span	4000	3950	3950	5500	4600	3750	4450	3200	4600	5100
Shear modulus (for panel shear)										
Parallel and perpendicular to face grain	660	630	660	600	600	590	570	570	570	480

Table 4.7 Dry grade stress and moduli for sanded COFI Exterior Douglas Fir plywood[96].
(Good two sides and good one side grades)

Type and direction of stress and modulus (N/mm²)	Nominal thickness and number of plies (in parentheses)									
	6 (3)	8 (3)	11 (3)	11 (4)	11 (5)	14 (5)	17 (5)	17 (6)	17 (7)	19 (5)
Extreme fiber in bending										
Face grain parallel to span	11.2	9.85	11.25	8.11	9.63	8.06	6.98	7.11	7.78	7.37
Face grain perpendicular to span	3.28	3.05	2.96	4.36	4.51	3.99	4.76	4.11	4.14	5.25
Tension										
Parallel to span	4.45	3.33	4.69	2.45	4.16	3.31	3.11	3.52	3.52	3.50
Pependicular to span	2.67	2.47	2.38	2.96	2.79	2.21	2.59	1.83	2.66	2.94
Compression										
Parallel to span	6.95	5.20	7.30	3.82	5.78	4.60	4.37	4.99	4.99	4.95
Perpendicular to span	4.01	3.72	3.58	5.04	4.21	3.33	3.90	2.76	4.01	4.44
Panel shear										
Parallel to span	1.88	1.44	1.20	1.44	1.76	1.42	1.15	1.39	1.63	1.04
Perpendicular to span										
Rolling shear in plain of plies										
Face and Back	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Modulus of elasticity in bending										
Face grain parallel to span	11850	10450	12050	8650	9700	8100	7050	7150	7850	7400
Face grain perpendicular to span	1250	1100	1000	2150	3250	2750	3650	3150	3150	4200
Modulus of elasticity in tension and compression										
Parallel to span	9150	6850	9650	5050	7450	5950	5600	6350	6350	6350
Perpendicular to span	5000	4600	4450	6250	5200	4150	4850	3450	4950	5500
Shear modulus (for panel shear) Parallel and perpendicular to face grain	640	610	650	580	570	560	560	560	560	560

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Table 4.8 Modification Factor[99] (denoted by K_{36} in BS 5268) by which the dry stress and moduli for plywood should be multiplied to obtain values applicable to Wet Exposed condition.

Property	Modification Factor
Bending stress	0.7
Tension stress	0.7
Compression stress	0.6
Shear stress (rolling and panel)	0.8
Modulus of elasticity	0.9
Shear modulus	0.9

Table 4.9 Modification Factor[99] (Denoted by K_3 in BS 5268 for duration of loading.

Duration of Loading	Modification Factor
Long term (e.g. dead + permanent imposed)	1.00
Medium term (e.g. dead + snow, dead + temporary imposed)	1.25
Short term (e.g. dead + imposed + wind dead + imposed + snow + wind)	1.50
Very short term (e.g. dead + imposed + wind)	1.75

4.2.7 AMERICAN PLYWOOD

The woods which are used to manufacture American plywood under US. product standard PS 1-83 are classified into five groups based on the elastic modulus in bending and important strength properties.

The group classification of plywood panels is usually determined by the face and back veneer with the inner veneer allowed to be a different group. Certain grades such as Marine and the structural I Grades, however, are required to have all piles of group 1 species.

4.2.7.1 VENEER CLASSIFICATION

Veneers used for construction of American plywoods are divided into five levels as follows:

N and A_   Highest grade level. No Knots, restricted patches. N is intended for natural finish while A is intended for paintable surface.

B_   Solid surface _ Small round knots. Patches and round plugs are allowed. Most common use is faces for plyform.

C_
(plugged)   Special improved C grade. Used in APA rated structural-I-floor and under layment.

C-   Small knots, knotholes, patches. Lowest grade allowed in exterior type plywood for sheathing faces, and inner piles in exterior panels.

D_   Layer knots, knotholes, some limited white

pockets in sheathing grades. This grade is not permitted in exterior panels.

4.2.7.2 EXPOSURE DURABILITY CLASSIFICATION

American plywood is made in four exposure durability classifications. Exterior 1, IMG or exposure 2, and interior. The classification is made on the basis of the resistance of the glue to moisture as affected by the adhesive used, veneer grade and panel construction.

Exterior: Plywood that is permanently exposed to the weather shall be exterior. Exterior American plywood is made with fully water proof glue and, in addition, is composed of C-grade or better veneer throughout. This combination provides maximum resistance to the effect of daily cyclic variations of moisture and temperature caused by permanent exposure to weather.

Exposure 1: This type of American plywood may be used for application which are not permanently exposed to the weather. Exposure 1 plywood is made with fully water proof glue, but may include D-grade veneer. It is suitable for application where long construction delays may be expected prior to providing protection, or where high moisture condition may be encountered in service. It is also suitable for pressure-preservative or fire related treatment.

IMG (intermediate glue) or Exposure 2: IMG or Exposure 2 American plywood may be used for protected applications which are not continuously exposed to high humidity conditions. These are made with glue with intermediate resistance to moisture. It may be used where moderate delays in providing protection may be expected or where condition of intermittent high humidity may exist.

Interior: Interior American plywood may be used for permanently protected interior applications. Interior plywood is made with moderately moisture resistance interior glue. Short construction delay or short periods of humidity up to 90% in service can usually be tolerated.

Table 4.10 Allowable stress for APA Structural I rated Sheathing EXP1[100].

Type of Stress	Species Group of face Ply	Grade Stress N/mm^2
Extreme fiber stress in bending Tension in plane of plies. Face grain parallel or perpendicular to span	1	11.377
Compression in plane of plies Parallel or perpendicular to face grain	1	10.618
Rolling shear in the plane of plies	1	0.517
Shear modulus in plane perpendicular to plies	1	✗ 620.55
Modulus of elasticity in bending in plane of plies Face grain parallel or perpendicular	1	12411

Approximate Weight (Kg/m^2)

12.7mm = 7.18
18.26mm = 8.62
19.05mm = 10.53

Table 4.11 Allowable stress for APA rated Sheathing EXP 1 or 2[100].

Suitable for wall, roof and Subflooring.

Type of Stress	Species Group of face Plies	Grade Stress N/mm^2
Extreme fiber stress in bending Tension in plane of plies. Face garin parallel or perpendicular to span	1 2,3 4	11.377 8.24 7.653
Compression in plane of plies Parallel or perpendicular to face grain	1 2 3 4	10.618 7.585 6.826 6.550
Rolling shear in the plane of plies	Marine and structural I All other	- 0.331
Shear modulus in plane perpendicular to plies	1 2 3 4	565.39 468.86 379.23 310.28
Modulus of elasticity in bending in plane of plies Face grain parallel or perpendicular	1 2 3 4	12411 10342 8274 6895

Approximate Weight (Kg/m²)
```
 7.94mm =  4.79
 9.52mm =  5.27
12.70mm =  7.18
18.26mm = 10.53
```

Table 4.12 Allowable stress for APA rated Sheathing EXT[100].

Type of Stress	Species Group of face Plies	Grade Stress N/mm^2
Extreme fiber stress in bending Tension in plane of plies. Face garin parallel or perpendicular to span	1 2,3 — 4	13.79 9.653 9.170
Compression in plane of plies Parallel or perpendicular to face grain	1 2 3 4	11.309 8.274 7.3087 6.895
Rolling shear in the plane of plies	Marine and structural I All other	0.434 0.276
Shear modulus in plane perpendicular to plies	1 2 3 4	620.55 517.12 413.7 344.75
Modulus of elasticity in bending in plane of plies Face grain parallel or perpendicular	1 2 3 4	12411 10342 8274 6895

Approximate Weight (Kg/m²)
 7.94mm =   4.79
 9.52mm =   5.27
12.70mm =   7.18
18.26mm = 10.53

4.3 PARTICLEBOARD

An alternative method other than plywood is producing panels consists of preparing particles or chips which are then randomly mixed with adhesive and compressed to form a board.

Particleboards are defined in BS 5669 : 1979[101] as, panel material manufactured under pressure, essentially from particles of wood and /or other lingo-cellulosic fibrous materials. Particleboard can be manufactured with or without the addition of an adhesive. Some of the particleboard products can be used structurally in light frame construction. Such products typically will gain their strength and stiffness form their higher adhesive content.

Originally, particleboard was devised as a means for utilising waste cutter shavings but their inconsistent size and shape tended to produce a poor quality board. Manufacturers then switched to chipping fresh logs, creating a new market for logs which, together with paper pulp manufacture, seriously affected the availability of wood. In recent years there has been a tendency for more mills to become integrated so that suitable logs are converted to sawn wood whilst unsuitable small sizes and offcuts are used for the production of particleboard. In addition there have been serious attempts to use alternative materials which are completely unsuitable for conversion to solid wood,

such as flax shives or twig material from scrub. Particleboards are available in various types. Whilst many boards are marked as general purpose products, it is normal to distinquish interior structural with improved strength from interior non-structural board. Exterior structure or non-structural boards are basically similar , except that they have been manufactured using wood chips and finally a chemical treatment that will prevent the swelling and thus disintegration of individual chips. In fact this later requirement is difficult to achieve and true exterior boards are not normally available, but the critical adhesive and durability properties are also required in a number of other applications where may be a danger of fungal decay, and boards are now available which meet these requirement.

In addition to basic performance requirements, particleboards are described as being single, two or three or multi-layers, or alternatively produced by a graded density system; the purpose of these layer system is normally to include large, coarse particle in the core of the board in order to give good strength, but fine particles in the face.

Generally particleboards are marked with the manufacture's name together with the specification to which they are produced so that, as with stress-graded wood, it is relatively simple to check whether an

individual board is suitable for a particular purpose. Processed boards are produced, as with plywoods, but not in such an extensive range as the preferred uses for particleboards are rather more limited than for plywood. In the following some of the widely used particleboards are discussed.

4.3.1 FINSA   (Forest Product LTD)[102]

Finsa is a board made from wood particles of Irish pine, obtained by a suitable weight to volume ratio of the particles which form each of the three layers which make up the board. The weight to volume ratios ensure that the thicker particles form the inner layer, while the finer particle make up the two outer layers.

The manufacturer claims that FINSA board (FINSAPAN V313) can be used for flooring board, roofing board, construction board and livestock sheltering. The board has special resins, which enable it to maintain it's mechanical properties in damp atmospheres.

In the following the desired physical and mechanical properties of a 18mm board as given by the manufacturer are listed.

Density	690 Kg/m^3
Bending strength	19 N/mm^2
Modulus of elasticity	2750 N/mm^2
Tensile strength perpendicular to the plane of the board	0.5 N/mm^2

Impact strength   525 m m.

Thickness swelling

_ 1h immersion   8%

_ 24h immersion   8%

4.3.2 CABERBOARD[103]

Caberboard limited products include Caberboard high quality chipboard, Caberfloor flooring grade chipboard and Caberwood medium density fibreboard.

Caberboard is a high quality smooth surface medium and high density chipboard. Available in nine thicknesses and various panel sizes, suitable for partitions, workshops, furniture, access and general construction use.

Caberfloor is a top quality smooth surface high quality density chipboard specially designed for flooring use. It can be used for all domestic and most other suspended floors. Caberfloor type II is right for most other uses type II/III has moisture resistance properties.

In the following some of the desired physical and mechanical properties of an 18mm Caberboard are listed.

	Caberfloor type II	Caberfloor type II/III
Density	700 Kg/m^3	700 Kg/m^3
Internal Bond	0.5 N/mm^2	0.8 N/mm^2
Modulus of Rupture	22.5 N/mm^2	24.5 N/mm^2

Modulus of elasticity	3200 N/mm^2	3400 N/mm^2
Impact Strength	550 m.m.	700 m.m.
Thickness Swelling:		
1 hour	7.5%	3.0%
2 hours	N/A	7.0%
Thermal Conductivity	0.14 W/m ^{o}C	0.14 W/m ^{o}C
Flame resistance	class 3	class 3

4.3.3 TORVALE-SASMOX[104]

Torvale_sasmox is a gypsum bonded wood particleboard. The board contain no glues and due to its composition and high density, it has good fire resistance properties. It is manufactured from gypsum and wood particles, with a ratio of 83% by weight of gypsum to 15% wood. At normal temperature the board has moisture content of approximately 2%.

The board has been tested in accordance with BS 476: part 6 1981[105] (fire propagation) and BS 476: part 7 1987[106] (surface spread of flame), resulting in class `0' designation in accordance with current building regulations. It also achieved class `I' surface spread of flame rating to BS 476: part 7[106]. In Germany gypsum flakeboard is being used as facing of sandwich panels with polystyrene foam core. The manufactured panels are laid as dry floor. The desired physical and mechanical properties of the board are as follows:

| Density | 1180 Kg/m^3 |
| Modulus of Elasticity | 4000 N/mm^2 |

Bending Strength	8 N/mm^2
Tensile Strength Parallel to Surface	3.5 N/mm^2
Tensile Strength Perpendicular to surface	0.6 N/mm^2
Compressive Strength Perpendicular to surface	9.5 N/mm^2
Thermal Conductivity	0.24 W/m^o C
Thickness swelling	< 3%

4.3.4 ORIENTED STRAND BOARD

Oriented strand board (OSB) Is a panel product composed of three to five layers of strands or rectangular shaped flakes which are typically three to five times longer than their width. Strands are produced by a variety of flaking machine. Strands are from roundwood, which are logs transferred directly from the forest.

Oriented strand board get it's name from the fact that the strands are oriented, that is strands within a layer are aligned in the same general direction. Each layer is oriented perpendicular to the next, as veneers in plywood are also perpendicular to each other in alternative layers.

The strands are orientated to provide product flexibility so that it may be designed with stiffness and strength characteristics in particular panel directions.

Oriented strand board is manufactured with liquid

phenolic resin and wax applied just prior to pressing.

4.3.5 STERLING BOARD

Sterling board is an oriented strand board (O.S.B) panel produced using only prime raw materials. Sterling board is a British-made exterior grade structural building panel produce by Highland Forest Products PLC [107]. It is composed of oriented strands of wood, machined from quality scots pine logs and blended with lightly sprayed wax and weather/boil-proof phenolic resin. The prepared strands are arranged in three layers. The top and bottom layers to run parallel to the length of the panel. The core strands are laid at right angles to the panel length *for maximum strength.*

4.3.5.1 STERLING BOARD APPLICATIONS

1) wall sheathing

2) flat roofs

3) roof sarking

4) farm work

5) flooring

6) crating/packing/pallets

7) site boarding

8) agricultural floors/building

9) Industrial floor shelving

10) relocatable/portable buildings

11) composite panel systems

12) decorative panelling

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13) D.I.Y projects

Sterling boards are now being used as facings for sandwich panels with plastic rigid foam core. Morecambe, Lancs - Purlboard Ltd, Morecambe developed an insulation roof decking with sterling board facing and Extruded polystyrene foam core. The product is marketed as `Purldek plus' which is being used for school and commercial structures [108]. Montague L. Meyer (Widnes) Ltd are using Sterling board in the production of their `high-seal' roof decking and `high-seal double deck'. Meyer claim that the materials offer user-fixing and cost advantages over existing roofing boards. Meyer achieved this by bonding to the upper surface of the sterling board a layer of bituminous felt, or sealing the board by the pre-seal hot applied bitumen system and waxing the under-side. Hi-seal double deck is bonded on the under side with 50mm urethane foam with an aluminium liner that provides a moisture barrier.

The facings of four of the sandwich beams tested in chapter 5 have been constructed from sterling board (beams 7 to 10 listed in table 5.1).

The desired physical properties of sterling board are as follows:

Modulus of rupture	
parallel to panel length	40 N/mm^2
perpendicular to panel length	20 N/mm^2
Modulus of elastisity	5000 N/mm^2
Internal bond	0.42 N/mm^2

4.4 COMPARISON OF DESCRIBED PLYWOOD AND PARTICLEBOARDS

4.4.1 GENERAL

The types of timber based material suitable for *sandwich* panel facings have been discussed together with some examples of available commercial timber based material. The selection of timber based material for sandwich panel facings will be dependent upon the end use of the panel, such as; whether the sandwich panel is going to be used as a load bearing member or simply as a cladding or sheathing member; the environment to which the panel is going to be exposed; the fire resistance requirement. In the case of load bearing sandwich panels it is important to use a board with a high strength but where the strength is not critical the main consideration would be the cost of the panel. If the cost of the facings are marginal to the overall cost of the panel the choice would be the cheapest which would provide the necessary material qualities.

In the following, timber based materials discussed earlier in this chapter are compared in terms of their mechanical and physical properties.

4.4.2 COMPARISON OF AMERICAN PLYWOOD

WITH CANADIAN COFI   PLYWOOD

The two plywoods are compared on the basis of their mechanical properties, weight and costs. Tables 4.5 to 4.12 list the boards modulus of elasticity and their allowable stresses in bending, tension, shear and compression.

In tension and compression parallel and perpendicular to the face grain, American Plywood (APA) rated sheeting were found to be superior to the COFI Exterior DFP and CSP.

In rolling shear COFI exterior DFP were found to have greater rolling shear strength than APA rated sheathing EXT and EXP 1 or 2, but lower value of rolling shear in comparison to APA structural I, rated EXP 1.

In terms of modulus of elasticity in bending only APA rated sheathing EXT of species group of face ply 1 were found to have a higher value of modulus of elasticity compared to Canadian COFI but over all Canadian COFI Douglas Fir plywood were found to be superior.

In terms of shear modulus, Canadian Douglas Fir plywood (sheathing grade) were found to have the largest value of shear modulus.

In terms of weight per meter square, not much difference was to be found between the two plywoods. In terms of cost COFI Exterior plywood is found to be 2.5% to 5% more expensive than APA rated sheathing.

4.4.3 COMPARISON OF PLYWOOD AND PARTICLEBOARD

In the following, plywoods and particleboards previously described are compared on the basis of their mechanical properties. Table 4.13 lists the bending strength, modulus of elasticity, impact strength, tensile strength and weight of the described particleboards.

Comparison of tables 4.5 to 4.12 with table 4.13 indicates that in terms of elastic modulus in bending for similar board thickness, plywoods are found to be superior.

The two described plywoods were found to have a lower density for similar board thickness.

In a study by Lee and Stephens[109], plywood and particleboards were evaluated in terms of their edgewise shear and interlaminar (or rolling) shear at 85% and 50% relative humidity (RH). The results of these tests are summarised in table 4.14. This table shows the average values of density, edgewise shear strength at each RH, and percentage reduction in strength from 50% to RH 85% RH. The result indicate that plywood had the smaller edgewise shear strength reduction from 50% RH to 85% RH.

Table 4.13 Stress and Moduli for Particleboards

Type of board	Thickness (mm)	Bending Strength (N/mm²)	Modulus of Rupture (N/mm²)	Modulus of Elasticity (N/mm²)	Impact Strength (m.m)	Tensile Strength (N/mm²)		Weight (Kg/m²)
						perpendicular	Parallel	
Sterling board	8		40.0	5000.0	-	-	-	5.3
	9							6.0
	11							7.3
	15							9.6
	18							11.5
FINSA (forest product)	8		-	2750	525	0.5	-	12.42
	22		-	2750	525	0.5	-	12.92
CABERFLOOR	II 18	-	22.5	3200	550	-	-	12.6
	II 22	-	20.7	3200	600	-	-	14.96
	II/III 18	-	24.5	3400	650	-	-	12.6
	22	-	24.0	3400	700	-	-	14.96
KRONOFLOOR*		8	-	4000.0	-	0.6	0.35	11.8
TRVALESASMOX (gypsum wood particleboard)	10.00							14.2
	12.00							
	>12.00							

* 18mm maximum imposed load = 1.5 KN/m²
22mm maximum imposed load = up to 2.00 KN/m²

Table 4.14 Results of study by Lee and Stephens[109].

Panel Thickness (mm)	Density (Kg/m³)	Moisture Content		Edgewise Shear Strength		Strength * Reduction
		50% RH	85% RH	50% RH	85% RH	
Plywood	484.1	7.2	14.6	807	668	17
Particleboard	702.1	8.1	14.7	672	420	37

* Reduction precentage represent edgewise shear strength loss from 50% RH to 85% RH.

4.5 SUITABILITY FOR SANDWICH PANELS CONSTRUCTION

In order to investigate the suitability of the timber based materials previously discussed, use was made of the computer program discussed in (2.1.3.3). Simulated flexural tests were carried out on sandwich beams having timber based facings discussed earlier.

Details of the beams are presented in table 4.15. The result of the computer runs are listed in tables 4.16-4.17. Table 4.16 lists the result of the simulated flexural test on beams having polystyrene foamed core. The result shows that in all the cases except were plywood facing were used, the core shear stress at 1.5 (KN) load exceed the core shear strength, resulting in a core shear failure of the beam. Similar behaviour was observed when the Polystyrene foamed core was replaced with a stronger core, Styrofoam (see table 4.17).

The stiffnesses of the beams were calculated from the overall flexural rigidity (D) using equ (2.1)[12] (see table 4.18). Sandwich beams with plywood facings were found to have the highest stiffness value.

Table 4.18 list the stiffness to weight ratio of each beam. These figures indicate that among the timber based facing materials under investigation beams constructed from plywood facings would produce the most efficient sandwich panels.

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4.6 CONCLUSION

The two plywoods under investigation were compared in section (4.4.2). Comparison was made in terms of their mechanical and physical properties (i.e. modulus of elasticity, modulus of rupture and density).In terms of these properties not much differences were found between the two plywoods. However, in comparison to other timber based materials discussed previously, plywoods were found to be superior.

Simulated flexural tests were carried out using the computer program discussed in section (2.1.3.3). These simulated tests were conducted to examine the influence of each board up on the behaviour of the whole sandwich beam. The result of the simulated tests indicate that the sandwich beams made up of plywood facings appear to be the stiffest and lightest.

Real flexural tests were also carried out on timber-based facings sandwich beams for the verification of the theory used for the analysis of modelled beams. This work is presented in chapter 5.

In conclusion the results of this investigation suggest that plywood facings appear to be the most efficient facings in comparison to the particleboards and oriented strand board discussed here.

Table 4.15 Details of the Simulated flexural Tests

Case No.	face material (12 mm thick)	width (mm)	span (mm)
1	COFI (sheathing grade)	94	600
2	APA (structural I EXP1)	94	600
3	Finsa	94	600
4	Caberboard	94	600
5	Troval-Sasmox	94	600
6	Sterlingboard	94	600

Table 4.16 Summary of the Results for Beams With

50 mm Thich Polystyrene Foamed Core.

Case No.	Load (N)	deflection at mid span (mm)	face bending stress N/mm^2	core shear stress N/mm^2	m.o.r* N/mm^2	core shear strength N/mm^2
1	700	4.19	8.59	0.09	22.0	0.11
2	700	4.17	8.64	0.09	22.0	0.11
3	700	5.79	3.47	0.12	19.0	0.11
4	700	5.61	3.37	0.12	24.5	0.11
5	700	5.38	4.22	0.11	8.0	0.11
6	700	5.15	4.81	0.11	40.0	0.11

* modulus of rupture of the face material

Table 4.17   Summary of the Results for the Beams with

50 mm Thick Styrofoam Foamed Core.

Case No.	Load (N)	deflection at mid span (mm)	face bending stress N/mm^2	core shear stress N/mm^2	m.o.r[*] N/mm^2	core shear strength N/mm^2
1	2700	8.51	19.30	0.42	22.0	0.44
2	2700	8.45	19.34	0.42	22.0	0.44
3	2700	11.87	10.15	0.45	19.0	0.44
4	2700	11.37	10.50	0.46	24.5	0.44
5	2700	10.72	11.18	0.45	8.0	0.44
6	2700	10.18	12.09	0.45	40.0	0.44

[*] modulus of rupture of the face material

Table 4.18 Calculated Stiffness of the beams

Case No.	beam flexural rigidity (D)	weight of the beam[+] (W) (Kg)	EI/W[*]
1	2.64×10^{10}	0.95	2.69×10^{10}
2	2.67×10^{10}	0.95	2.81×10^{10}
3	5.92×10^{9}	1.56	3.79×10^{9}
4	6.89×10^{9}	1.56	4.42×10^{9}
5	8.16×10^{9}	1.47	5.86×10^{9}
6	1.08×10^{10}	0.96	1.13×10^{10}

[*]   stiffness to weight ratio of each beam.
[+]   the damnation of the beams for which the weight have been calculated is 600 x 94 mm^2.

CHAPTER 5
FLEXURAL TESTING OF SANDWICH BEAMS WITH TIMBER BASED FACING AND PLASTIC RIGID FOAMED CORE

CHAPTER 5

FLEXURAL TESTING OF SANDWICH BEAMS
WITH TIMBER BASED FACINGS AND
PLASTIC RIGID FOAMED CORE

5.1 INTRODUCTION

In chapter two, certain patterns regarding the flexural behaviour of thick faced sandwich beams were established with the aid of theoretical analysis, using the approach of Stamm and Witte [30].
The theoretical studies of thick faced sandwich beams required verification with regard to application to "real" sandwich construction with semi-thick facings. This chapter details the finding of associated laboratory testing programmes which were conducted to test the validity of the theoretical analysis.

In all, a total of 15 beams with 94 mm width and varying spans were tested using a four point loading system. The deflection was measured at the centre of the beam and under the point loads using dial-gauges. The details of the test series are presented in table 5.1. Beams numbered 1 to 10 were supplied by the manufacturer and beams numbered 11 to 15 were manufactured by the author. In each of the above cases sandwich beams were fabricated from the component parts of sheet facings and 50mm thick blocks of extruded and expanded polystyrene foam.

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Flexural tests were carried out on the facing materials. Core shear tests were performed on samples cut from sheet material using the joined square shear test.

An appreciation of the validity of the theory may be made by reference of the comparison of calculated and measured deflections and calculated stresses at failure of the tested beams.

TABLE 5.1 Details of Test Series

test No	face material	face thickness top	bottom	core (50 mm)	width (mm)	span (mm)
1	sterling board	14.74 (mm)	14.74 (mm)	EXT. POL*	94	710
2	sterling board	14.74	14.74	EXT. POLY	94	710
3	sterling board	14.74	14.74	EXT. POLY	97	1100
4	pine board	11.82	11.82	EXT. POL Y	97	1222
5	pine board	11.82	11.82	EXT. POLY	97	790
6	pine board	11.82	11.82	EXT. POLY	94	1000
7	sterling board	9.14	12.59	EXP. POLY+	94	710
8	sterling board	12.59	9.14	EXP. POLY	94	710
9	sterling board	9.14	12.59	EXP. POLY	94	710
10	sterling board	12.59	9.14	EXP. POLY	90	710
11	plywood	4.0	4.0	EXT. POLY	90	1159
12	plywood	4.0	4.0	EXT. POLY	90	1160
13	plywood	4.0	4.0	EXT.POLY	90	1047
14	plywood	6.0	6.0	EXT. POLY	98	1870
15	plywood	6.0	6.0	EXT. POLY	98	1820

* extruded polystyrene.
+ expanded polystyrene.

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5.2 MANUFACTURE OF THE TEST BEAMS

Five sandwich beams (numbered 10 to 15 in table 5.1) were manufactured with plywood faces bonded to extruded polystyrene foam using polyurethane based adhesive (Apollo Astrolok)[91].

A thin layer of adhesive was applied over the surface of the plywood faces via a roller. The panel was then assembled in a specially designed wooden mould. With the aid of two I-beams laid on the top of the sandwich a uniform pressure of 0.035 N/mm^2 were applied by a universal testing machine. The pressure was maintained for 45 minutes. The arrangement of the beam and the mould and the method of applying the pressure is illustrated in plate No. 5.1.

5.3   Small Scale Tests.

5.3.1 Tests : Small scale tests on both facing and core material were required to establish independent values of the material property constants for comparison with the analysis of sandwich beam model tests described in section 5.4. Simple flexural tests were considered to be appropriate for the facings. In plain shear properties were required for the cores. The background to all test methods for such properties has been already described in chapter 3. Lessons learned from these investigations were applied to this part of the work.

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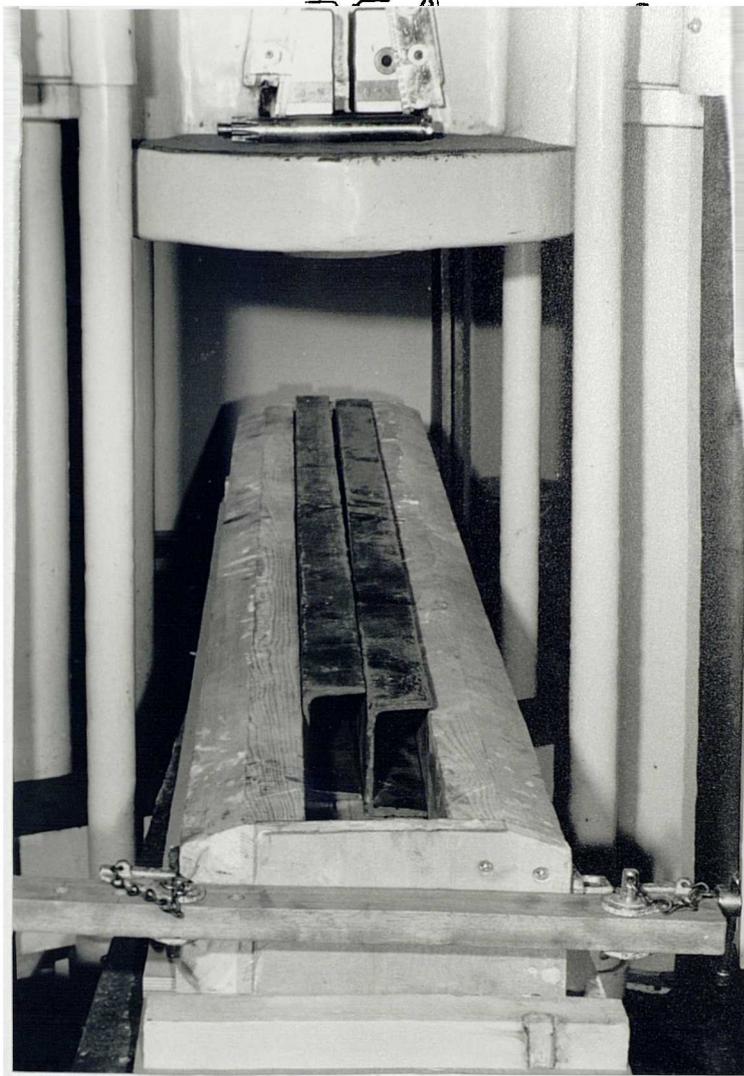
Plate   5.1   The arrangment of the beam in the mould and the method of applying the presure

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Test specimens were chosen to be as representative as possible of the material used in the fabricated sandwich construction. Representative samples of facing materials were cut directly from the sheet material. Core specimens were also cut from the sheet material. Specimens were cut with similar orientation to that with in the beam models. A summary of the results is presented in appendix B.

Timber Based Facings: Moduli were obtained from a simple three point bending test, as detailed in BS 5669: 1979[101] (particle boards) and BS 4512 1969[98] (plywood). The displacement at the midpoint of the test piece was measured with the aid of a dial-gauge. Load/displacement responses were satisfactorily linear
Figures 5.1 and 5.2 show typical load/displacement curves.

Core Shear: The four square hinged method was used for shear modulus evaluation as described in section 3.3.2.3. The test specimens ($50 \times 50 \times 50$ mm^3) were glued to four steel plates using Apollo astrolok adhesive. The test specimen were tested in compression (with rate of loading of 2mm/minute) and the diagonal displacement of the upper and lower corners against load were plotted. The shear modulus, was determined from the slope of initial linear portion of load/displacement curve.
Figure 5.3 shows a typical load/displacement curve.
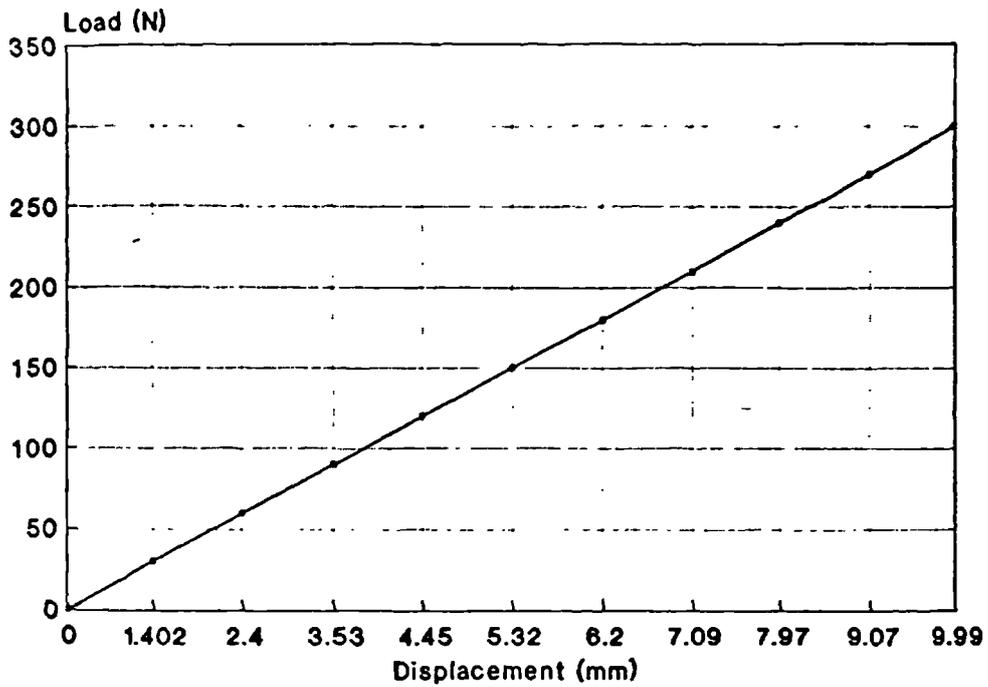
Figure 5.1 Load displacement graph of
plywood used for facings of beam No. 13
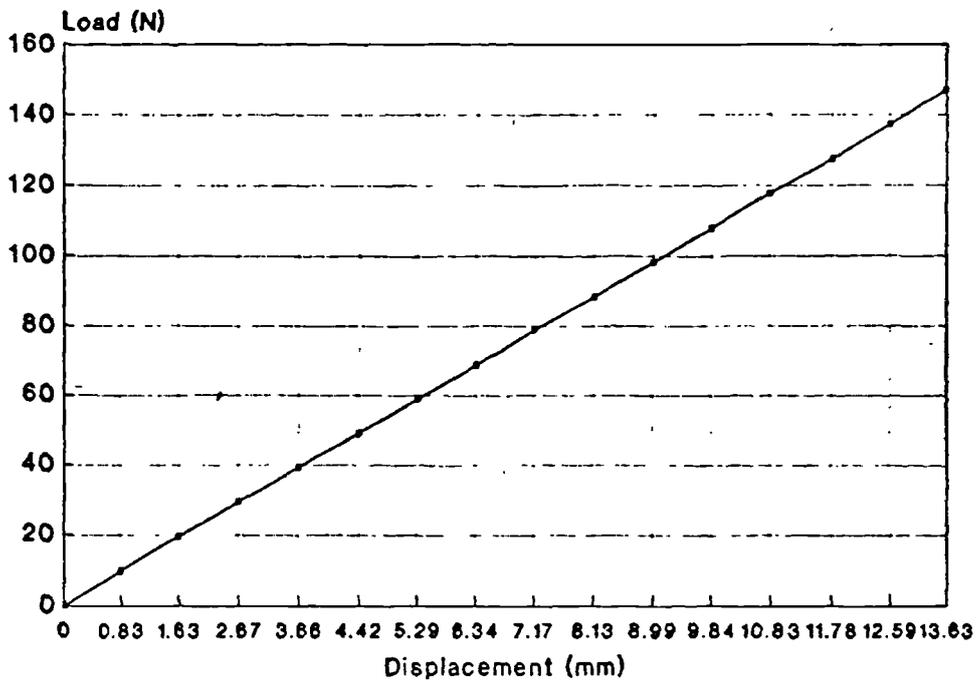
Figure 5.2 Load displacement graph of
plywood used for facings of beam No.1

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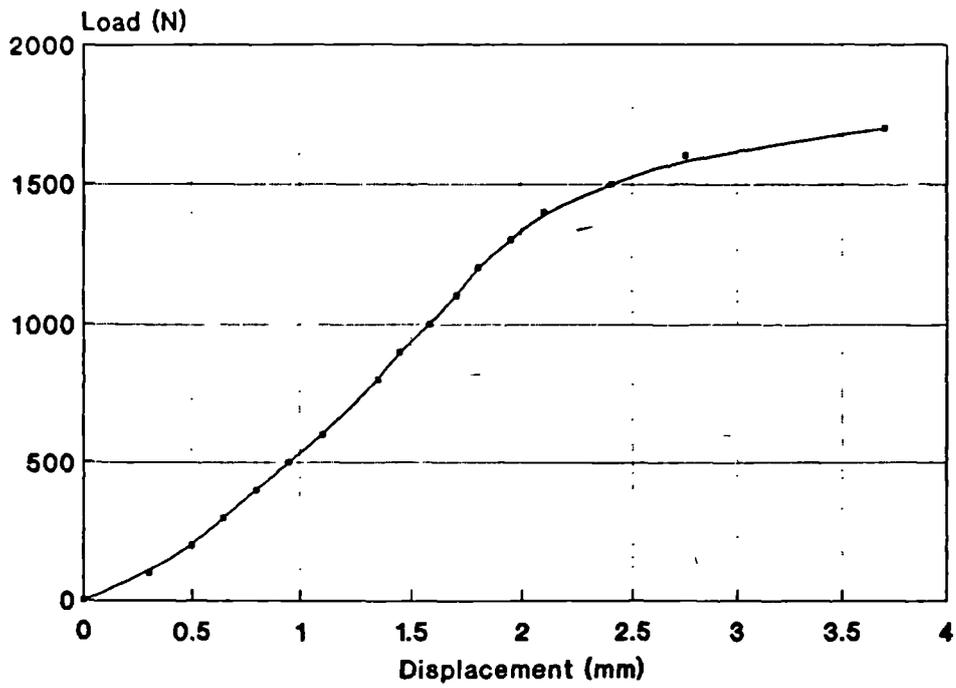
Figure 5.3 Load/displacement graph for
styrofoam tested in four square hinged.

Results relating to all the small scale tests are given in Appendix B.

5.4 FLEXURAL TESTS

Fifteen sandwich beams with wood-based facings and polystyrene foamed core were tested with varying face thickness and span. These beams were tested to check if the method of analysis for thick face given by Stamm and Witte[30] is valid for semi-thick wood base facings and to investigate the modes of failure.

This test method pertains to the bending of sandwich so that the applied moments produce curvature of the plane of a sheet of sandwich construction. The usual procedure applies shear as well as bending moment, on the sandwich.The test can produce failure in the sandwich by shearing the core, by shearing the bond between the core and facings, by direct compression or tension failure of the facings, or by localized wrinkling of thin facing at load points or reactions. Long spans produce high facing stresses so that the core failure or bond failures would not be expected. Short span tend to produce core shear or bond failures, providing the facings are thick enough to carry the stresses produced by bending moments and also local stresses at the load point.

The test arrangement and the method of applying the load are shown in fig 5.4 and plate No. 5.2.
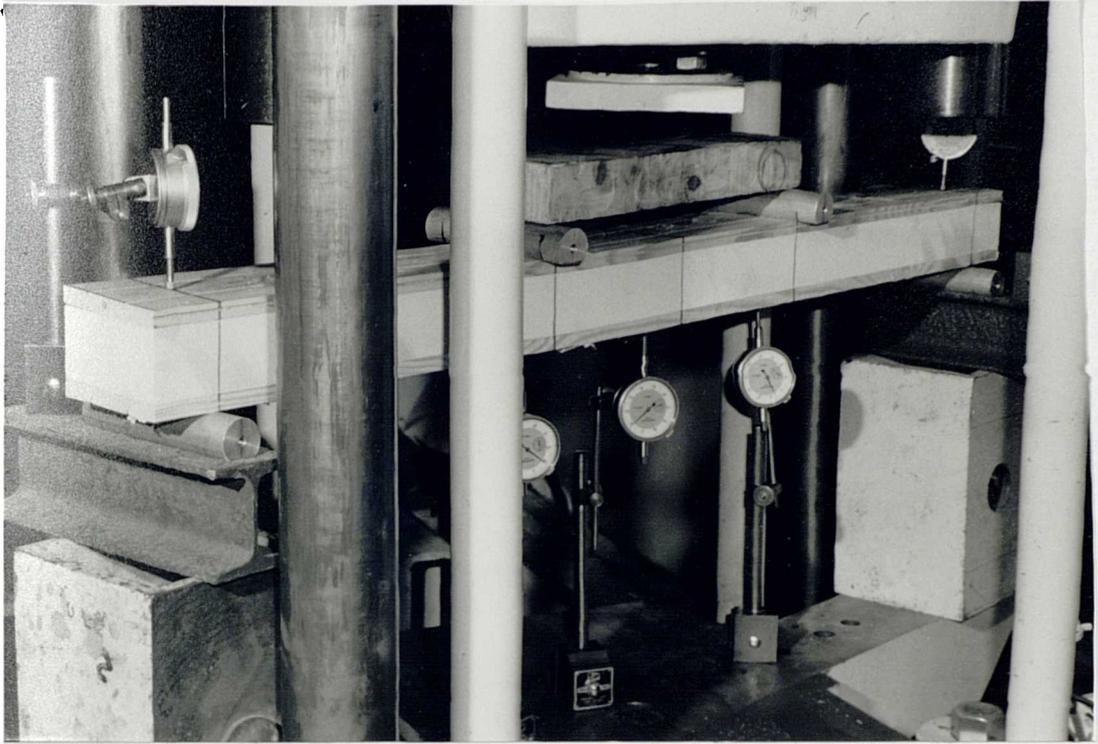
Plate 5.2   Test arrangement

The beams were simply supported and the loads were applied through two half cylinders using a universal testing machine. The two half cylinders were laid on two steel plates each of 50 mm wide to minimise the effect of concentrated load and avoid local crushing under the lines of loading.
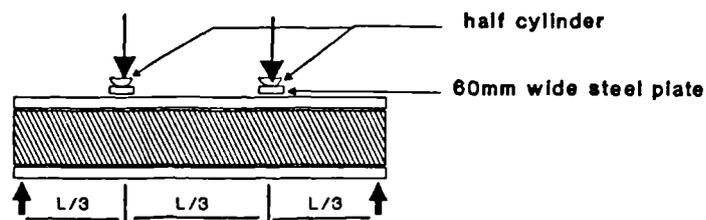
Figure 5.4   4-point loading system

This method of loading allows the portion of the beam between the loads to bend under constant moment without shear and constant shear in the portions out side the loads.

Deformation of the beams were measured at the centre of the beam and at the points under the lines of loading.

5.5 TEST RESULTS

In this section the results obtained are summarised and these will be discussed later and will be compared with the theoretical results.

Table 5.2 shows the result of fifteen tests carried out on simply supported sandwich beams subject to four-point loading. Eleven of the beams tested failed in core shear and the five remaining beams were manufactured with longer span so that the core failures or bond failures would not be expected.

Table 5.2 Summary of the results from Sandwich Beam tests.

test No	failure load (KN)	deflection at[1] mid span (mm)	observed failure mode	face bending stress at failure (N/mm^2) top	bottom	core shear stress at failure (N/mm^2)
1	6.66	2.0	shear	19.25	19.25	0.51
2	5.5	1.8	shear	15.89	15.89	0.42
3	5.6	5.0	shear	14.13	14.13	0.45
4	4.0	4.4	shear	14.62	14.62	0.33
5	5.2	2.6	shear	13.44	13.44	0.43
6	5.0	-[2]	shear	15.32	15.32	0.43
7	1.64	7.07	shear	5.04	6.38	0.14
8	1.79	6.7	shear	6.97	5.49	0.15
9	1.64	6.7	shear	5.04	6.04	0.14
10	1.7	9.56	shear	6.62	5.23	0.14
11	3.93	10.7	crushing[3]	22.70	22.70	0.15
12	4.5	10.0	flexural	47.98	47.98	0.43
13	4.3	8.13	shear	41.38	41.38	0.44
14	2.5	33.0	crushing	26.09	26.09	0.23
15	2.2	21.0	crushing	24.34	24.34	0.21

1 mid span deflection at 1.5 KN.
2 not available
3 crushing of the face

Table 5.3 The calculated stresses at failure and strength of the materials

test No	face bending stress at failure (N/mm^2)		core shear stress at failure (N/mm^2)	modulus of rupture of the face (N/mm^2)	core shear strength (N/mm^2)
	top	bottom			
1	19.25	19.25	0.51	22.0	0.44
2	15.89	15.89	0.42	22.0	0.44
3	14.13	14.13	0.45	22.0	0.44
4	14.62	14.62	0.33	——[1]	——
5	13.44	13.44	0.43	——	0.44
6	15.32	15.32	0.43	——	0.44
7	5.04	6.38	0.14	22.0	0.1
8	6.97	5.49	0.15	22.0	0.1
9	5.04	6.04	0.14	22.0	0.1
10	6.62	5.23	0.14	22.0	0.1
11	22.70	22.70	0.15	45.6	0.44
12	47.98	47.98	0.43	45.6	0.44
13	41.38	41.38	0.44	45.6	0.44
14	26.09	26.09	0.23	45.6	0.44
15	24.34	24.34	0.21	45.6	0.44

1   not available

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5.6 ANALYSIS AND DISCUSSION

Table 5.1 shows that tests No. 1, 2 and 3 were carried out on beams with identical faces and core materials and thicknesses. The graphs of applied load versus the midspan deflection for test Nos. 1 and 3 are presented in figure 5.5. Also are shown are the corresponding theoretical curves obtained using the *Stamm and Witte* theory[30]. Since the results for test No. 1 and 2 are identical only one of them is presented in figure 5.5. The result shows a good agreement between the experimental and theoretical values.

Three tests on sandwich beams with pineboard facing and expanded polystyrene foamed core with different spans, were carried out (see table 5.1). The load deflection urves obtained from the tests result for beams No. 4 and 5 are shown in figure 5.6. Also shown are the corresponding theoretical curve obtained using the Stamm and Witte theory. Typical test results of beams constructed from Sterling board and extruded polystyrene core are shown in figure 5.7.

The load deflection curves obtained from the tests results on sandwich beams with plywood facings and extruded polystyrene core are shown in figure 5.8 together with their corresponding theoretical curves.

For the tested beams Nos. 1-10 and 13, the failure was observed to initiate by core shear and for beams numbered 11-15 the failure was in bending.

In the case of tested beams numbered 11,14 and 15, it

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was observed that before the failure occurs the edge of the load distribution plates which was used to minimise the effect of concentrated load were pushed into the plywood face. This resulted in a premature flexural failure of the face due to the local crushing of the face. Table 5.3 shows face bending stress at failure and core shear stress at failure together with the modulus of rupture of the face material and core shear strength of each beam tested. It would appear from these figures that the failure of the beams numbered ――― 1-10 and 13 was initiated by core shear failure as the value of the shear stress in the core is greater than the shear strength of the core and the stresses in the faces were considerably less than the strengths of the Sterling board and Pine board. In the case of beams numbered 11,14 and 15 the results indicate that the failure of the beams was neither initiated by core shear nor by rupture of the face, since the stress in the faces and the core was considerably less than their strength. It appear that the failure of these beams was initiated by crushing of the face at point of loading. The calculated stress at failure for tested beam numbered 12 indicate the failure was initiated by the plywood board as the stress in the faces was more than the strength of the plywood board.

The theoretical analysis using the Stamm and Witte theory presented in chapter 2 shows good agreement when compared with the experimental results as illustrated in

figures 5.5-5.8.

A typical distribution of deflection, bending moment and shearing force for the tested beams given by Stamm and Witte[30] analysis are shown in figure 5.9.

The bending moment is divided into two components, face and the sandwich parts. The total bending moment of the beam is the summation of the two as illustrated in figure 5.9 b.

In the case of shear force, as it is illustrated in the shear force diagram shear force is absorbed by the core. The shear force in the core is a pronounced factor in design of sandwich panels. As shown in figure 5.9 c the maximum vales of the core shear forces are at the supports and this decreases within the span. The distribution of the facing shear force show that the peak values are adjacent to the applied concentrated loads.

5.7 CONCLUSION

The experimental investigation on the behaviour of the 15 sandwich beams with relatively thick plane face and subjected to four point loading have been described. A Fortran programme based on Stamm and Witte[30] theory was written (appendix A) for the calculation of deflection, shear forces and bending moment distribution of a simply supported sandwich beams with four point loading. Consequently, the theoretical and experimental load deflection curves are given and can be compared. A good agreement between theoretical and experimental results was found with regard to midspan deflection and calculated stresses at failure as illustrated in figures 5.5-5.8 and table 5.3 respectively.

on Curve
For Beams Numbered 1 and 3

Load (KN)

Deflection (mm)

Theoretical Curve
Test result (No.1)
Test Result (No.3)
No.1: L ▪ 710 mm
No.3: L ▪ 1100 mm

for
5

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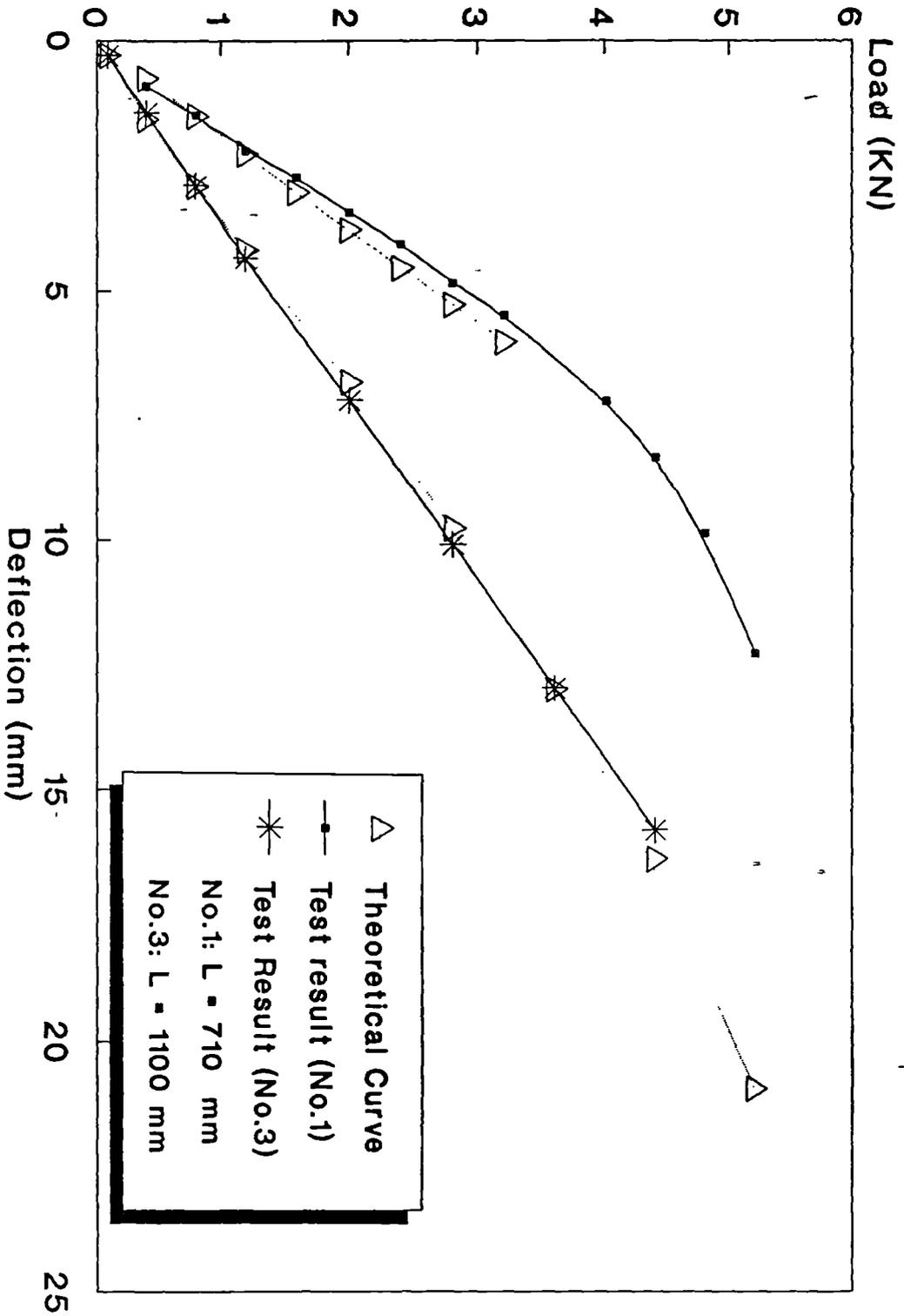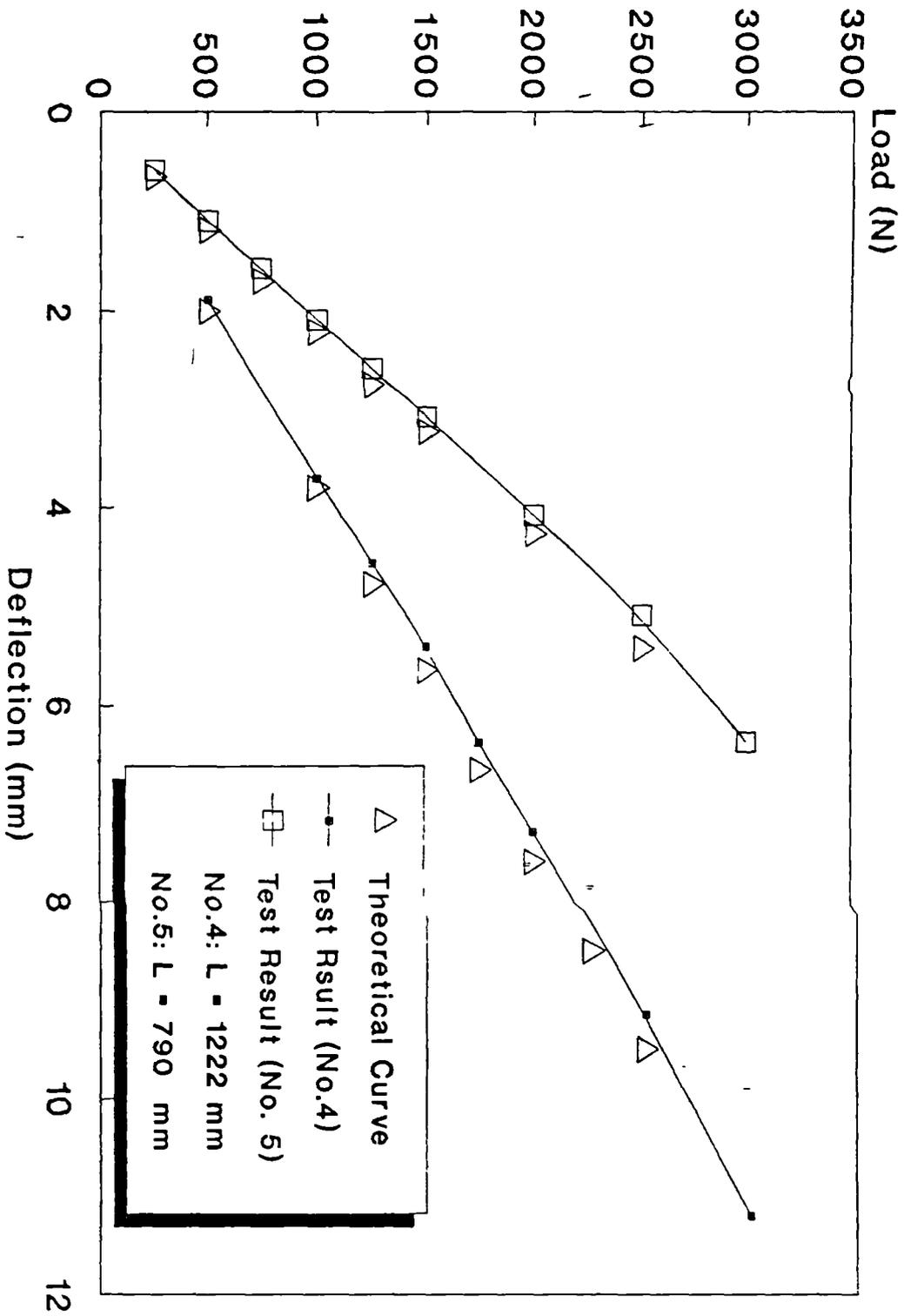
Figure 5.7 Load Deflection Curve for
Tested Beams Numbered 8 and 10

Load (N)

Deflection (mm)

△   Theoretical curve

━■━   Test result (No.10)

━✳━   Test Result (No.8)

No. 8: L = 710 mm
Thick Face in Compression

No. 10: L = 710 mm
Thick Face in Tension
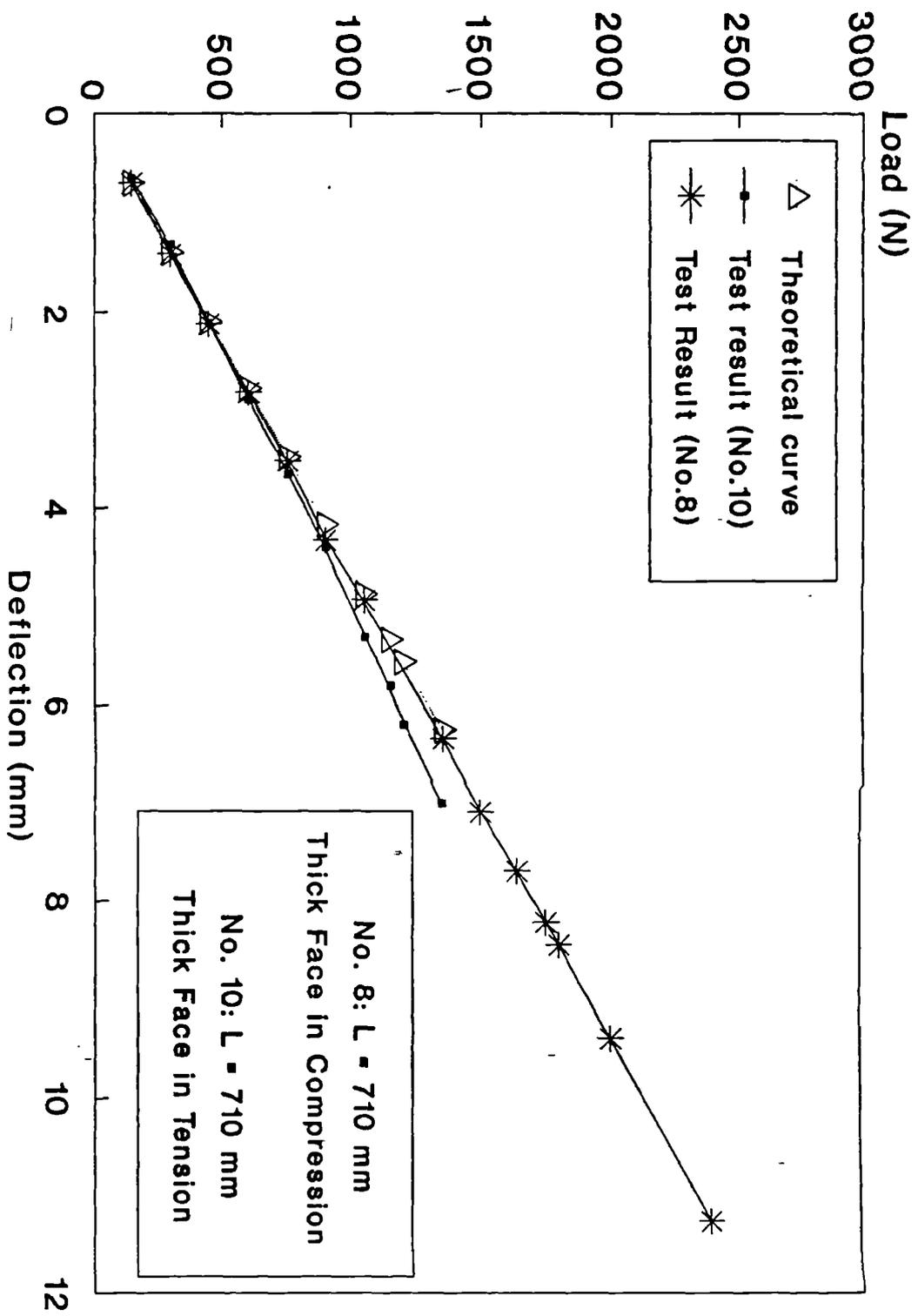
Figure 5.8 Load Deflection Curve for
Tested Panels Numbered 11-15

Deflection (mm)

a) Deflection (mm)

Moment N.mm (Thousands)

—— Sandwich Part   —— Flange Part   ···· Total
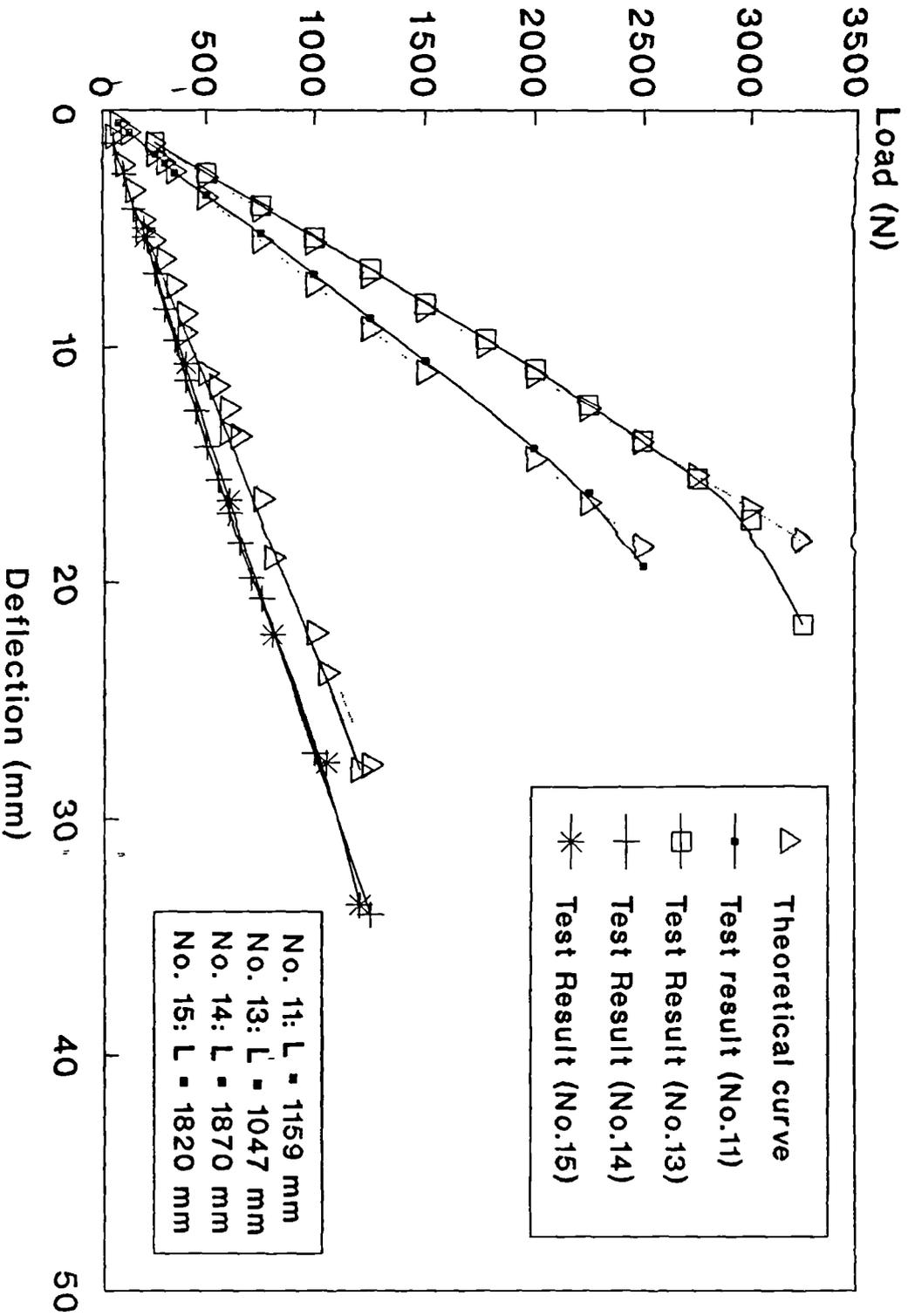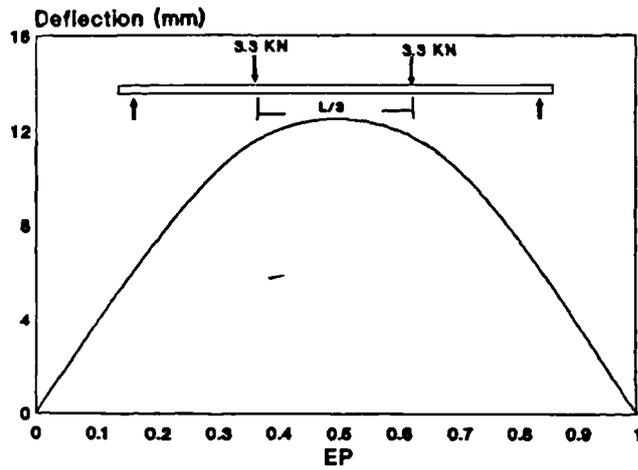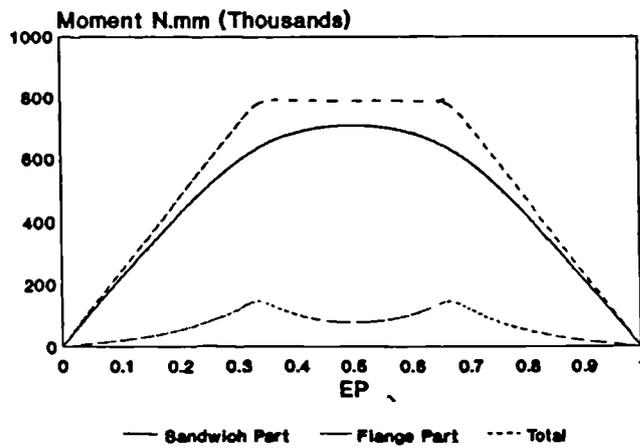
b) Bending Moment Diagram (N.mm)
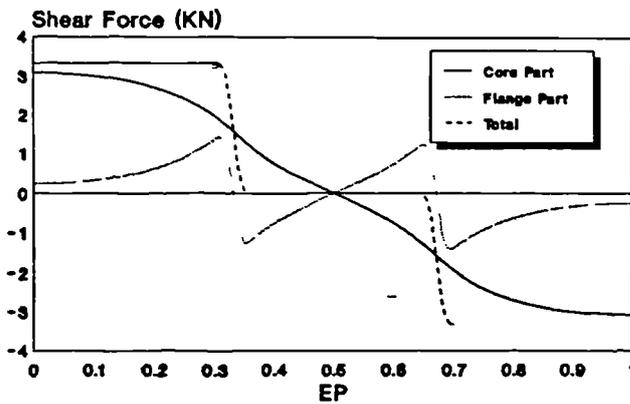
Shear Force (KN)

c) Shear force Diagram (KN)

Figure 5.9 Deflection and stress
resultants for test No. 1.

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CHAPTER 6

DEVELOPMENT OF A STRUCTURAL

FIRE RESISTANT SANDWICH

CORE

CHAPTER 6

DEVELOPMENT OF A STRUCTURAL FIRE

RESISTANT SANDWICH CORE

6.1 INTRODUCTION

Fire safety is an increasingly important subject. Building legislation exists in all the developed nations of the world which attempts to minimise the hazard to life which may be caused by the use of flammable materials in the construction of buildings. High energy costs have lead to vastly improved insulating levels in modern buildings. This can lead to increased fire hazard if careful consideration is not given to their fire properties.

Sandwich panels with rigid plastic foam cores are being used extensively by the building industry and because they have low fire resistance, it is important to evaluate alternative core materials with properties that would reduce the risks of fire propagation and smoke and toxic fumes emission on burning.

Much development work has been done in trying to reduce ignitability and to improve the fire resistance capacity of plastic foam.

The aim of the present study is to develop an alternative core material which would meet the various requirements by having the following characteristics:

1.   Good mechanical properties,

2.   Good thermal insulation,

3.   Substantially improved fire resistance.

For a sandwich panel to be truly resistant to fire, it should:

a)   _ contain the fire,

b)   _ not sustain or contribute to the fire,

c)   _ not propagate a fire due to transmission of heat,

d)   _ retain structural integrity, and stability

e)   _ not emit smoke or toxic fumes,

f)   _ not produce hot droplets that can propagate fire.

The rigid plastic cores employed in sandwich panels often do not meet the above criteria. However various researchers (47,48,49,50) suggest that sandwich panels do not contribute to the fire. Results on smoke and toxic gas emission (43,50) indicate that there is no additional hazard associated with sandwich panels compared to acceptable lining systems comprising steel cladding, mineral wool insulation, air gap and internal lining of treated organic fibre insulating board and timber frame. However, questions remain concerning the fire resistance and fire propagation of plastic rigid foamed core sandwich panels due to the transmission of heat and the production of hot droplets.

An alternative strategy to the rigid plastic core was to provide the structural requirement via a fire resistant honeycomb and the thermal resistance by using a suitable filling for the honeycombs in order to improve the fire and insulation characteristics.

Honeycomb sandwich panels can be made to transmit heat from one face to the other or to act as an insulating barrier. If, for example, it is required to keep both skins near the same temperature to minimise thermal curvature, metallic honeycombs can be used to transmit the heat from one face to the other.

The heat is transferred from one skin to the other by conduction through the cell walls, air convection currents in the cell and radiation (see fig. 6.1).

Commercially available honeycombs are usually stainless steel, aluminium, glass cloth or polyamide impregnated with resin[110]. These are excellent core material in terms of strength and stiffness but expensive. In terms of fire, metal honeycombs would rapidly transfer heat from the cold face to the hot face and non-metallic glass cloth or polyamed honeycomb cores are combustible. It was decided to investigate honeycombs made from very light gauge paper stiffened by dipping in sodium and /or potassium silicate. The function of the thin paper is simply a carrier and when impregnated with silicate it provides a non-combustible, low cost and high strength structural core. Apart from being non-combustible, sodium silicate also has intumescent properties when exposed to high temperature. The intumescent foam has a low thermal conductivity which will minimise the heat transmission through the core. At the beginning of the programme the paper honeycombs were made by hand since there was no readily available supply of a suitable

absorbent light gauge paper honeycomb. The paper
material used for construction of hand made honeycomb
was taken from out-of-date telephone directories. At a
later stage of the program, prefabricated paper
honeycombs with heavier gauge paper were supplied by the
Dufaylite company and this allowed larger panels to be
assessed.

convection   radiation   conduction
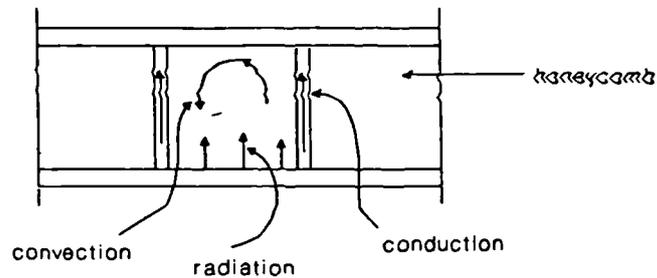
**Figure 6.1   Heat transmission from one face to another
in a honeycomb core**

6.2 HONEYCOMB SANDWICH CORE MATERIAL

In certain structural problems it is necessary to use unusual materials with the correct combination of properties, as well as economic and service requirements. One such group of materials which has been developed in recent years is the honeycomb core. The word honeycomb is used in a broader sense to describe any array of identical prismatic cells. For example the honeycombs produced by bees provided the original form found in nature and this same term has subsequently been applied to any structural form with similar geometries. A typical honeycomb is shown in figure 1.1. It is a two dimensional array of hexagonal thin-walled cells of uniform depth. It can be made in any configuration and from a number of materials, but in general can be classified as either corrugated or expanded, depending on the manufacturing process used. Corrugated honeycomb produced by a rolling operation is illustrated in figure 6.2a. A thin sheet of selected material is fed through a set of rollers designed to form it to a predetermined profile. The corrugated sheet are then cut into strips and bonded together with adhesive to form a cellular matrix in which two sides of each cell have double thickness. In the other manufacturing process, the expansion technique (see fig. 6.2b) a continuous length of sheet is taken from a coil and fed past a series of printing rollers which apply patches of adhesive. The strips is then cut into lengths to form slices which are

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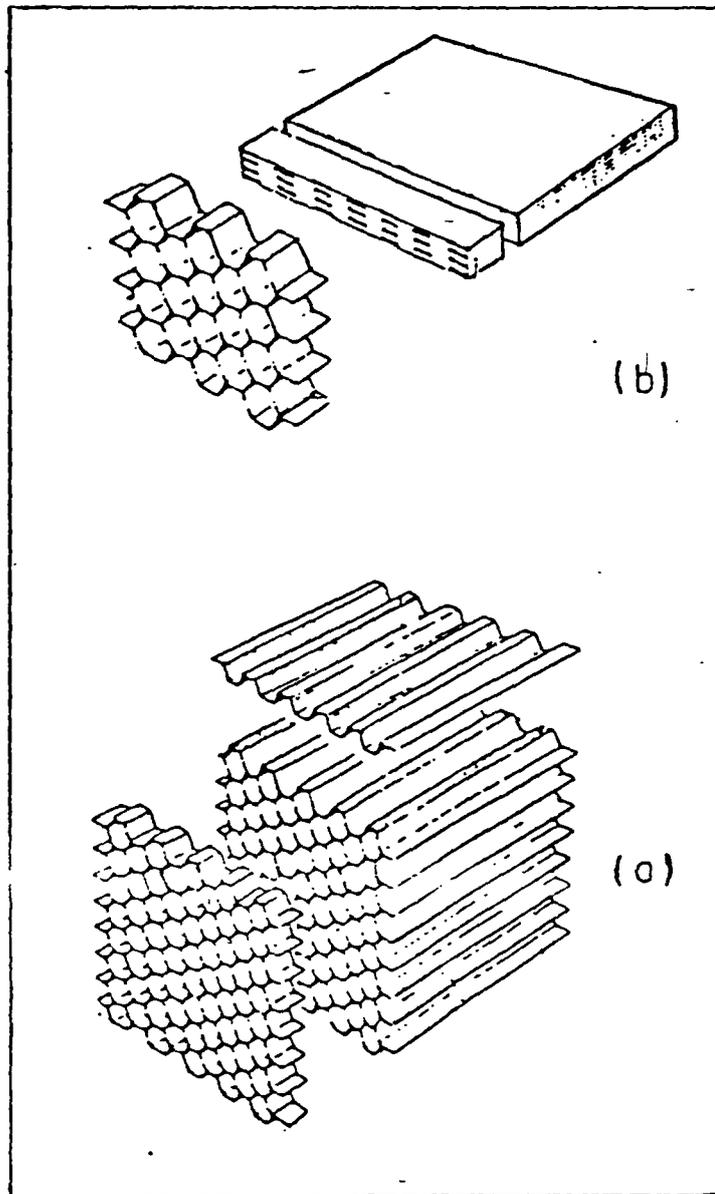
Figure 6.2. Manufacturing methods for honeycomb
(a) corrugated honeycomb
(b) expanded honeycomb

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compressed so that they stick to each other. The units are then expanded laterally to form the honeycomb sheet. The expansion technique has the advantage that all bonds are made simultaneously whereas in the corrugated process one layer is formed at a time. On the other hand, the principal advantages of the corrugated method is that honeycombs of much greater cell depth can be produced and it is particularly suitable for making material of high cell density with more accuracy.

Materials such as aluminium, resin-impregmented paper, resin-impregmented glass cloth, mild steel, stainless steel and titanium can be used to form the honeycombs. Aluminium honeycomb is widely used as a core material in sandwich construction, especially in the aircraft industry, because of it's high strength-to-weight ratio (the density varies between 50 and 170 Kg/m^3 depending on the cell size and the foil thickness).

A high degree of stiffness can be achieved in honeycomb sandwich panels under compression. This is due to the well known fact that stability against buckling is dependent on the geometry of the cross-section as well as it's material properties. Hollow sections and corrugated sheets are structurally more efficient when loaded in compression than solid sections and flat sheets respectively with the same cross-sectional area of material. This is because the former have larger moments of inertia and hence more resistance to buckling. This has been emphasised by Holt[111] comparing
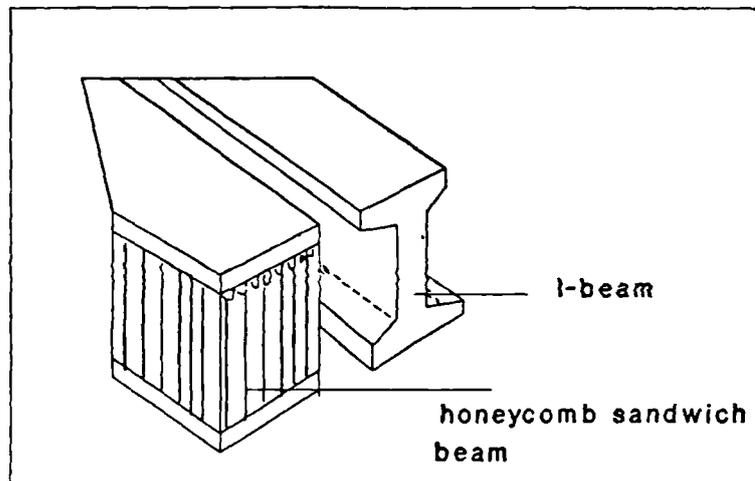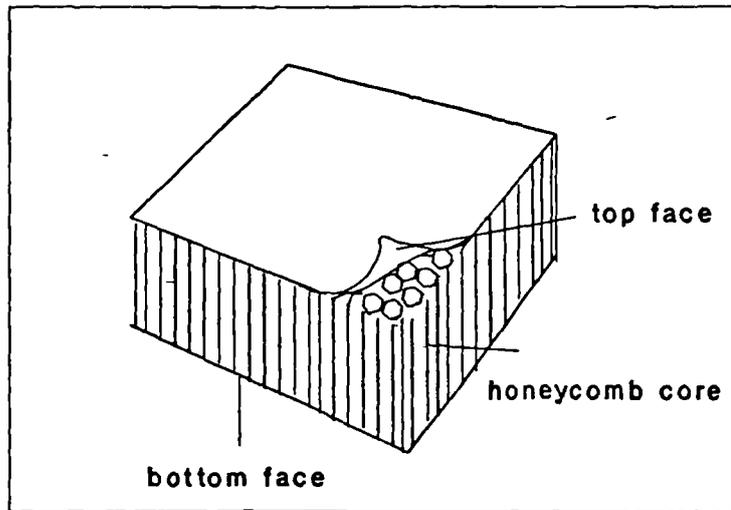
Figure 6.3 Honeycomb sandwich beam compared with an I-beam

the buckling of a solid plate and a honeycomb sandwich
(see fig. 6.3). In addition to high strength-to-
weight ratio there are other reasons for the
popularity of this structural form such as it's property
of high-energy-absorption. In the context of civil
engineering aluminium honeycomb sandwich panels are not
in great demand as they cost more than equivalent
conventional panels. One possible and cheap way of
manufacturing honeycomb is to replace aluminium by a
cheaper material such as paper.

6.3 PAPER HONEYCOMB CORE

The core consisted of a expanded type paper honeycomb core impregnated sodium silicate /or a mixture of sodium silicate and ball clay.

Three sizes of hexagonal-honeycomb specimens were fabricated using untreated papers. For accuracy in the fabrication of the specimen, sheets of A4 paper were laid up and inter spaced with strips of wood glue at 50, 40 and 30 mm sizes. The successive layers were then staggered so that the centres of the strips of any one layer were positioned at the mid point between the strips of preceding and succeeding layers. The carefully laid-up blanks of papers and wood glue-strips were placed in a pre-heated oven at 60°C for 15 minutes.

After being bonded, the flat blanks were trimmed to 25 mm length (i.e. core depth) with a Stanley knife.

The blanks were then expanded to form a hexagonal cell section.

At a later stage in the programme, sandwich beams were manufactured using paper honeycomb core supplied by Dufaylite. The paper honeycombs were manufactured with a heavier paper gauge than telephone directory which allowed the impregnating process in isolation, giving more control over the density of the impregnated core.

6.4 IMPREGNATION OF PAPER HONEYCOMB

WITH SODIUM SILICATE SOLUTION

The expanded paper honeycombs were clamped at the two
ends on a degreased galvanised steel face forming one of
the faces of the sandwich beam. Then with the aid of a
spray gun potassium silicate were sprayed on to the
specimen to bond the paper core to the steel face and to
make the paper honeycomb rigid. The specimens after
being sprayed and dried were then submerged in a sodium
silicate solution and placed in the oven at 65° C to
dry. In order to produce cores of different density, the
process of submerging was repeated several times for
different core specimens (at the CIBA-GEIGY company up
to twenty separate impregnations are used.).

The reason for choosing telephone directory pages and
sodium silicate is that both materials are cheap and can
be easily obtained. Sodium silicate is commonly used as
binder and it also behaves as an intumescent in fire.
The thin absorbent paper is simply a carrier for the
sodium silicate which when dried provided structural
properties.

6.4.1 MODIFICATION OF SODIUM SILICATE

In the early stage of the program, the paper silicate composite were found to possess micro-cracks in the plane of dried sodium silicate as illustrated in plate No. 6.1. The author attributed this to shrinkage of silicate due to loss of moisture.

From the results of the tensile tests on the sodium silicate impregnated paper strips (see chapter 7) it was concluded that it would be desirable to introduce inorganic fillers into the component to form a composite free from micro-cracks.

Work was then undertaken by the author to investigate the effects of adding inert fillers to sodium silicate solutions with intention of eliminating the cracks without having any adverse effect on the fire resistant and adhesion properties of sodium silicate. As the result of this work, modified sodium silicates were produced by addition of inorganic fillers e.g. ball clay and vermiculite. The effect of introducing controlled amount of fillers such as latex as well as glass fibre was also studied.

A comparative tensile test on strips of paper stiffened with modified sodium silicate using different fillers will be discussed in chapter 7.

In the following sections the method of mixing, the ratios of the composite mixes and the visual inspection of modified silicate using a Scanning Electron Microscopic are discussed.

(a) magnification 20x
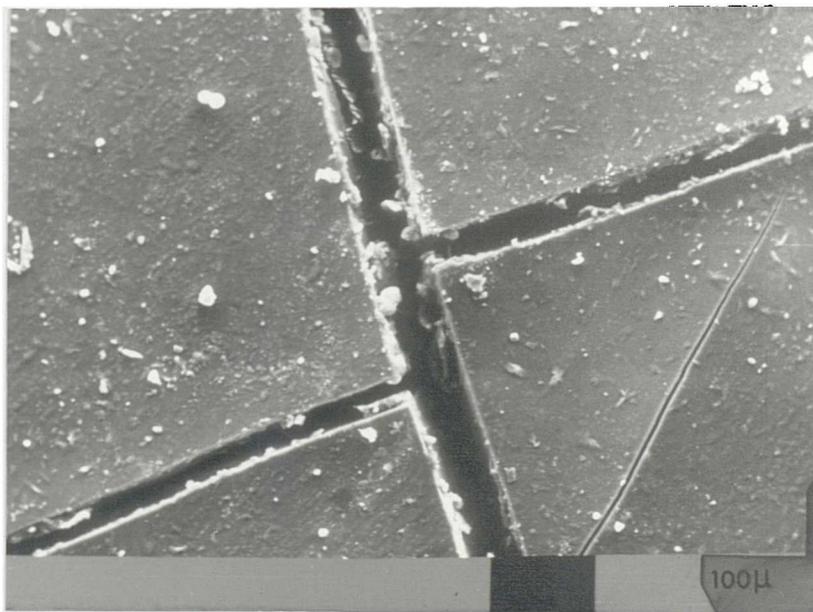
(b) magnification 200x

**Plate 6.1 Scanning Electron Microscopic of
Paper Treated 3 times with Sodium Silicate**

The discussion and comparison of each mix together with the results of tensile tests are presented in chapter 7.

6.4.1.1 ADMIXTURE OF SODIUM SILICATE AND LATEX

Latex was introduced into the sodium silicate solution to reduce and control crack growth and also to produce a more flexible matrix. Sodium silicate and latex were mixed with the aid of a liquidizer with two different ratios of 1:1 and 2:1 respectively. Strips of papers were then submerged in the mixture and were left to dry at the ambient temperature after which they were prepared for Scanning Electron microscopic (see plate No. 6.2.).

6.4.1.2 REINFORCEMENT OF SODIUM SILICATE WITH
GLASS FIBER

Glass fibre was blended with sodium silicate solution (4.4% by weight of glass fibre) using a liquidizer. It was thought that, glass fibre would limit the cracks and would have beneficial effect on the strength of the composite. Paper specimens were coated with the mixture and were dried in ambient temperature.
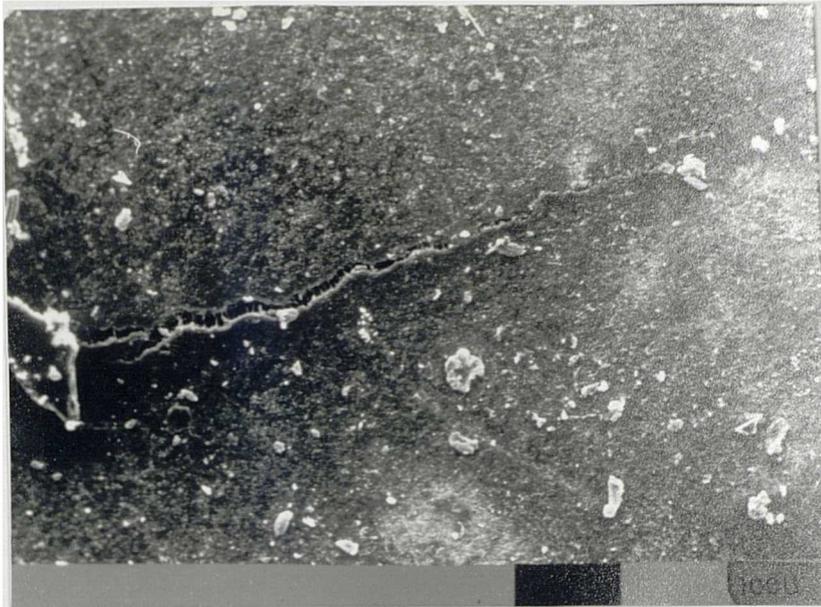
(a) magnification 20x
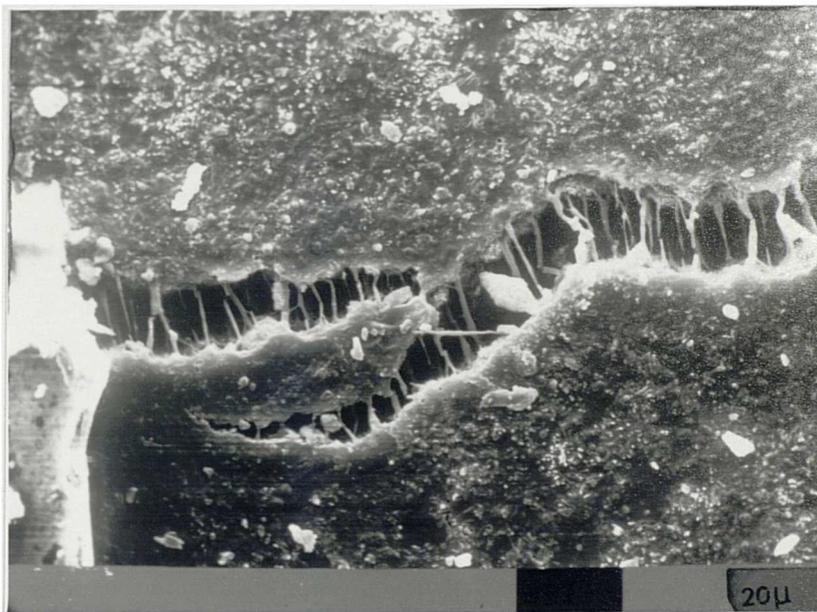
(b) magnification 1000x

Plate 6.2 Scanning Electron Microscopic of
Paper Treated with Sodium Silicate and Latex

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6.4.1.3 INORGANIC FILLER - REINFORCED SODIUM SILICATE

In polymer materials inorganic fillers are used to raise the modulus, and for a variety of other purposes[112] such as to increase surface hardening, reduce shrinkage and eliminate crazing after moulding, improve fire retardancy and reduce cost without necessarily sacrificing the other desirable properties. Ball clay was used as a filler in this investigation. It was mixed with sodium silicate solution using a liquidizer. In order to study the effect of ball clay on sodium silicate, two different mixes were prepared with ratios of 4:1 and 2:1 by weight of sodium silicate to ball clay respectively. It was thought that the presence of ball clay in sodium silicate would improve the bond between all structural elements of the mix and, since sodium silicate is inorganic and compatible with ball clay, would result in a completely inorganic mixture. Plate No. 6.3. shows the electro microscopic photograph of paper impregnated with mixture of sodium silicate and ball clay.

6.4.1.4 SODIUM SILICATE AND VERMICULITE

Vermiculite was mixed with sodium silicate to improve the strength, temperature resistance and to reduce the thermal conductivity of the silicate. A fine grade of vermiculite with a density of 88-112 Kg/m^3 and 0.062-0.065 W/m^o C thermal conductivity was blended with the sodium silicate solution. The control weight of the
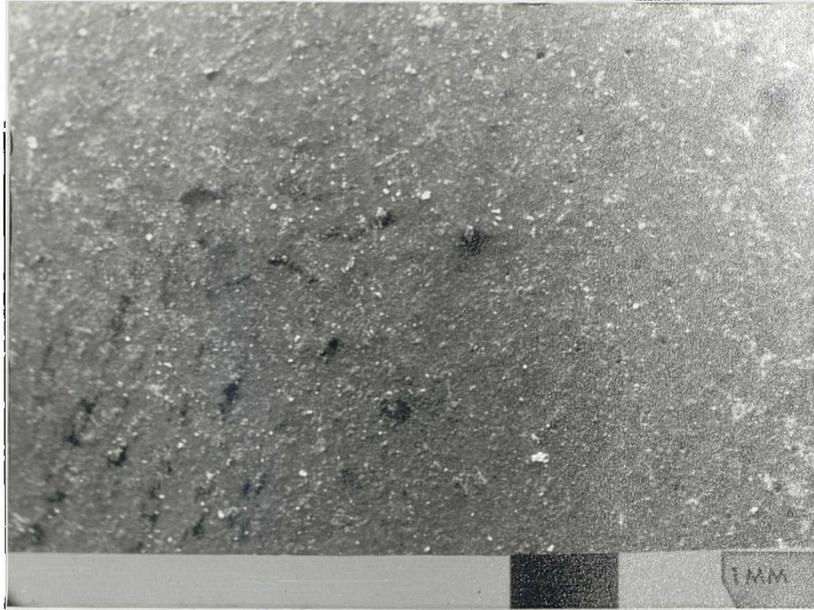
(a) magnification 20 x
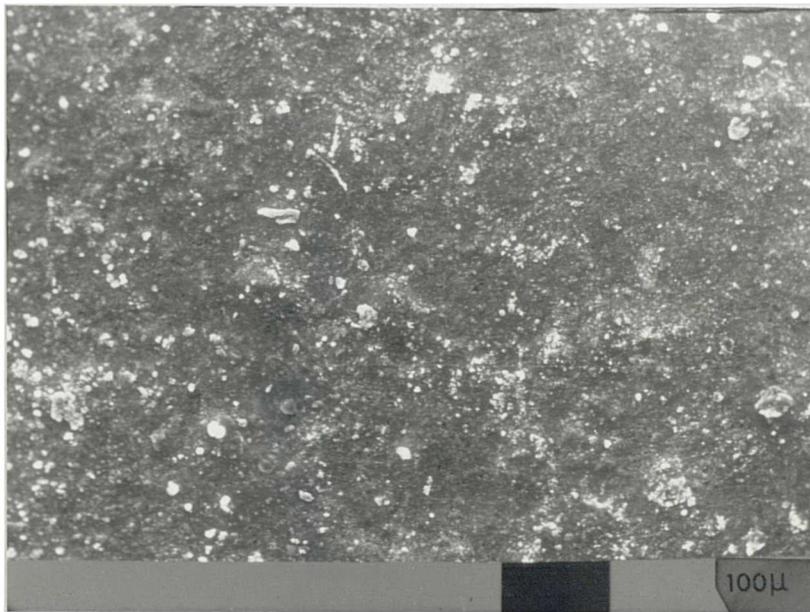
(b) magnification 200x

Plate 6.3 Scanning Electron Microscopic of Paper treated with sodium Silicate and ball clay

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vermiculite was 0.5% of the mix.

A electro microscopic photograph of the paper coated with the mixture is shown in plate No. 6.4.

A series of tensile tests on strips of paper treated with the above mixtures have been performed. The method of the test and the results of the tests together with discussion on each mix are presented in chapter 7.
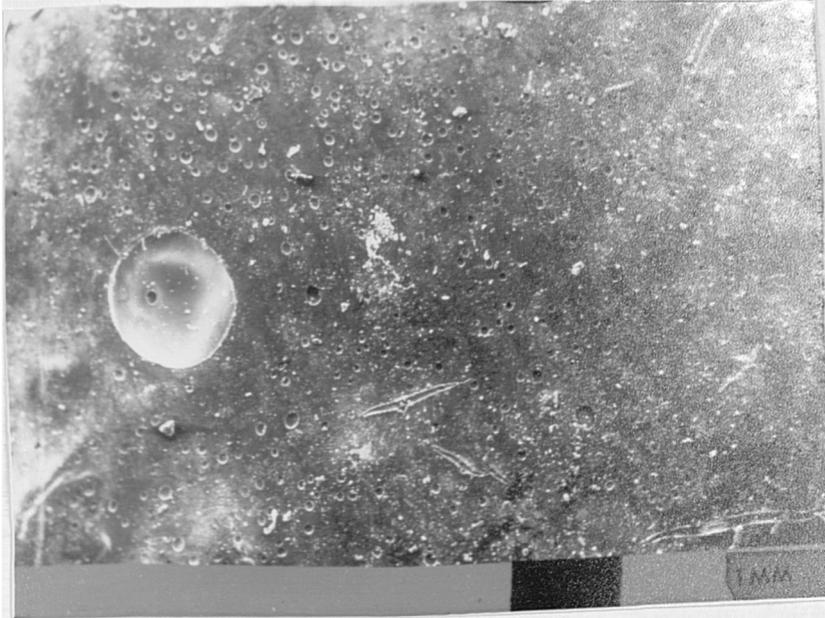
(a) magnification 20x
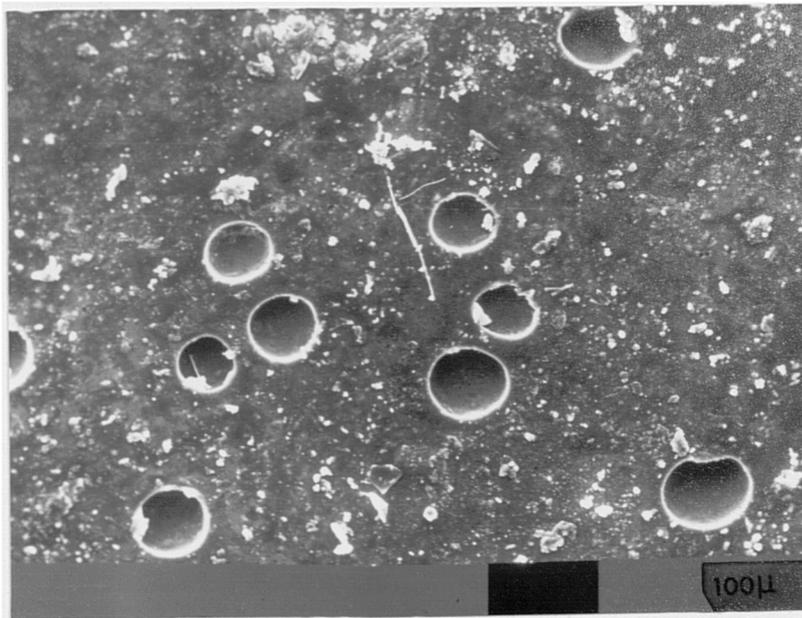
(b) magnification 200x

Plate 6.4 Scanning Electron Microscopic of Paper Treated with Sodium Silicate and vermiculite

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CHAPTER 7
COMPARATIVE TENSILE TEST
ON STRIPS OF STIFFENED
PAPER

CHAPTER 7

COMPARATIVE TENSILE TEST ON STRIPS

OF STIFFENED PAPER

7.1 INTRODUCTION

Tensile tests were carried out in order to examine the stiffness and strength properties of different mixes used for stiffening paper and to find the elastic modulus of the solid material forming the honeycomb core which is needed for calculating the core shear modulus (see chapter 8).

A total of 146 tensile tests were carried out on treated and untreated strips of paper with following arrangements:

- 16 untreated paper strips;

- 17 strips treated with potassium silicate;

- 36 strips treated with sodium silicate;

- 4 strips treated with a mixture of sodium silicate and glass fibre;

- 40 strips treated with mixture of sodium silicate and ball clay with the ratios of 4:1 and 2:1 by weight of sodium silicate to ball clay;

- 24 strips treated with sodium silicate and latex with ratios of 1:1 and 2:1 by weight of sodium silicate to latex;

- 5 strips treated with sodium silicate and vermiculite.

-    4   strips treated with sodium silicate and
     ball clay with glass fibre reinforced.

7.2   PAPER AS A MATERIAL

Paper is a sheet material, two of it's dimensions are larger than the third, it's thickness. It is composed of ribbonlike elements: collapsed (or partially collapsed) wood pulp fibres, or other types of organic fibres as illustrated in plate No. 7.1. The fibres form a network in which externally applied loads must be transmitted to the individual fibre segments through the bonded contact between the fibres. Since the fibres are laid down in layers with their axis in the plane of the sheet, the bonded areas between fibres are generally oriented with their normal direction perpendicular to the plane of the sheet. Commercial paper is manufactured in such a way that the axes of the fibres tend to be aligned parallel to the flow of the paper through the paper making machine. This micro structure arrangement, combined with web tension and drying resistance, gives rise to an orthotropic material response. The three, mutually perpendicular, principal directions are referred to as the machine direction (MD), cross-machine direction (CD), and the through thickness (or Z). Paper strength must be considered in terms of this anistropy.(see fig. 7.1).

Failure phenomena in paper are highly dependent on the direction of the applied loads relative to the principal

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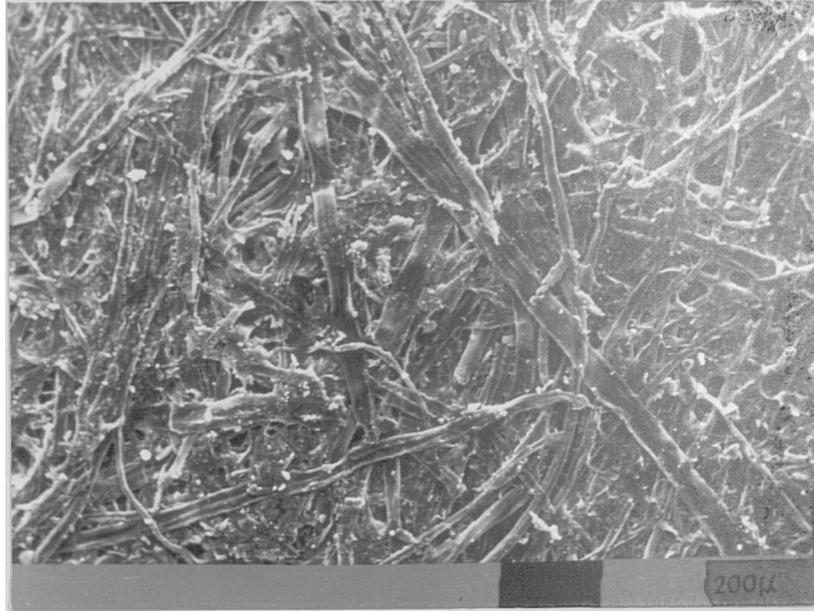
Plate 7.1 Scanning Electron Microscopic of untreated paper (magnification 100x)

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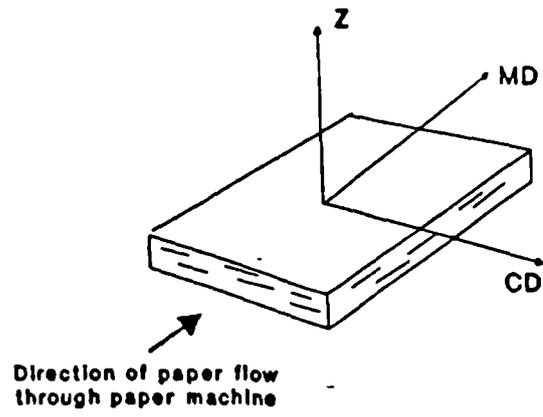
Figure 7.1. Principal material direction of paper
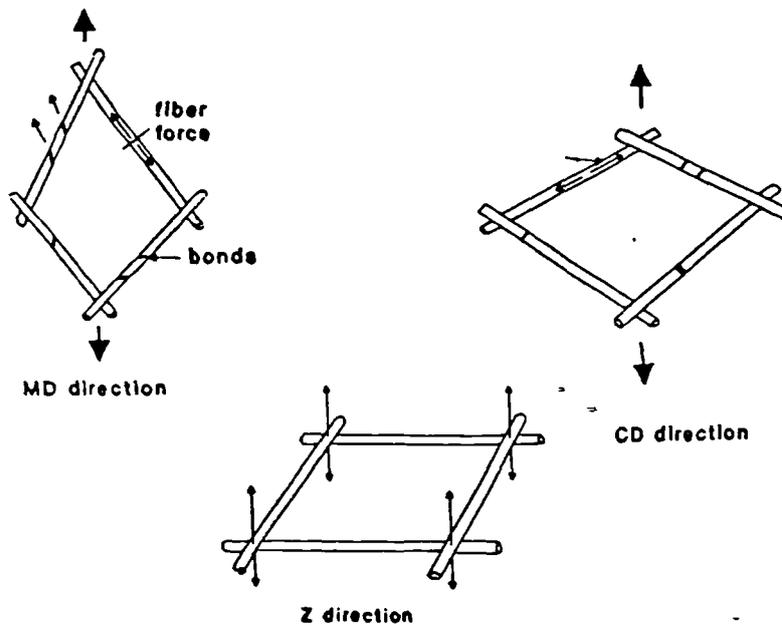
Figure 7.2. Hypothetical force direction in fiber network for tensile loading along principal material direction

material directions. The response to the the tensile forces applied in each of the directions will be different due to the orientation of the fibre segments and the bonded area connecting them. Figure 7.2 shows forces acting on a hypothetical diamond-shaped of aligned fibre network. It can be seen that the resultant forces in the fibre element are quite different when loaded in the machine direction. The bonded areas, consequently, will be subjected to different shear transfer stresses.

7.3   DETERMINATION OF THE PAPER THICKNESS

The thickness of the paper (ex British Telecom directory pages) under study have been determined in accordance with BS 3983 : 1989[113].

Sheets of paper were cut from the representative source at random. Six test pieces made from a pack of ten sheets was prepared. The thickness of a single sheet was determined by dividing the thickness of each test pack by ten. The average thickness of the paper sheet was found to be 0.062 mm with 0.0177 standard deviation.

7.4 PREPARATION OF THE TEST PIECES

A total of 146 strips of paper with dimension of 25mm wide and 200mm long were prepared for tensile test. 98 of the strips were cut from pages of an ex Telephone directory. 23 strips were cut from representative sheets of chipboard paper which made up the honeycomb core supplied by Dufaylite. 25 strips were cut from sheets of Kraft paper

Typical tensile specimens for most materials are dog-bone shaped (fig.7.3) In this way a large tensile force can be transmitted to a sample through a larger transfer area which minimises stress concentrations near the grips. The "necked-down" portion of the sample magnifies the uniform tensile stress through the narrow section. To obtain a pure tensile stress-strain diagram for the material, the strain is measured over the portion of the specimen that is under pure tension. The tensile strain is computed by dividing the elongation of a preselected gauge length by the original gauge length. For the paper it is difficult to measure the elongation of a gauge length marked on a necked down portion of a dog-bone specimen. It is more convenient to use the crosshead or other movement that separates the grips. After cutting the strip to the right size and shape, the weights of each strip were measured using an electronic scale with an accuracy of 0.1 gram prior to coating. The strips were then treated with the appropriate coating and left to dry in the ambient temperature for a minimum

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'dog_bone'
specimen

constant width
strip
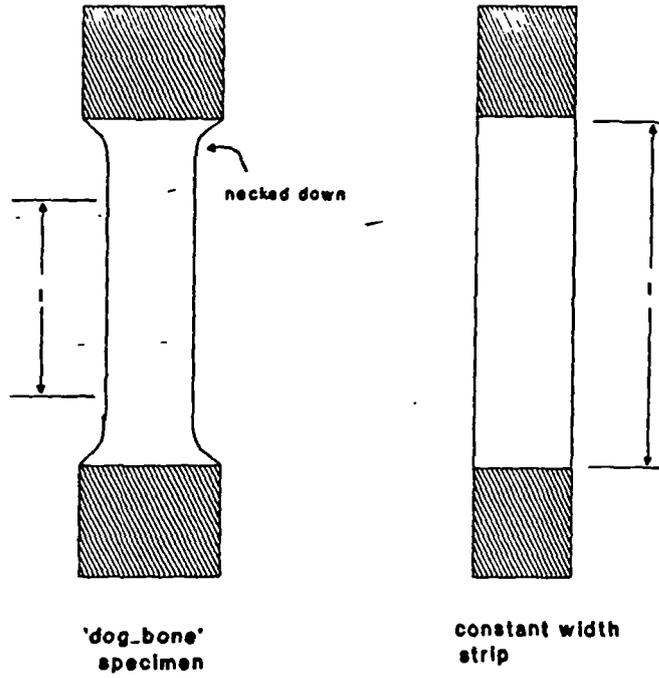
Figure 7.3. Tensile test specimens

of four days. The weights of the strips were then recorded and left to dry at room temperature for another two days and then re-weighed. This drying process was repeated until no change was detected in the weight of the strip.

7.5 TENSILE TEST PROCEDURE

A constant rate of elongation method was used in accordance with BS 4415 : part 2 : 1986[114].

The specimens were held in position by two gripping devices which were attached to the testing machine. The grips were tightened mechanically, compressing the paper through the thickness. To prevent grip slippage, the two ends of the test specimen were sandwiched between coarse sandpaper inside the grips. Tensile loads were applied by pulling the grips with a constant rate of elongation (1mm/min.) up to rupture. Consequently as result a load-elongation curve was obtained by plotting the movement of the grips against the applied load.

A pair of dial gauges with an accuracy of 0.01mm were set to measure the lateral reduction of strip width for a possible calculation of Poison's Ratio.

The result of the tests for specimens breaking near or within the grip area have been rejected.

7.6 ANALYSIS OF THE RESULTS

A typical load extension graph is shown in the appendix C.

For each specimen tested, tensile strength (σ_u) and elastic modulus (E) were determined using the equations 7.3 and 7.4.

$$\sigma = \frac{F}{C.A} \qquad \ldots\ldots\ldots\ldots(7.1)$$

$$e = \frac{1}{1_o} \qquad \ldots\ldots\ldots\ldots(7.2)$$

$$E = \frac{\sigma}{e} \qquad \ldots\ldots\ldots\ldots(7.3)$$

$$\sigma_u = \frac{F_u}{C.A} \qquad \ldots\ldots\ldots\ldots(7.4)$$

where
σ	is stress	(N/mm^2)
F	is tensile force	(N)
C.A	is cross-section area of the strip	(mm^2)
1	is elongation of the strip	(mm)
1_o	is gage length of the strip	(mm)
E	is modulus of elasticity	(N/mm^2)
σ_u	is tensile strength	(N/mm^2)

The results (σ_u and E) are shown in table 7.1-7.3 for strips of untreated paper. These figures shows that Kraft paper appear to have the highest E and σ_u in comparison to telephone directory pages and chipboard paper.

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The figures in tables 7.1-7.3 shows that elastic modulus of the Kraft paper is 53% and 18% higher than telephone directory and chipboard respectively. Tensile strength appear to be higher by 53% and 28%. When stiffened with sodium silicate, Kraft paper found to be 49% and 22% higher than the two paper under investigation. Similar results were obtained for papers stiffened with sodium silicate and ball clay (see tables 7.4 and 7.5) . Tables C1- C9 (appendix C) shows the result of tests for strips of paper with various coatings. The values of E and σ_u which are shown in these tables are calculated by dividing the tensile load over the cross-section of the strip (i.e. thickness of the paper + thickness of the coating). In the case of paper from telecom directory pages the result show that, as the thickness of coating increases the values of σ_u and E decrease. This could be due to the poor quality of the paper. In the case of Chipboard and Kraft paper this is only true where sodium silicate was used as coating. But when sodium silicate and ball clay was used the result shows that the values of σ_u and E increases with increase in the thickness of coating. For strips coated with sodium silicate this could be duo to the presence of micro-cracks in the plain of dried sodium silicate (as explained in section 6.4.1) which were eliminated by introduction of ball clay into sodium silicate. For the purpose of comparison, the thickness of coating have not taken into account and the stress have been calculated by dividing

the load over the thickness of the untreated paper.

Table 7.6 shows the tensile strength of paper strip that can be achieved by various coatings. The best results were obtained using sodium silicate and ball clay with a ratio of 4:1 respectively which achieved a strength ratio of 8.9 when compared with the strength ratio of untreated paper. A ratio of 8.4 was achieved by the use of sodium silicate and ball clay with a ratio of 2:1.

Table 7.7 gives an idea in terms of improvement of elastic modulus of paper that can be achieved by using different coating materials. Unlike strength, a higher factor of 31.9 improvement achieved by sodium silicate and ball clay with a ratio of 2:1.

Table 7.8 shows the stiffness to weight ratio for various coatings under investigation. The results indicate that potassium silicate was found to be the most efficient coating.

The effect of different coatings on tensile strength of paper strips is shown graphically in fig.7.4 as a function of the amount of coating. The plotted result indicate a sharp increase in tensile strength up to certain coating thickness over which the intensity of increase in tensile strength reduces.

Stress-strain curves based on paper cross-section for various type of coating are shown in fig. 7.5. This indicates that, in the case of sodium silicate and ball clay, a remarkable strain improvement has been achieved by increasing the amount of ball clay in the matrix.

Stress-strain curves for paper stiffened with sodium silicate for various numbers of coating is presented in fig.7.6.

Fig.7.7 shows that a remarkable improvement has been achieved by reinforcing sodium silicate and ball clay with glass fibre.

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NOTE: Sodium silicate is highly alkaline and will
        degrade glass fibre in the medium to long term.

7.7 COMMENT ON EACH TYPE OF COATING

Group A (potassium-silicate)

Group A was found to be the most efficient coating in terms of stiffness to weight ratio. In comparison to group B according to the manufacturer [115] it also has a slightly higher softening point but it is more expensive.

Group B (sodium-silicate)

Paper strips coated with group B coating showed a higher stress at failure when compared to group A. The stress-strain curve (see fig. 7.5) for group A coatings shows hardly any plastic range as for group B coating it indicate yield has occurred before failure took place. This could be due to the presence of microscopic cracks in the material.

Group C (ball clay and sodium-silicate)

The introduction of ball clay into the sodium silicate as a filler increased both the elastic modulus and the tensile strength of the paper strip.

A higher ball clay ratio in the composite enhanced the elastic modulus of the strips whereas reducing the amount of clay increased the tensile strength of the strips. Fig. 7.7 indicates that the plastic range for group C, with a ratio of 2:1, extends to only small values of strain compare to a 4:1 ratio.

group D (sodium-silicate and latex)

In order to enhance the flexibility of sodium-silicate, a small amount of latex was mixed with the silicate

solution. The result shows a higher elastic modulus and tensile strength for a 2:1 ratio of sodium-silicate to latex compared to groups A and B. It was also found to be more efficient in terms of stiffness to weight ratio compared to group B and C. More research is required to find the effect of latex on the fire performance of silicate.

Group E (sodium silicate and vermiculite)

The result of the tensile tests on strips of paper stiffened with sodium silicate and vermiculite shows that presence of vermiculite in the sodium silicate reduce both E and σ_u in comparison to the paper stiffened with sodium silicate. However, these values shown in table C4 (appendix C) are not the true values because the effective thickness of the strips believed to be less than the measured thickness. This is due to the fact that the surface of the coated paper was not smooth because of the vermiculite particles on the surface of the strip which produce a rough surface.

Figure 7.4 Comparison of the Stiffness
Power of Various Coatings

Ultimate stress (N/mm**2)

Coating thickness (mm)

——— 1 potassium silicate
——— 2 sodium silicate
——— 3 S.S+ball clay 4:1
····· 5 S.S + latex 1:1
——— 4 S.S + latex 2:1
——— 6 S.S+ball caly 2:1
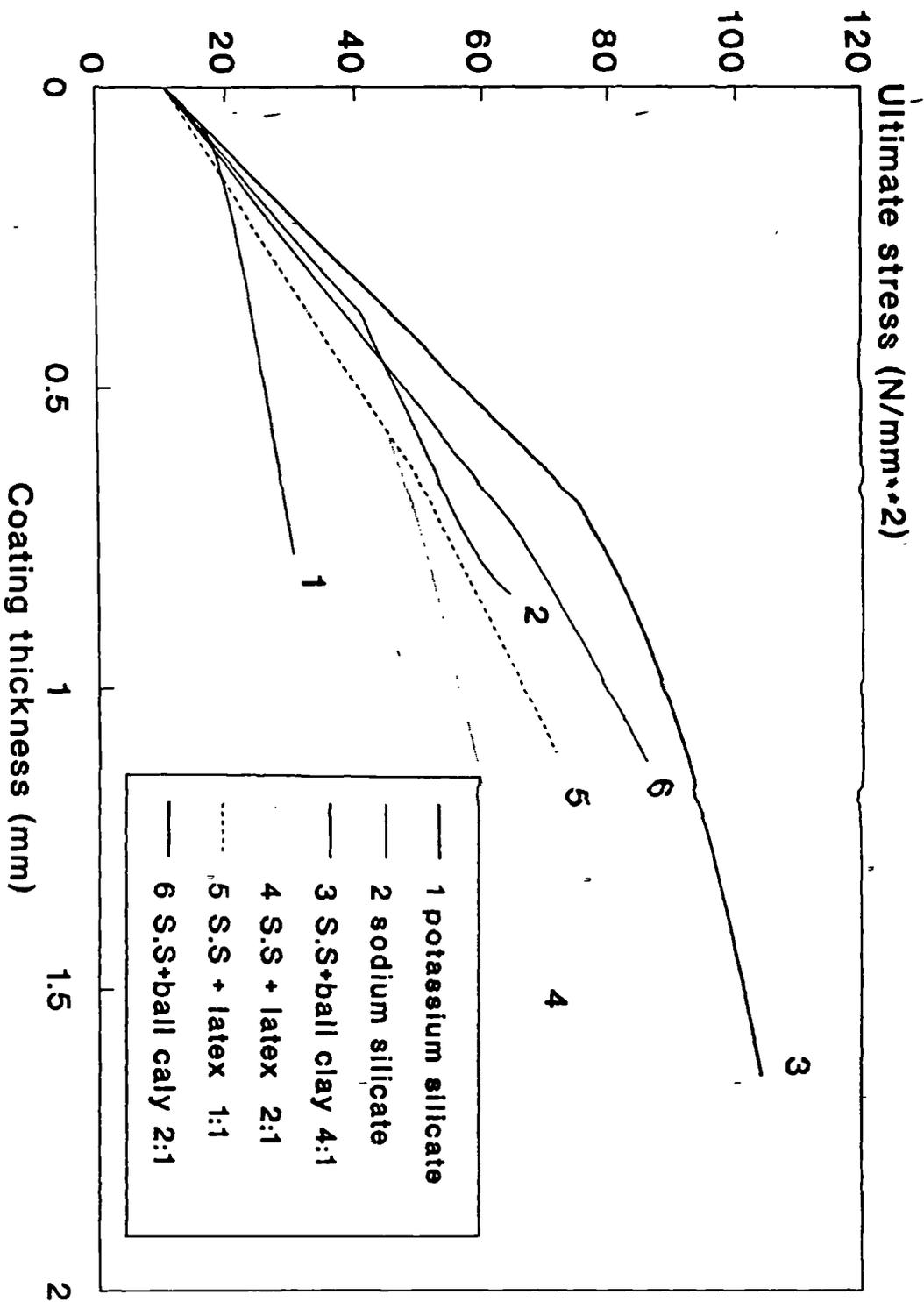
FIG 7.5 Stress vs Strain
for Various Coatings

Strain 10**-3

paper weight in g/m²

S.S = 1767
untreated = 40
S.S & B.C 2:1 = 2240
Potassium silicate = 648
S.S & B.C 4:1 = 1996
S.S & latex 1:1 = 1231
S.S & latex 1:2 = 1162

— S.S.   + untreated   * B.C & S.S 1:4   □ B.C and S.S 1:2
* P.S.   ◇ latex & S.S 1:1   △ latex & S.S 1:2
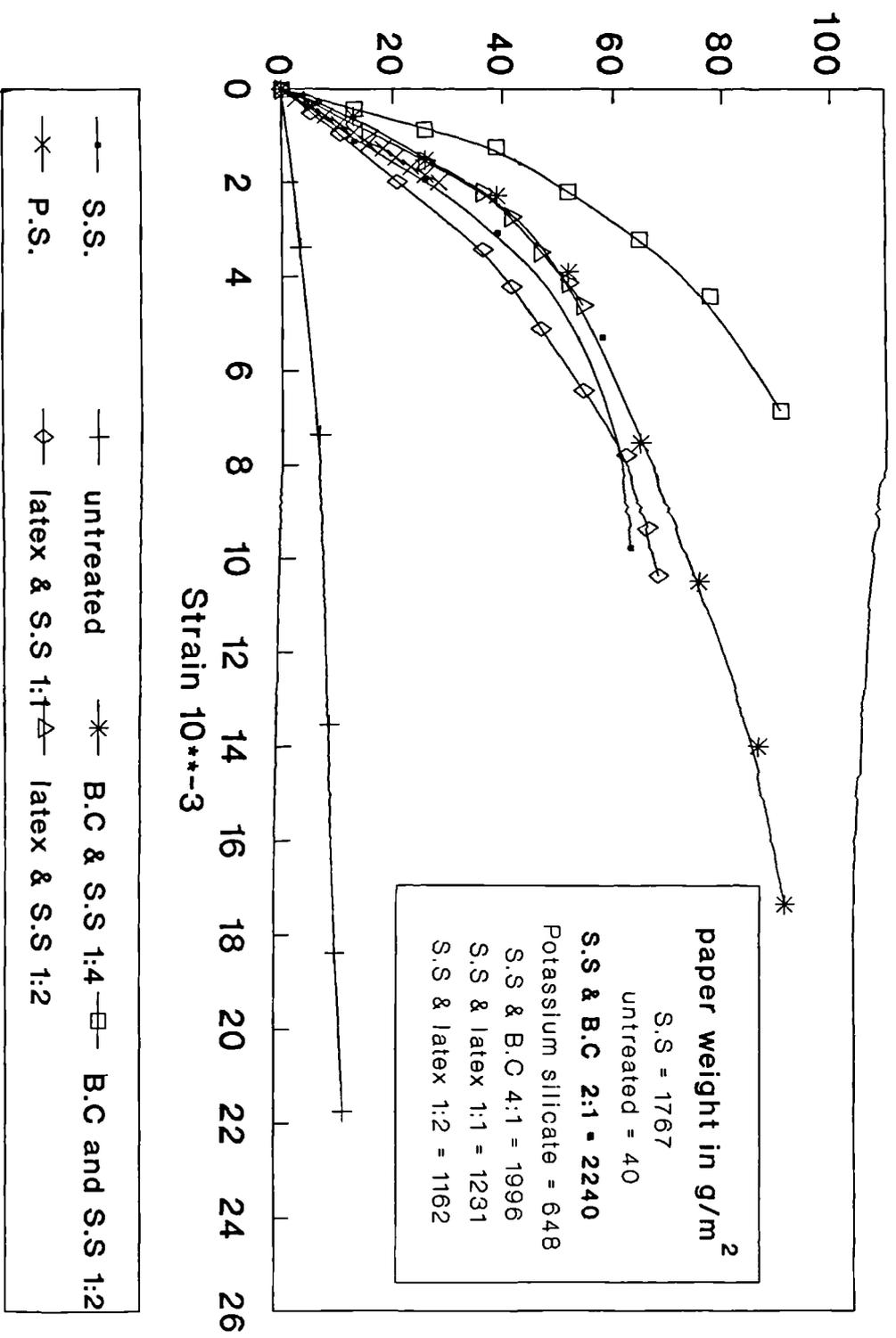
Figure 7.6 Stress vs Strain
Paper Coated With Sodium Silicate
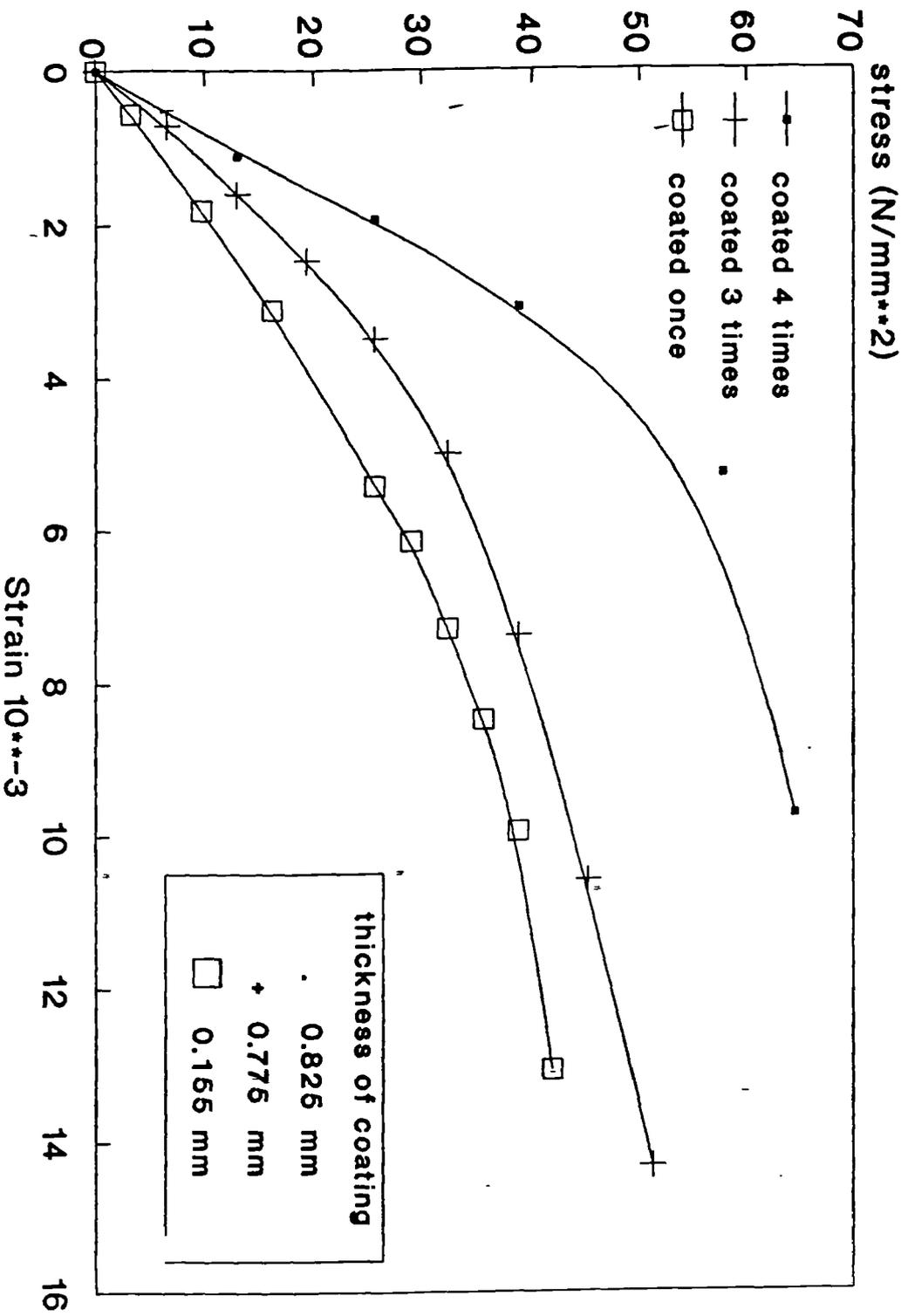
Figure 7.7 Stress vs Strain
Sodium silicate and Ball Clay Coating

Stress (N/mm**2)

Strain (N/mm**2) 10**-3

1 S.S & B.C 2:1 1*
2 S.S & B.C 2:1 2*
3 S.S & B.C 4:1 1*
4 S.S & B.C 4:1 2*
5 S.S & B.C+fiber 2*
(* No. of dipping)

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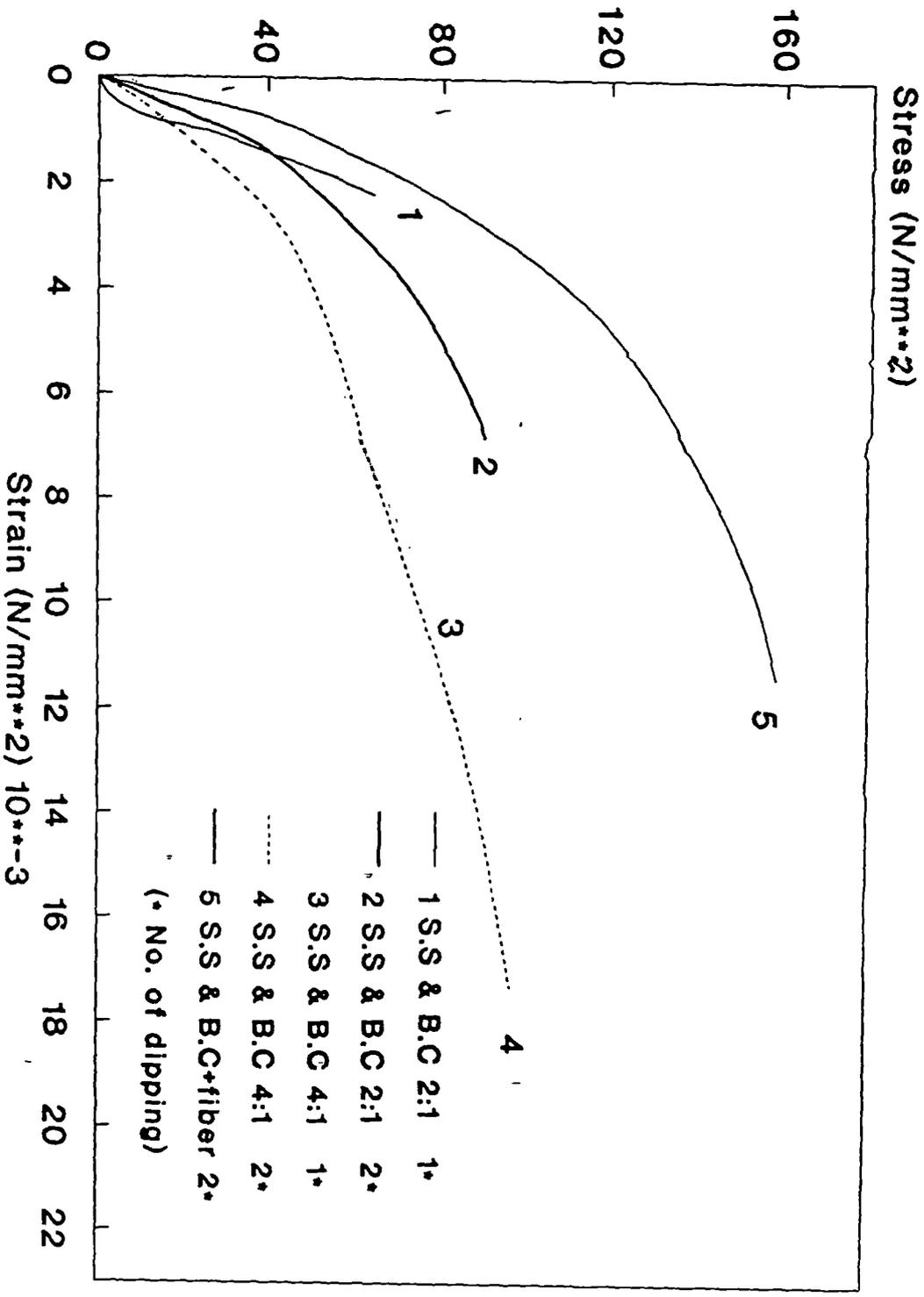
7.8 DISCUSSION AND CONCLUSION

Kraft paper appear to have the highest E and σ_u in comparison to telephone directory pages and chipboard paper. The E values of the untreated Kraft paper found to be higher by factor of 2.2 and 1.2 when compared with Telephone directory page or Chipboard.

Table 7.4 shows the average values of E and σ_u of papers stiffened with sodium silicate. It appears from these figures that Kraft paper has achieved a modulus of elasticity of 3108.53 N/mm^2. This figure is six times grater than the elastic modulus of Telephone directory page with the equal coating thickness. This indicate that the quality of the paper has a strong influence on the elastic modulus of the stiffened paper.

Incorporation of sodium silicate as a paper coating has been found to increase the tensile strength and elastic modulus of the paper strips. However, the tested paper with sodium silicate was found to be extremely brittle because of this brittle nature the tensile properties are most effectively improved by the use of ball clay, which contributed an integrity of it's own to the composite.

The presence of ball clay in sodium silicate (group C) considerably enhances the tensile properties of paper stiffened with sodium-silicate. The Scanning Electron Microscopic of paper treated with sodium silicate and ball clay revealed that no cracks exist in the sample (see plate No. 6.3 on page 174).

The use of glass fibre in sodium silicate did not have any great effect on the tensile properties of *sodium silicate*. This could be due to the poor bonding of fibres to the silicate matrix which allowed separation at low stress level.

Addition of latex into the sodium-silicate solution improved the tensile strength and the elastic modulus of paper stiffened with sodium silicate and was found to be the most efficient coating after group A (with 2:1 ratio of sodium silicate to latex respectively). However, it found to have an adverse effect on the intumescent property of sodium-silicate when exposed to high temperature.

The result of the tests on strips of paper stiffened with sodium silicate and Vermiculite did not show any improvement in the tensile properties of paper when compared to the paper stiffened with sodium silicate alone. However, these results are effected by the fact that the effective thickness of the strips believed to be less than the measured thickness. The scanning electron microscopic of paper treated with sodium silicate and ball clay illustrate that no cracks exist in the sample (see plate No. 6.4 on page 176).

Later in the programme it is shown that the introduction of Vermiculite into the sodium silicate used as coating the paper honeycomb cores has enhanced the fire resistance of the honeycomb core.

TABLE (7.1) Result of Tensile Tests on Untreated British

Telephone directory page

test No.	strip weight (g/m^2)	thickness of the paper strip (mm)	elastic modulus of the strip (N/mm^2)	tensile strength of the strip (N/mm^2)
1B	40.2	0.062	795.95	8.91
2B	40.2	0.062	976.36	7.99
3B	40.6	0.062	818.34	11.36
4B	40.61	0.062	1045.74	11.98
5 B	40.2	0.062	840.57	11.91
6B	40.4	0.062	864.59	10.59
average	40.4	0.062	864.31	10.59

TABLE (7.2) Result of Tensile Tests on Untreated

Chipboard Paper

test No.	strip weight (g/m^2)	thickness of the paper strip (mm)	elastic modulus of the strip (N/mm^2)	tensile strength of the strip (N/mm^2)
1C	172.0	0.28	1226.7	13.6
2C	185.0	0.28	1755.1	13.9
3C	179.0	0.28	1445.5	11.9
4C	179.1	0.28	1578.2	13.4
5C	172.0	0.28	1600.0	—
average	177.4	0.28	1521.1	13.2

TABLE (7.3) Result of Tensile Tests on Untreated

Kraft Paper

test No.	strip weight (g/m^2)	thickness of the paper strip (mm)	elastic modulus of the strip, E (N/mm^2)	tensile strength of the strip, σ_u (N/mm^2)
1K	180.0	0.26	1708.5	16.0
2K	188.0	0.26	2564.4	20.3
3K	172.0	0.26	1591.11	17.8
4K	179.0	0.26	1637.6	19.23
5K	185.0	0.26	1835.3	18.9
average	180.8	0.26	1867.4	18.4

TABLE (7.4) Effect of paper Quality on E and σ_u

Stiffened with Sodium Silicate

type of paper	strip weight (g/m^2)	thickness of coating (mm)	E (N/mm^2)	σ_u (N/mm^2)	No. of dipping
BTD[1]	590.5	0.22	2477.98	9.27	once
	1345.7	0.79	504.3	4.28	3 times
CB[2]	930.5	0.34	3753.18	9.04	once
	2010.0	0.78	3067.3	5.3	3 times
KB[3]	985.1	0.35	4873.38	10.17	once
	2155.5	0.78	3108.53	5.9	3 times

1 British telecome directory, average of eight tests.
2 Chipboard paper, average of 10 tests.
4 Kraft paper, average of 9 tets.

TABLE (7.5) Effect of paper Quality on E and σ_u

Stiffened with Sodium Silicate and Ball Clay

type of paper	strip weight (g/m^2)	thickness of coating (mm)	E (N/mm^2)	σ_u (N/mm^2)	No. of dipping
BTD[1]	1238.1	0.58	2419.82	6.59	once
	—	—	—	—	3 times
CB[2]	643.3	0.16	6510.94	—	once
	1566.0	0.67	11673.39	—	3 times
KB[3]	703.0	0.17	5943.0	15.4	once
	1744.0	0.79	10507.3	—	3 times

1 average of five test results.
2 average of 3 tests for dipped once and 3 tests for dipped 3 times.
4 average of 4 tests for both dipped once and 3 times.

TABLE (7.6) Strength Potential of Various Coatings

coating	ratio by weight	coating thickness (mm)	No. of coating	strip weight (g/m^2)	tensile strength (N/mm^2)	factor[*]
P.S.		0.293	4	648.705	30.33	2.9
S.S		0.841	4	1767.62	63.87	6.0
S.B	4:1	1.098	2	1996.19	93.93	8.9
S.BC	2:1	1.036	2	2240.0	88.92	8.4
S.LX	2:1	1.008	2	1162.77	65.98	6.2
S.LX	1:1	1.103	2	12311.89	71.16	6.7

[*]   this value has been calculated by dividing the tensile strength of the stiffened paper by the tensile strength of untreated paper.

P.S = potassium silicate.
S.S = sodium silicate.
S.BC = sodium silicate and ball clay.
S.LX = sodium silicate and latex.

TABLE (7.7) Effect of Coating on the Elastic Modulus

coating weight	ratio by weight	thickness of coating (mm)	No. of coating (mm)	strip weight (g/m^2)	elastic[*] modulus (N/mm^2)	factor
P.S.	1	0.293	4	648.71	14395.62	16.7
S.S	1	0.841	4	1767.62	12586.99	14.6
S.BC	4:1	1.098	2	1996.19	17610.74	20.4
S.BC	2:1	1.036	2	2240.00	27614.07	31.9
S.LX	2:1	1.008	2	1162.77	15850.48	18.3
S.LX	1:1	1.103	2	1231.89	10542.08	12.2

[*]   the stress calculation was obtained by dividing the load by the net thickness of the paper.

TABLE (7.8) Stiffness to weight ratio

coating	ratio by weight	strip weight (g/m^2)	elastic* modulus (N/mm^2)	modulus/weight ratio
P.S	1	648.71	14395.62	22.2
S.S	1	1767.62	12586.99	7.1
S.BC	4:1	1996.19	17610.07	8.8
S.BC	2:1	2240.00	27614.07	12.3
S.LX	2:1	1162.77	15850.48	13.6
S.LX	1:1	1231.89	10542.08	8.6

*   the stress was calculated by dividing the load by the net thickness of the paper.

CHAPTER 8

EXPERIMENTAL WORK ON SANDWICH BEAM WITH NEWLY DEVELOPED HONEYCOMB CORE

CHAPTER 8

EXPERIMENTAL WORK ON SANDWICH BEAMS

WITH HONEYCOMB CORE

8.1 INTRODUCTION

In this chapter the authors experimental work related to the determination of shear modulus and compression properties of developed honeycomb core will be discussed. Later the experimental results of the core shear modulus will be compared with the theoretical calculations of honeycomb shear modulus as discussed in section 2.5.

A total of 39 honeycomb core sandwich beams with various cell geometry, core depth and core density were tested using a four point loading system to determine the shear modulus of the core. Representative samples were cut from unaffected areas of the beams for compression tests. The details of the test series for four point loading are presented in tables 9.1A and 9.2B respectively. Tables 9.2A and 9.2B show the cell geometry of the honeycomb core specimens listed in tables 9.1A and 9.1B.

TABLE 8.1A   Details of the Test Series

test No.	face thickness (mm)	core depth (mm)	core density (kg/m^3)	width of the beam (mm)	span of the beam (mm)
1	0.52	25.0	50.8	100.0	600.0
2	0.52	25.0	104.0	100.0	600.0
3	0.52	25.0	108.5	100.0	600.0
4	0.52	25.0	119.9	100.0	600.0
5	0.52	25.0	110.5	100.0	600.0
6	0.56	25.0	150.7	100.0	600.0
7	0.56	25.0	138.8	100.0	600.0
8	0.56	25.0	112.5	100.0	600.0
9	0.56	25.0	177.1	100.0	600.0
10	0.56	25.0	260.3	100.0	600.0
11	0.56	25.0	93.5	100.0	600.0
12	0.56	25.0	130.3	100.0	600.0
13	0.56	25.0	164.9	100.0	600.0
14	0.56	25.0	189.7	100.0	600.0
15	0.56	25.0	168.9	100.0	600.0

The paper material used for honeycomb core for the beams listed in this table was from out-of-date telephone directories.

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TABLE 8.1B Details of the Test Series

test No.	core depth (mm)	core density (Kg/m^3)	width of the beam (mm)	span of the beam (mm)
16	25	23.4	100.0	610.0
17	50	40.0	100.0	610.0
18	25	70.8	100.0	610.0
19	25	36.3	100.0	610.0
20	25	71.7	100.0	610.0
21	25	48.0	100.0	610.0
22	25	108.0	100.0	610.0
23	25	65.0	100.0	610.0
24	25	66.7	100.0	610.0
25	75	79.8	100.0	610.0
26	75	71.0	100.0	610.0
27	75	64.8	100.0	610.0
28	50	53.9	100.0	610.0
29	25	62.5	100.0	610.0
30	25	68.0	100.0	610.0
31	25	137.8	100.0	610.0
32	25	267.7	100.0	610.0
33	25	214.8	100.0	610.0
34	25	161.2	100.0	610.0
35	50	240.6	100.0	610.0
36	50	108.0	100.0	610.0
37	50	80.0	100.0	610.0

continue next page

Table 8.1B continued

38	50	55.1	100.0	610.0
39	75	105.2	100.0	610.0

The honeycomb core used for the beams in the above table have been supplied by Dufalyte company.

TABLE 8.2A Cell Geometry of the Honeycomb Core Listed in Table 8.1A

test No.	t^* (mm)	l^* (mm)	h^* (mm)	e^* (mm)	core treatment
1	0.22	16.2	9.8	24.5	*sodium silicate*
2	0.25	18.0	8.0	27.0	sodium silicate
3	0.41	18.8	9.0	20.6	sodium silicate
4	0.38	21.3	10.2	23.0	sodium silicate
5	0.41	14.2	6.0	19.3	sodium silicate
6	0.50	15.17	6.0	21.7	sodium silicate
7	0.38	19.4	6.6	25.6	sodium silicate
8	0.22	15.5	4.7	23.8	sodium silicate
9	0.50	16.0	5.1	22.0	sodium silicate
10	0.72	17.6	5.4	17.5	sodium silicate
11	0.32	10.3	5.4	17.3	sodium silicate
12	0.80	10.7	4.3	15.2	sodium silicate
13	0.85	15.0	5.5	15.3	sodium silicate
14	0.40	10.0	4.5	16.5	sodium silicate
15	0.37	9.6	5.5	13.9	sodium silicate

* see figure 8.3.

TABLE 8.2B   Cell geometry of the Honeycomb core
Core Listed in Table 8.2B

test No.	t (mm)	l (mm)	h (mm)	e (mm)	core treatment
16	0.26	16.8	13.6	25.6	untreated
17	0.28	17.0	13.0	25.0	untreated
18	0.30	13.0	10.6	25.8	once in S.S
19	0.33	14.0	12.0	25.0	once in S.S
20	0.42	14.9	10.4	22.9	2 x in S.S
21	0.39	14.2	14.0	26.2	2 x in S.S
22	—	—	—	—	
23	—	—	—	—	
24	0.46	14.4	11.4	23.4	once in S.S
25	0.60	12.6	12.4	24.1	2 x in S.S
26	0.90	12.8	12.2	25.4	2 x in S.S
27	0.70	13.0	12.2	24.3	2 x in S.S
28	0.36	16.0	13.0	24.5	3 x in S.S
29	0.60	15.0	14.0	22.0	3 x in S.S
30	0.33	13.7	10.6	25.8	once in S.BC
31	0.60	13.6	13.0	26.8	2 x in S.BC
32	1.32	13.3	12.8	29.2	3 x in S.BC
33	1.03	14.0	14.0	24.7	3 x in S.BC
34	1.10	15.6	14.2	23.8	3 x in S.BC
35	1.50	13.6	13.6	21.6	4 x in S.BC
36	0.63	13.6	13.0	26.5	2 x in S.BC
37	0.70	18.4	16.3	34.2	2 x in S.BC

Table 8.2B continued

38	0.61	19.8	16.0	33.2	2 x in S.BC
39	0.82	18.6	16.5	33.8	2 x in S.BC

S.S = sodium-silicate.
S.BC = sodium-silicate and ball clay.

8.2 Authors Experiments to Determine

Honeycomb Core Properties

In the following the author's experimental work related to determination of shear and compression properties of the developed honeycomb core will be discussed.

8.2.1 SHEAR TESTS

Since a pure shear test on the newly developed honeycomb core in isolation is not reliable, flexural tests were carried out on sandwich beams which were thought to give more valid results.

The shear modulus of the developed honeycomb core was therefore determined by using four point loading test as described in section 5.3.

The test arrangement and the method of applying the load are shown in figure 5.4 (page 145).

8.2.2 COMPRESSION TESTS

Compression properties of the developed honeycomb were determined by using the test method described in section 3.6.2. Two flat-wise compression specimens 100 mm by 100 mm and thickness equal to the core thickness were cut from the unaffected core area of each of the beams tested previously in flexural tests.

8.3 RESULT OF THE TESTS

The result of shear tests and compression tests on honeycomb cores are summarised in this section.

The results of the experimental work will be compared with the calculated shear explained in section 2.5.

Table 8.3A shows the results of four point loading tests and compression test on paper honeycomb core sandwich beams manufactured from out-of-date telephone directories. Test results for prefabricated paper honeycomb supplied by Dufaylite are listed in table 8.3B.

TABLE 8.3A Summary of the Results

test No.	core shear modulus (N/mm^2)	core compression modulus (N/mm^2)	core compression strength (N/mm^2)
1	——[1]	2.82	0.17
2	9.83	9.76	0.24
3	33.1	15.27	0.32
4	25.26	10.5	0.21
5	30.49	9.12	0.16
6	17.15	61.0	0.99
7	23.12	65.0	0.99
8	——	35.6	0.43
9	15.24	38.34	0.98
10	33.72	——	——
11	21.64	47.81	0.4
12	40.42	86.67	1.207
13	57.7	60.73	0.95
14	43.16	——	——
15	25.81	27.18	0.66

[1] no data available

TABLE 8.3B Summary of the Results

test No.	core shear modulus (N/mm^2)	core compression modulus (N/mm^2)	core crushing strength (N/mm^2)
16	4.38	5.65	0.17
17	4.86	20.0	0.21
18	8.60	17.53	0.57
19	15.15	39.31	0.52
20	1.78	21.49	0.65
21	14.76	24.82	0.54
22	21.96	39.73	1.00
23	27.03	———[1]	——
24	41.52	——	0.66
25	20.00	——-	0.89
26	36.40	108.05	0.75
27	16.21	99.30	1.02
28	34.37	35.76	0.7
29	71.19	37.73	0.81
30	17.33	30.48	0.64
31	20.45	61.97	1.50
32	22.72	97.78	2.76
33	20.58	73.33	1.91
34	64.10	115.09	4.50
35	69.83	109.09	6.14
36	63.58	89.47	1.50

[1] no data available

TABLE 8.3B continue

test No.	core shear modulus (N/mm^2)	core compression modulus (N/mm^2)	core crushing strength (N/mm^2)
37	33.96	81.92	0.81
38	42.81	66.01	0.80

8.4 DISCUSSION OF THE RESULTS

These results are affected by the properties of the faces and the core-face bond. Particularly in the case of the shear test, imperfect bond between the core and the faces in some cases, may have caused slippage at the interface between the core and the face. In fact in some cases this has caused significant creep and the tests had to be abandoned and the specimens were reconstructed. The effective density listed in table 8.1A was found to be less than the measured density. This was due to the fact that the paper honeycomb core had to be bonded to a face prior to the impregnation process, resulting in concentration of sodium silicate at the bottom of the core. However, this problem was overcome by using a heavier paper gauge honeycomb (supplied by Dufaylite) which allowed the impregnation to be made in isolation. The elastic modulus E_s, of the cell wall material was measured from the load elongation curve for stiffened paper strips.

The developed honeycomb core shear modulus was estimated from the expression presented in section 2.5.

The shear modulus G, was measured by four point loading test on honeycomb core sandwich beams, and calculating the modulus from the slope of the load-deflection curve.

The result of the four point loading tests are presented in table 8.3A and 8.3B.

Theoretical and experimental values of the shear modulus are plotted in Fig. 8.1. Agreement between the theory and experiment is good for honeycombs stiffened with sodium silicate expcet for tests 13, 21 and 27. In the case of tests 21 and 27 the poor agreement could well be due to the imperfect bond between core and facing.

The agreement between theory and experiment is poor for honeycombs stiffened with sodium silicate and ball clay. The *error are larger than that of the honeycomb* stiffened with sodium silicate. The discrepancy may be due to the fact that the geometry of these honeycombs was found to be less regular than that *of honeycombs* stiffened with sodium silicate. The honeycombs stiffened with sodium silicate and ball clay found to be extremely rigid and did not provide an even surface on which to bond the facing, therefore providing less contact area to bond the facing to the core.

The dependence of shear modulus on the product of relative density (t/l) and elastic modulus of the cell wall material E_s is shown in fig. 8.2. The curve shows a linear relation followed by an almost horizontal plateau.

Figure 8.1 Comparison of Experimental and Theoretical Honeycomb Core Shear Modulus

Experimental shear modulus (N/mm2)

Theoretical shear modulus (N/mm2)
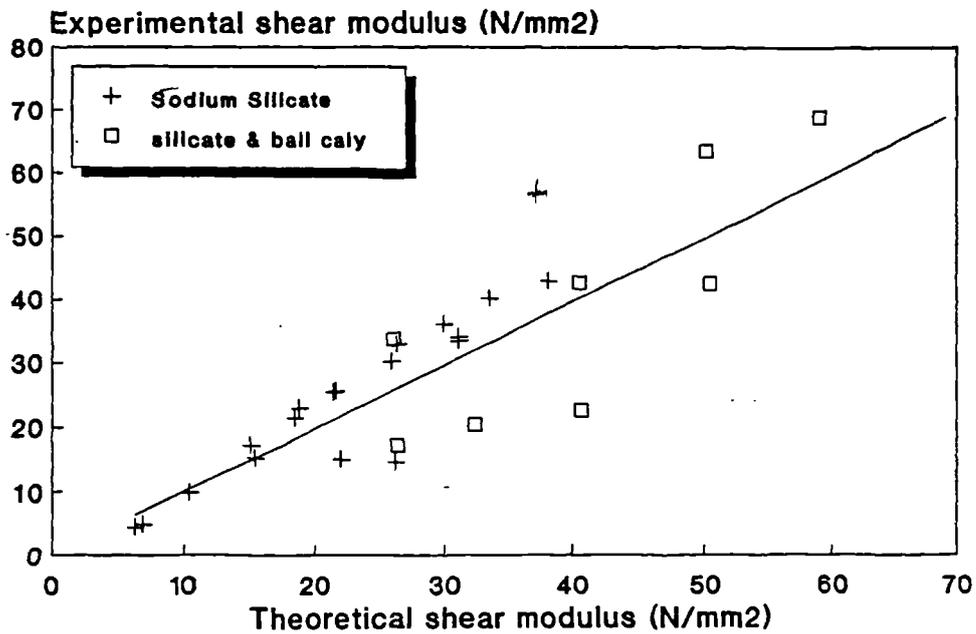
Figure 8.2 Shear modulus as a function t/l*E for honeycomb cores stiffened with sodium silicate

Core shear modulus, G (N/mm2)

Thickness/length * E
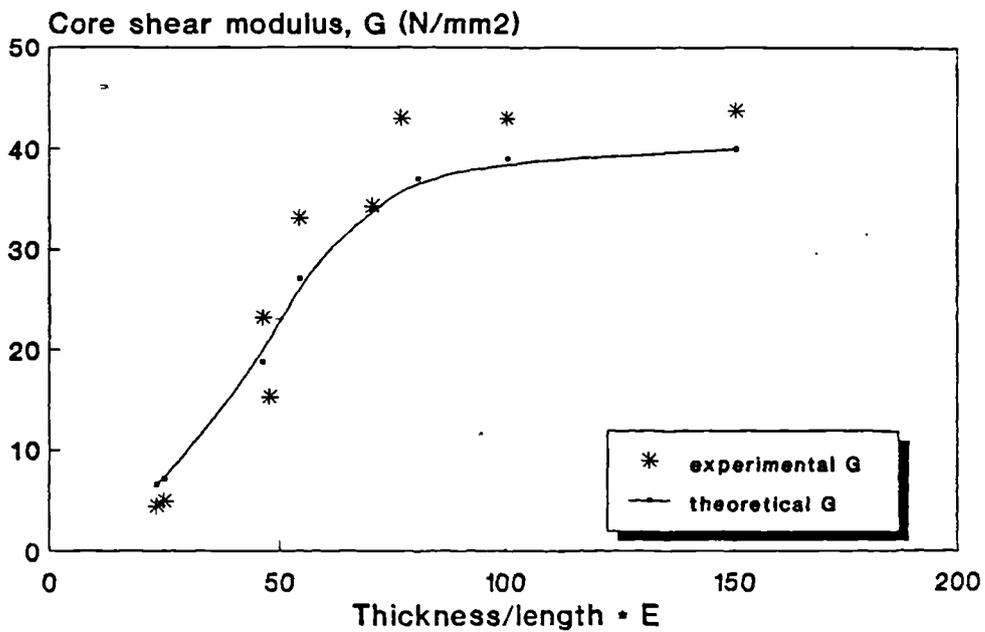
8.5 SHEAR MODULUS OF THE

CELL WALL MATERIAL

In order to calculate the developed honeycomb core shear modulus by using the expression developed by Gibson and Ashby [35], it was necessary to obtain the shear modulus of the material forming the honeycomb cell walls.

Since a shear test of the honeycomb cell wall material found to be extremely difficult, it was decided to calculate the shear modulus by using the following relationship :

$$G_S = \frac{E_S}{2(1 + \mu_S)} \qquad \ldots\ldots\ldots\ldots(8.1)$$

where

G_S = shear modulus of the cell wall material

E_S = modulus of elasticity of the cell wall material

μ_S = poisson's ratio of the cell wall material

The above relationship is only applicable to an isotropic body in which there is only one value for the elastic constant independent of direction. But according to Kingery and Brown [116] and Gibson and Ashby [35] it is a good approximation for glass and for most polycrystalline ceramic materials. After consulting Mr M. Woodfine[*] of Watts Blake Bearne & Co plc[117] and Mr Mike wood of Crossfield Chemicals[115], sodium silicate

* chemical engineer at WBB and Co plc (CDL ball clay manufacturer).

and ball clay mixture was discovered to be a polycrystalline ceramic. This is due to the fact that ball clay contains 45% quartz which is a rigid mineral and it is also mixed with sodium silicate by a large amount, then the whole mixture can safely assumed to be a polycrstaline ceramic.

The modulus of elasticity of the cell wall material was determined from the tensile test of the strips of coated paper with the materials under investigation as described in chapter 7. The Poisson's ratio of the cell wall material estimated to be 0.3 as the Poisson's ratio of ceramics and glasses are roughly 0.3 [35]. The shear modulus of the cell wall material was then estimated by substituting the obtained value of E_s and estimated value of μ_s in equation 8.1. The shear modulus of the developed honeycomb core was then obtained by using the following calculations.

(I) calculation of honeycomb cell geometry

$$c = \frac{e}{2} \qquad\qquad \dots\dots\dots\dots(8.2)$$

$$b = \sqrt{\{(1)^2 - (c)^2\}} \qquad\qquad \dots\dots\dots\dots(8.3)$$

$$\sin\theta = \frac{b}{1} \qquad\qquad \dots\dots\dots\dots(8.4)$$

$$\cos\theta = \frac{c}{l} \qquad \dots\dots\dots\dots(8.5)$$

where

l,b,c are the dimension of the typical

element of core shown in fig. 8.3

e is the diameter of the cell

θ is the core cell angle

(II) calculation of shear modulus of the cell wall, G_S

using equation (8.1)

(III) calculation of honeycomb core shear modulus, G

using the expressions developed by Ashby and

Gibson[35] for upper and lower bound core shear

modulus discussed in section 2.2.2

(a) upper bound core shear modulus

$$G = \frac{1}{2} \cdot \frac{h/l + 2.\sin^2\theta}{(h/l + \sin\theta).\cos\theta} \cdot (t/l).G_S$$

(b) lower bound core shear modulus

$$G = \frac{h/l + \sin\theta}{(1 + (2.h)/l).\cos\theta} \cdot (t/l).G_S$$

A typical calculation of G_C for the honeycomb core of the

tested beams is presented in appendix D.
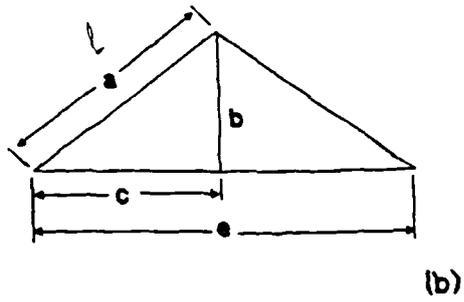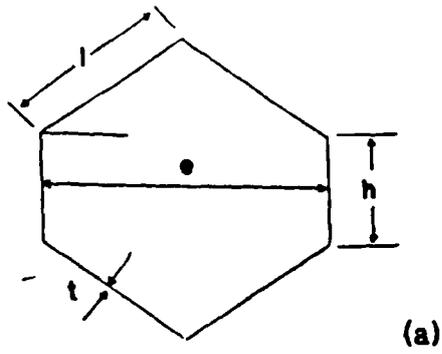
Figure 8.3 (a) Typical honeycomb cell showing the walls l and h with thickness t; (b) typical element of the cell for the calculation of core shear modulus

8.6 CONCLUSIONS

In this chapter the results of bending tests on developed honeycomb core beams have been presented. The results are then compared with the theoretical values obtained from the expression for shear modulus presented in section 2.5. This study found that the expressions predict the measured behaviour well for the shear modulus of the paper honeycomb core stiffened with sodium silicate.

The shear modulus of the developed honeycomb core was found to be highly dependent to the product of relative density (t/l) and elastic modulus of the cell wall material.

CHAPTER 9
DEVELOPMENT OF A FIRE
RESISTANT HONEYCOMB
CORE

CHAPTER 9

DEVELOPMENT OF A FIRE RESISTANT

HONEYCOMB CORE

9.1 INTRODUCTION

This chapter deals with the second part of the work, in which small sandwich panel systems containing developed honeycomb cores were exposed on one face to a furnace which was controlled to follow a time/temperature curve given in BS 476[118]: Part 20 and illustrated in fig. 9.1. These tests were carried out to provide a means of quantifying the ability of the panels to withstand exposure to high temperature, by setting criteria by which the fire containment (integrity) and the thermal transmittance (insulation) functions can be determined and compared.

Later in the programme, research and development were undertaken by the author to improve the fire resistance of sandwich panels with the developed honeycomb core.

As a bench mark a series of sandwich panels with expanded and extruded polystyrene cores were tested. In addition some panels with mineral wool cores were also tested.

9.2 POTENTIAL FIRE HAZARDS

The following factors may have to be considered when the potential fire hazard associated with a specified building material are being assessed:

1. Ease of ignition

2. Flame spread properties

3. Rate of heat release

4. Smoke production

5. Evaluation of toxic products

6. Fire resistance (integrity, stability, insulation)

Ideally, material used in building would be accepted or rejected in use in accordance with it's performance history in the real life. In a constantly changing world this is not practicable. For this reason fire tests have been developed to enable new materials to be assessed under standard test conditions.

The primary objective of this research programme was to assess the fire resistance characteristics of the newly developed honeycomb cores .

9.3 PERFORMANCE CRITERIA

Fire barriers, i.e. walls and floors, can fulfil their function by preventing the transfer of flames or hot gases, and by restricting heat transfer through the construction in order to prevent ignition of combustible materials on the non-fire side (cold side). Cracks and opening formation through which gas and flame transfer can take place is restricted and limits are set on the transfer of heat by specifying temperature rise limits on the unexposed side. The performance criteria have been named in the standard as stability, integrity, and insulation. The fire resistance is therefore the time elapsed from the start of the test to the time of failure by any one of these criteria. These performance criteria can be expressed as follows :

Stability : the limit is reached when the specimen collapses or unacceptable deformation occurs. e.g. when the downward deformation of the flexural members exceed L/30 where L is the clear span.

Integrity : the limit is reached when cracks or other openings exist in a separating element through which flames or hot gases can pass which can ignite combustible materials on the cold side. This is measured by a cotton pad held

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close to the hot face for 10 seconds. When the level of radiation is such that cotton pads cannot be used, the failure occurs if a cracks *or opening* exists or develops exceeding *6mm x* 150mm.

Insulation : the limit is reached when the heat transfer through the *elements raises* the exposed face temperatures to a level considered to be unsafe *for* combustible materials in contact with the face. The unsafe temperature *is to* be reached when the mean temperature of the cold face increases by more than 140° C above the initial temperature or by more than 180° C above the initial temperature at any point.

In this investigation the insulation is the most important criterion

9.4 FIRE TESTING FACILITIES

9.4.1 FURNACE

A gas-fired kiln intended primarily for pottery firing was used for testing the fire resistance of the developed honeycomb core panels.

The kiln consisted of a cubic steel case (approx. 1m x 1m x 1m) lined with fire brick and with a glass fibre blanket infill.

The kiln had a heavy door hinged on one side. This was not needed for the fire testing and could be swung back out the way. Gudgeon pins were welded on the other side of the door opening and an open rectangular metal frame fitted. This frame could accommodate test specimens up to 0.9 x 1.2 m. When the frame was closed bringing the test piece into contact with the edge of the opening, it provided an exposed hot face area of 0.7 x 0.9 m.

9.4.2 FURNACE TEMPERATURES

The heating environment to which the test specimens were exposed was produced by two gas burners with controlled gas input which allowed the British standard time/temperature curve to be followed as shown in figure 9.1. The curve can be mathematically expressed[118] as:

$$T - T_o = 345 \log_{10} (8t + 1)$$

Where

t = time from the start of the test in minutes

T = furnace temperature at the time t in ^{O}C

T_O= initial furnace temperature in ^{O}C.

The temperature at given times are as follows:

Time,t(min)	15	30	60	90	120	180	240	360
Temperature rise,^{O}C	718	821	925	986	1029	1090	1133	1193

There is a wide range of furnace time/temperature graphs in use e.g. British, German, American, Sweden, etc. There are some differences between them. To remove these differences a new CEN[*] committee has been formed with a mandate to produce a European fire test standard. In due course this will replace the existing national standards. However all of these graphs are intended to relate to the testing of specimens when exposed to real fires. Real fires vary in temperature and duration and a real fire may have a quite different characteristic behaviour as shown in figure 9.1. The system does, however, work well in practice and allows manufacturers to introduce and develop new materials within the frame work of recognised guidelines.

* Comitó Euroóen de Normalisation.

Figure 9.1 BS 476:Part 20 Time/Temp.
Curve and natural Fire
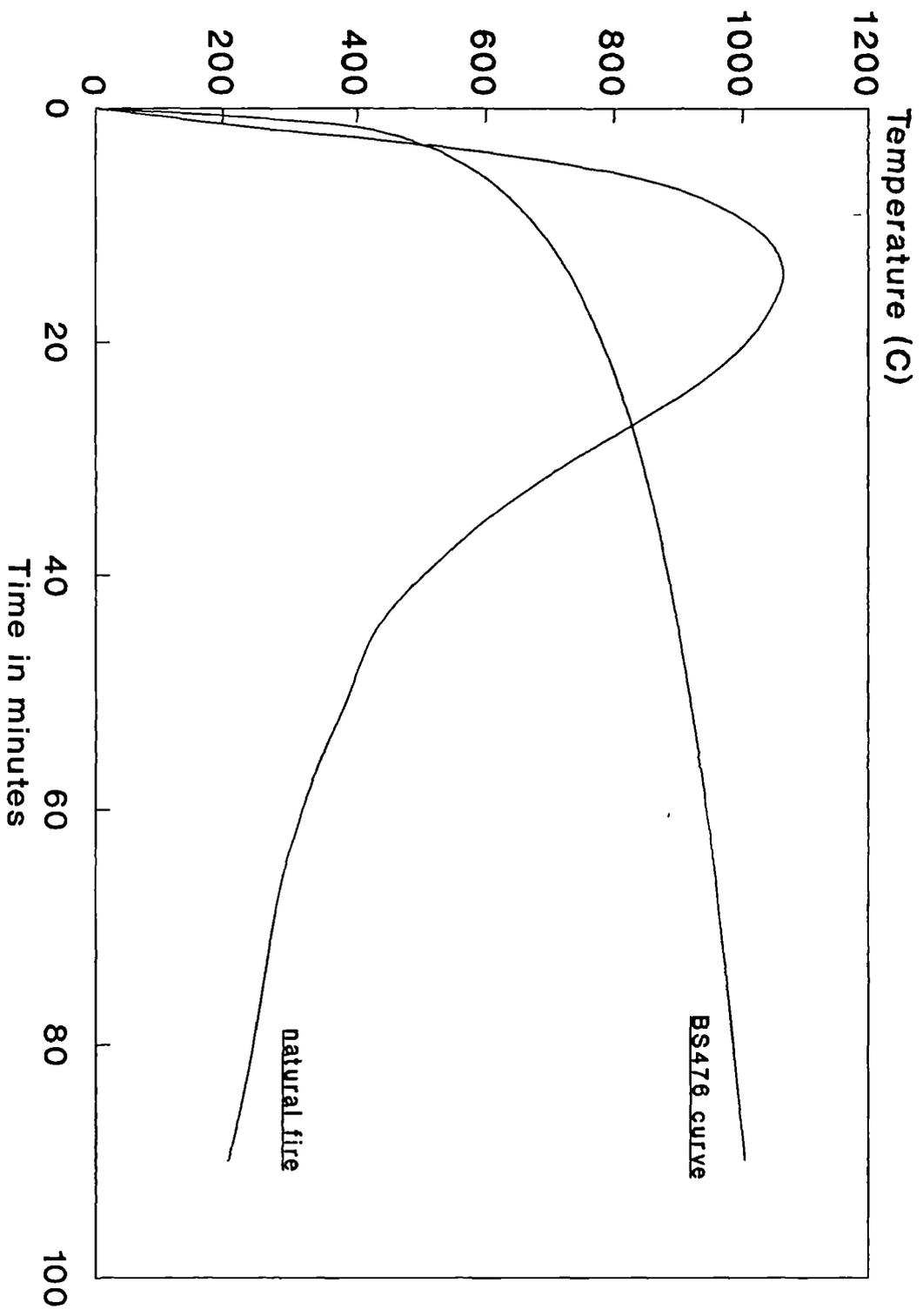
9.4.2.1 TIME/TEMPERATURE CONTROL

The initial control unit was supplied by the Eurotherm[119] company and offered a linear increase in temperature with time by operating the twin burners in either "low" or "high" setting mode. The original control system had to be scrapped and a computer control system was developed which operated a valve with a stepper motor attached to it. This was introduced to the main gas supply pipe feeding the two burners. The opening or closing of the valve was operated via a stepper motor which was signalled every second from the computer.

This programme controlled the furnace using a continuous proportional, differential and integral (PID) closed control loop system [120]. The PID will produce continuous control by acting on an error E(t) which is the difference between the set-point temperature and the measured furnace temperature. The control system can be defined in terms of three control function as follows :

1) The proportional control : which multiplies the error signal E(t) by a constant KP. The bigger the value of this constant the less sensitive the system will be.

2) The integral control : which multiplies the integral of the error signal by a constant KI. This will provide action to reduce the steady-state error.

3) The differential control : which generates a signal

which is proportional to the time derivative of the error signal. This will reduce the overshoots in the response. A large value of the differential control constant KD will cause the system to overshoot.

The values KP, KI, and KD will determine the behaviour of the controlled system. The values of these constants were found experimentally and a finer tuning of the system was obtained by changing these constants.

The hot face temperature was measured by four bare wire thermocouple[*] positioned in front of the furnace opening 100 mm clear (critical area for temperature control) from the hot face of the test panel.

The thermocouples used to measure the furnace temperature compiled with the requirement set in B.S. 476 : part 20.

[*] type R thermocouple (Platinum – 13 % Rhodium / Platinum) is a special type of thermocouples used for high temperature (up to 1600° C).

9.5 TEST ARRANGEMENT

A square " window " of 380 mm side was cut out of the middle of the blanking panel made up of two 6mm calcium silicate boards with 50 mm thick rockwool in-between (see fig. 9.2).

This windowed blanking panel was placed inside the open rectangular metal frame, forming the door of the furnace.

The specimen (with nominal dimension of 430 x 430 mm) allowing a 25 mm overlap on each side. Self tapping screws were used for fixing the specimen to the blanking panel. The surrounding space was packed with mineral wool to make an air-tight seal.

The temperature on the unexposed side were measured using a minimum of two type K[*] thermocouples. The thermocouples were tightly covered with an insulation pad, approximately 30 mm square and 2 mm thick.

In some cases thermocouples were placed between the interfaces of the core and the exposed and unexposed sides of the core. The thermocouples and the insulating pads met the required standard listed in B.S. 476 : part 20.

[*] type k thermocouple (Nickel _ Chromium / Nickel
    _ aluminium) operate up to 1100° C.
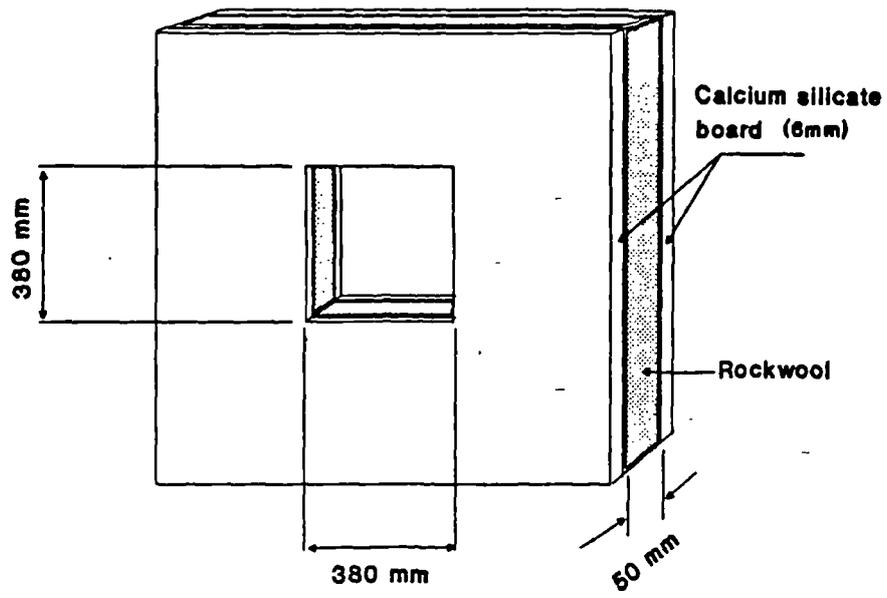
Figure 9.2 Blanking panel forming the door of the furnace

9.6 COMMERCIAL PANEL TESTS

A range of commercial sandwich panels with expanded and extruded polystyrene and mineral wool cores were tested to establish a base line performance standard. The tested panels had steel or aluminium alloy skins. Details of their geometries and fire resistance time based on failing by the insulation criterion are given in table 9.1.

9.7   TEST SPECIMEN CONSTRUCTION

At the start of this phase of research programme the core of the panels consisted of expanded paper honeycomb treated with sodium silicate. Panels $A_{B.T}$*, $B_{B.T}$, $C_{B.T}$, $D_{B.T}$, $F_{B.T}$, T, V, W, and X were treated with sodium silicate only.

The untreated paper honeycombs were first sprayed with potassium silicate using a paint sprayer and left to dry at room temperature. The specimens where then submerged into the sodium silicate solution (Crystal 79). This process of submerging was repeated several times.

Based on the observations made during fire tests the honeycomb matrix was found to burn back slowly. As the honeycomb disappears the space that is occupied is filled with sodium silicate intumescence foam at a temperature of about 160° C measured at the exposed side of the core (see plate No. 9.1). After some time the intumescence foam started to shrink back slowly away from the hot face. The shrinking of the intumescence foam continued until it cease to support the hot face as shown in plate No. 9.2).   This occurs when the temperature at the hot face of the core exceeds 550° C. In the absence of any support this would mark the end

* Through out this thesis letters with subscript B.T refer to honeycomb core constructed from ex. British Telcome Directory while those without a subscript refer to paper honeycomb cores supplied by Dufaylite Ltd.

Plate 9.1   Intumescence Foam Filling the Space Occupied by the Honeycomb core

Plate 9.2   Shrinking of the intumescant   foam

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of the life of the panel. Support can be provided by rivets. The rivets can hold the hot facing in position and retain it's integrity for a much higher cold face temperature, but this will create local `hot spots' on the cold side.

It was then decided to work on the development of honeycomb core fabricated from high temperature material to retains its structure for a much longer period.

Test panels $G_{B.T}$, $H_{B.T}$, $I_{B.T}$, $J_{B.T}$, $K_{B.T}$, $L_{B.T}$, $M_{B.T}$, $P_{B.T}$, R, $S_{B.T}$ and $Q_{B.T}$ were fabricated. The honeycomb matrix were first stiffened with sodium silicate and then submerged into the mixture of sodium silicate and ball clay with a ratio of 4 to 1 by weight. After applying and drying the final layer of sodium silicate and ball clay the core was then submerged into the sodium silicate solution. This provide a final layer of silicate on the stiffened core. The object of the silicate layer was to fill the cell with intumescence foam when exposed to temperature. An example of honeycomb core stiffened with silicate and ball clay is presented in plate No. 9.3. The decision to use sodium silicate and ball clay based on the following reasons :

1) The temperature capability of sodium silicate and ball clay system should be adequate.

2) The mechanical properties of sodium silicate and ball clay system is more than adequate, based on

experiments conducted in the second part of this research program.

3) The relative thermal conductivity of this system should be low enough to minimise temperature bridging.

In the case of panels with sodium silicate treated cores a thin layer of sodium silicate was used to bind the core to the faces and for ball clay and sodium silicate treated cores a thin layer of silicate and ball clay was used as binder.

In order to increase the core thermal insulation and improve the ability of the test specimens to restrict the temperature rise of the untreated face to below the specified level for a longer duration, the cells of some of the honeycomb cores were filled with inorganic components such as a mixture of high alumina cement with perlite. Also some were filled just with loose perlite or vermiculite. The low relative thermal conductivity of perlite and vermiculite are thought to be sufficient to provide the thermal barrier required.

The fabrication of these panels was accomplished by binding one face to the core, then filling the cells with dry loose filler and then bonding the second face to the core. An example of this type of core is illustrated in plate No. 9.4.
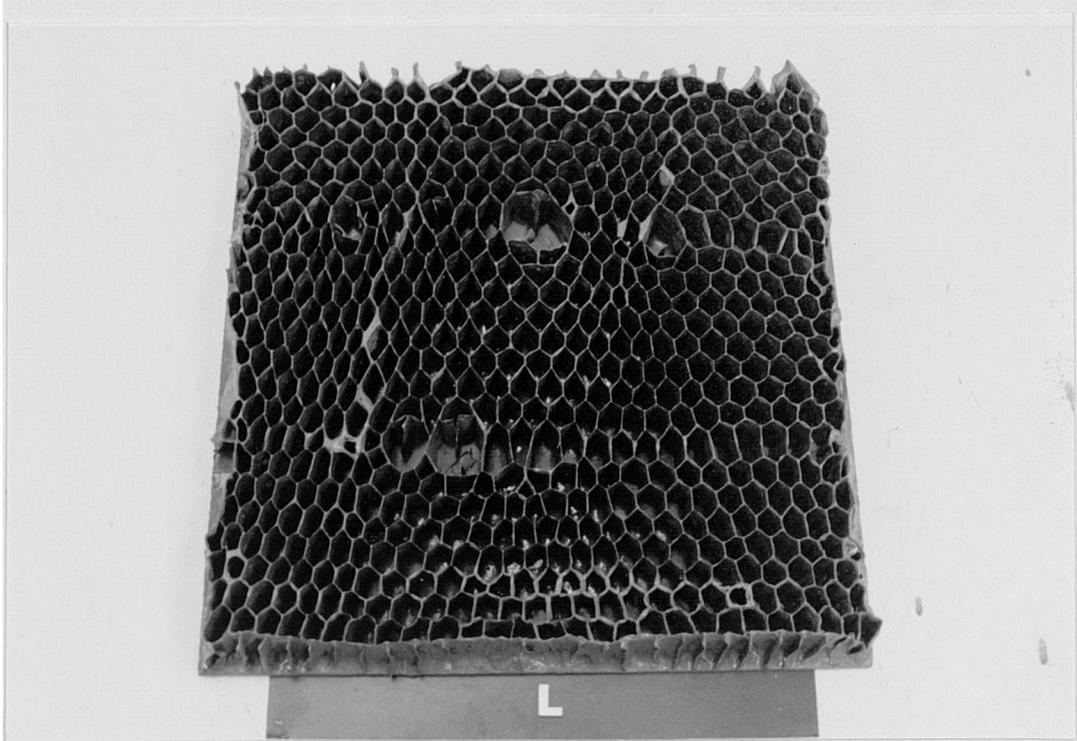
Plate 9.3 Honeycomb Core treated With Sodium Silicate and Ball Clay
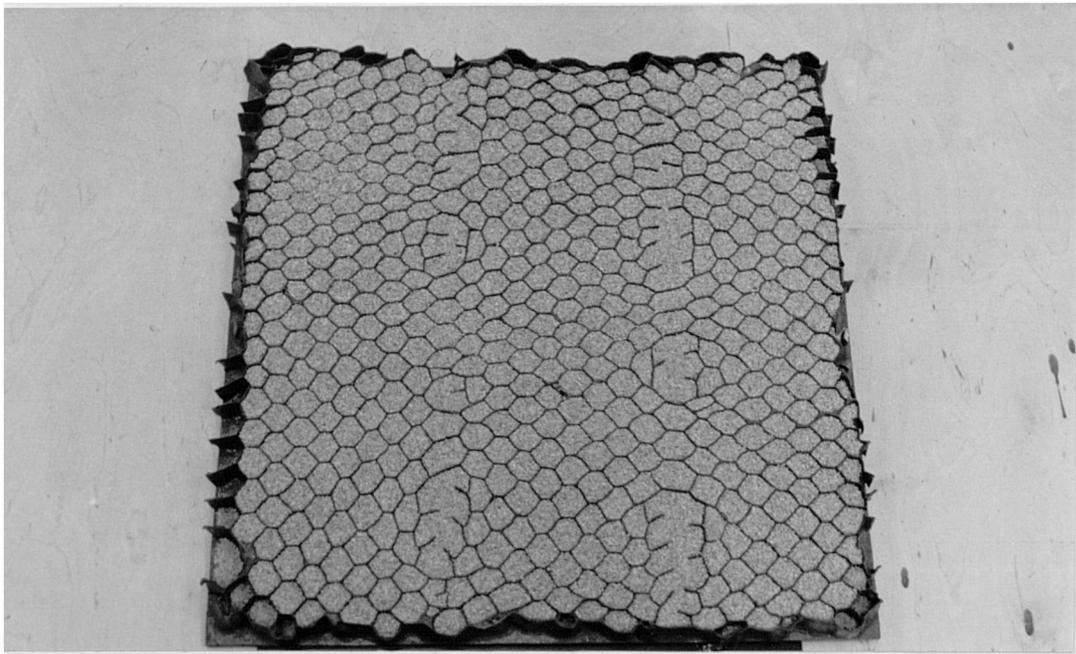
Plate 9.4 Honeycomb core filled with loose Vermiculite

9.8 FIRE TEST RESULTS

9.8.1 PRESENTATION OF THE TEST DATE

Panels dimensions and compositions are listed in tables 9.1 through to 9.7A. These tables list the panel dimensions, core density, skin type and in the case of filled honeycomb, type of filler/or fillers used.

The result of fire tests are shown in tables 9.1 to 9.7B, where the core insulation, panel insulation and panel integrity in minutes for each specimen are recorded.

Core insulation was determined by neglecting the effect of the exposed face (i.e. the core insulation time was measured from the moment the temperature of the interface between the core and exposed face reached 140° C + ambient).

The result of the fire tests have been plotted and are shown in figures 9.3 to 9.13.

TABLE 9.1 FIRE RESISTANCE TIME BASED ON INSULATION FOR COMMERCIAL PANELS

Panel No.	Core Type	Core Thickness mm	Core Density kg/m³	Skin Type	Thickness mm	Fire resistance minutes	vertical Joint
1	Extruded polystyrene	100	36	steel	0.70	8	No
2		100				8	No
3		100				7	No
4	Extruded Polystyrene	200	38	steel	1.0	15	No
5		200				16	No
6		200				13	No
7	Expanded polystyrene	100	18	steel	0.75	7	No
8		100				7	No
9		100				7	No
10	Mineral Wool	50	140	Aluminium Alloy	0.85	32	Yes
11		50				29	Yes
12		50				23	Yes

TABLE 9.2A TEST SERIES

Panel No.	Core Thickness (mm)	Core Density (Kg/m3)	Skin Type		Skin	
			Hot	Cold	Hot	Cold
A$_{B.I}$	25.0	316.0	steel	steel	0.6	0.6
B$_{B.I}$	25.0	217.0	C.B$^+$	steel	11.0	0.6
W*	50.0	136.0	plywood	plywood	6.0	6.0
X	50.0	75.0	plywood	plywood	6.0	6.0

The honeycomb cores listed in the above table have been treate
with sodium silicate.
* The core cell wall has been reinforced with vermiculite.
+ Calsium silicate board.

TABLE 9.2B TEST RESULT

Panel No.	Weight of the Panel (Kg/m^2)	Core Insulation (mins)	Panel Insulation (mins)	Integrity (mins)
A$_{B.I}$	17.64	*	32.0	
B$_{B.I}$	22.85		46.0	
W	17.35	30.0	48.0	54.0
X	14.00	10.0	37.0	42.0

* data not available

TABLE 9.3A TEST SERIES

Panel No.	Core Thickness (mm)	Core Density (Kg/m^3)	Skin Type	Skin Thickness	Filler Type
C	25.0	496.0	steel / steel	0.6 / 0.6	alumina cement and perlite
D	25.0	537.0	C.B+ / steel	11.0 / 0.6	alumina cement and perlite
F	25.0		C.B / C.B	11.0 / 11.0	*
T	50.0	183.0	plywood / plywood	6.0 / 6.0	loose vermiculite.
V	50.0	239.0	plywood / plywood	6.0 / 6.0	loose vermiculite and dried crushed silicate.

+ calcium silicate board.

* this panel were divided into four quarters, one quarter filled with loose perlite one quarter filled with loose vermiculite and remaining two left unfilled.

TABLE 9.3B TEST RESULTS

Panel No.	weight of the Panel (Kg/m^2)	Core insulation (mins)	Panel Insulation (mins)	Integrity (mins)
C	22.0		43.0	
D	31.0	62.0		
F				
T	18.0	41.0	80.0	173.0
V	22.0	72.0	105.0	164.0

TABLE 9.4A TEST SERIES

Panel No.	Core Thickness (mm)	Core Density (Kg/m^2)	Skin Type		Skin Thickness (mm)	
			Hot Face	Cold Face	Hot Face	Cold Face
$G_{B.T}$	25.0	370.0	plywood	plywood	6.0	6.0
$I_{B.T}$	25.0	325.0	steel	steel	0.6	0.6
$K_{B.T}$	50.0	205.0	C.B	C.B	6.0	6.0
$L_{B.T}$	50.0	260.0	plywood			6.0
$M_{B.T}$	50.0	288.0	plywood	plywood	6.0	6.0
R	50.0	214.0	plywood	plywood	6.0	6.0

TABLE 9.4B TEST RESULTS

Panel No.	Weight of the Panel (Kg/m^3)	Core Insulation (minutes)	Panel Insulation (minutes)	Integrity (minutes)
$G_{B.T}$	17.0		51.0	68.0
$I_{B.T}$	22.0		40.0	
$K_{B.T}$	31.0		101.0	
$L_{B.T*}$	16.0	41.0	56.0	
$M_{B.T}$	21.0	30.0	55.0	74.0
R	20.0	35.0	59.0	76.0

* with only hot face in place.

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TABLE 9.5A TEST SERIES

Test No.	Core Thickness (mm)	Core Density (Kg/m³)	Skin Type		Skin Thickness (mm)		Filler Type
			Hot Face	Cold Face	Hot Face	Cold Face	
$H_{B.I}$	25.0	465.0	C.B	C.B	6.0	6.0	lose vermiculite
$J_{B.I}$	50.0	390.0	plywood	plywood	6.0	6.0	lose vermiculite

TABLE 9.5B FIRE TEST RESULTS

Test No.	Panel weight (Kg/m²)	Core Insulation (mins)	Panel Insulation (mins)	Integrity (mins)
$H_{B.I}$	22.0	.	88.0	88.0
$J_{B.I}$	22.0		88.0	91.0

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TABLE 9.6A TEST SERIES

Panel No.	Core Thickness (mm)	Core Density (Kg/m^2)	Skin Type		Skin Thickness (mm)	
			Hot Face	Cold Face	Hot Face	Cold Face
P$_{B.T}$	20.0	203.0	plywood	——1	6.0	——1

1 only hot face in place

TABLE 9.6B TEST RESULTS

Panel No.	Weight of the Panel (Kg/m^3)	Core Insulation (minutes)	Panel Insulation (minutes)	Integrity (minutes)
P$_{B.T}$	27.6	22.0	---2	---2

2 not available.

TABLE 9.7A TEST SERIES*

Test No.	Core Thickness (mm)	Core Density (Kg/m³)	Skin Type		Skin Thickness (mm)	
			Hot Face	Cold Face	Hot Face	Cold Face
S$_{R}$I	30.0	404.0	plywood	plywood	6.0	6.0

TABLE 9.7B FIRE TEST RESULTS*

Tets No.	Panel Weight (Kg/m₂)	Core Insulation (mins)	panel Insulation (mins)	Integraity (mins)
S$_{R}$I	23.0	31.0	75.0	105.0

* The core of the panel listed in the above tables has been constructed using water entrapment technique.

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9.8.2 DISCUSSION OF THE TEST RESULTS

The construction of the test panels was symmetrical (except for panel $B_{B.T}$ and $D_{B.T}$), so that the same fire resistance would have been expected if the opposite side of the assembly have been exposed to fire.

The result of the tests on commercial panels with extruded and expanded polystyrene and mineral wool core are listed in table 9.1. Panels with polystyrene cores (100 mm thickness) and 0.7 mm steel facing achieved a very limited fire resistance time *of 7-16 minutes.*

Panels with mineral wool cores produced better results. Three panels with 50 mm thick mineral wool and 0.85 mm aluminium alloy faces achieved a fire resistance time in insulation of 23-32 minutes. The performance of these panels was adversely effected by the method of manufacture as explained in chapter one (section 1.6.2). From the inspection of the tested panels it was concluded that shrinkage of mineral wool strips caused opening up of the joints between each strip and through these opening the heat was able to penetrate to the cold face of the panel.

Samples of the output graphs are given in figures 9.3, 9.4 and 9.5.

The result of test panels with unfilled paper honeycomb core impregnated with sodium silicate are listed in table 9.2B. Panel $A_{B.T}$ with a core density of 316 Kg/m^3

Figure 9.3

Test Panel with Expanded Polystyrene
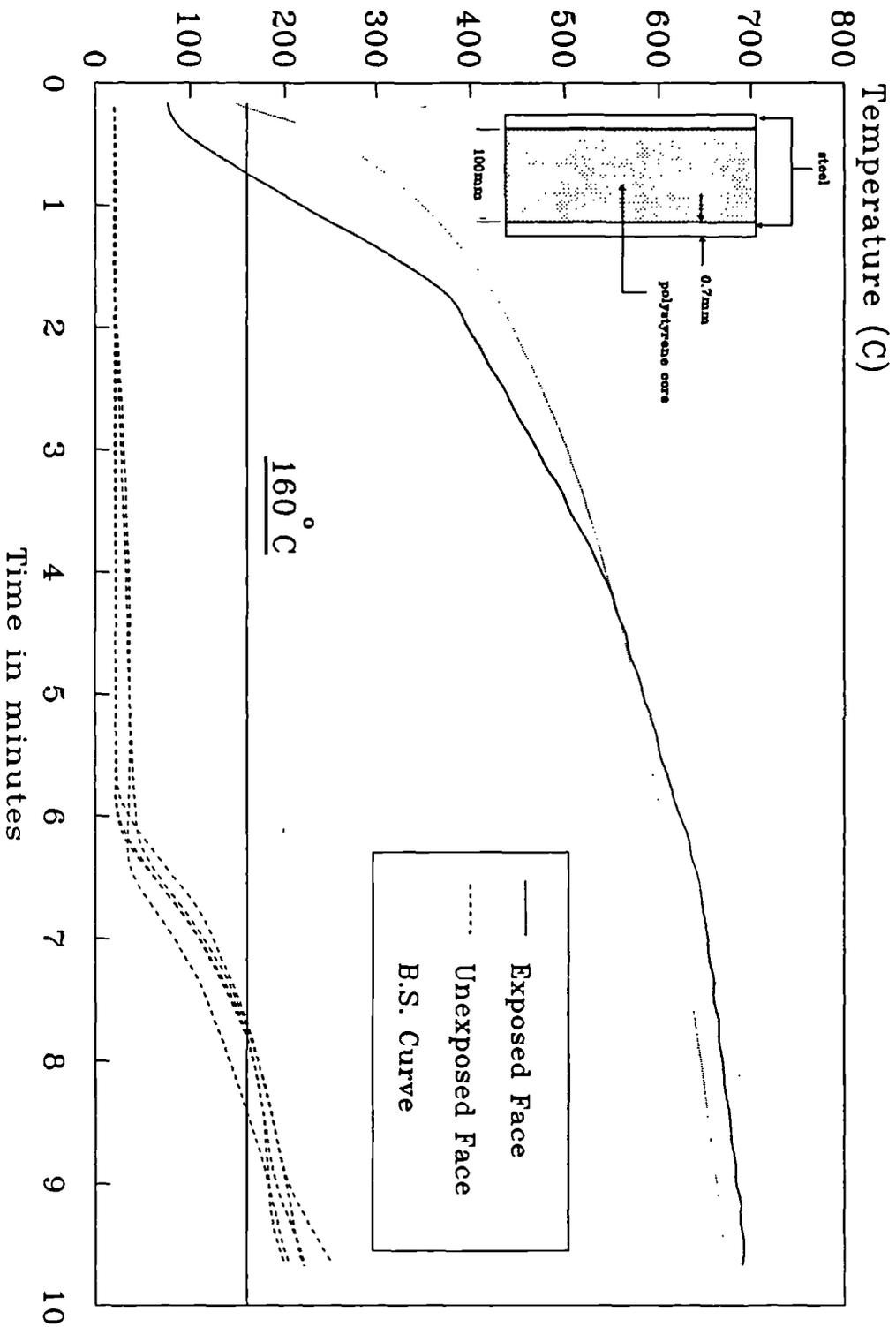
Figure 9.4

Test Panel with Styrofoam Core
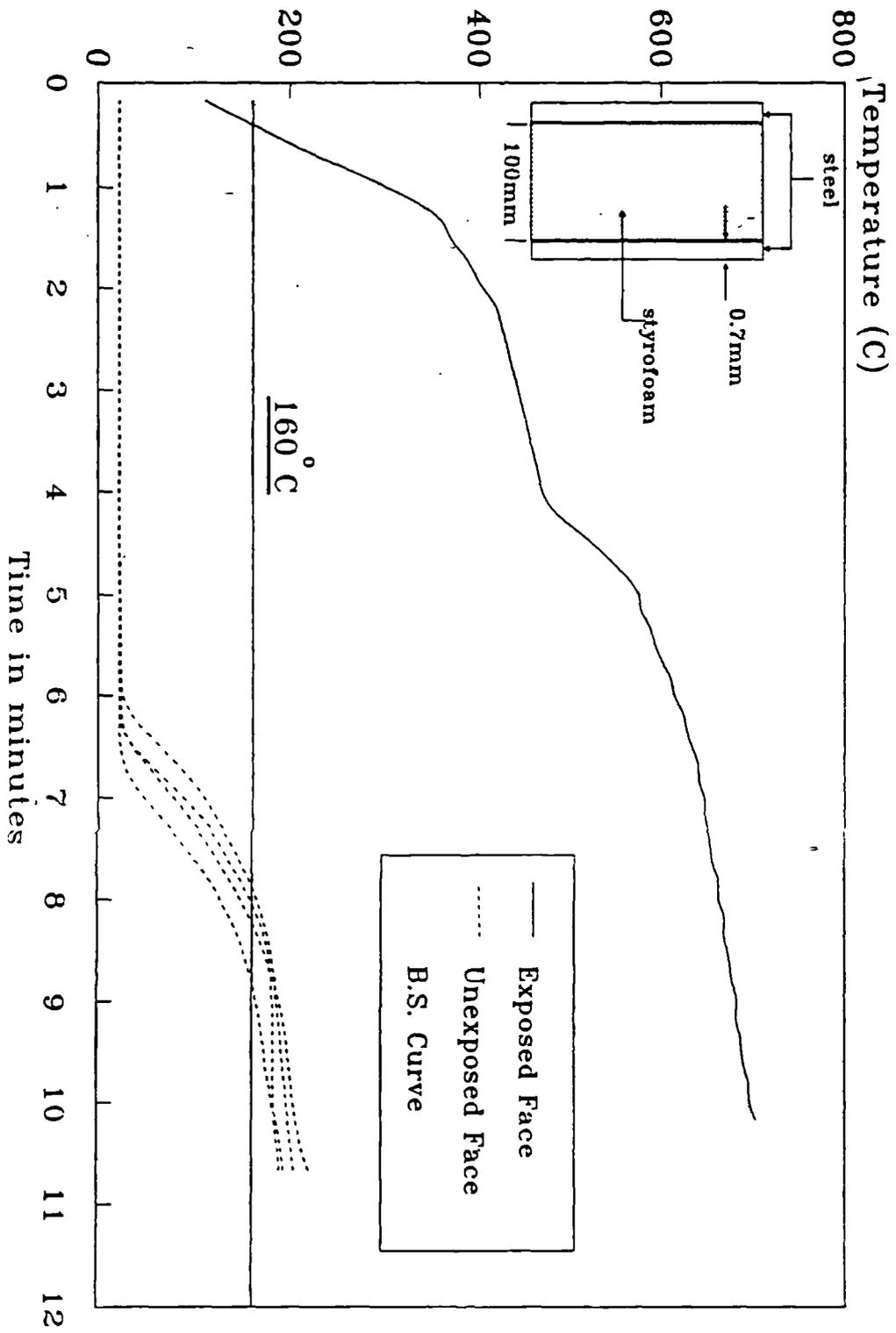
Figure 9.5
Test Result of Sandwich Panel with
Mineral Wool Core.
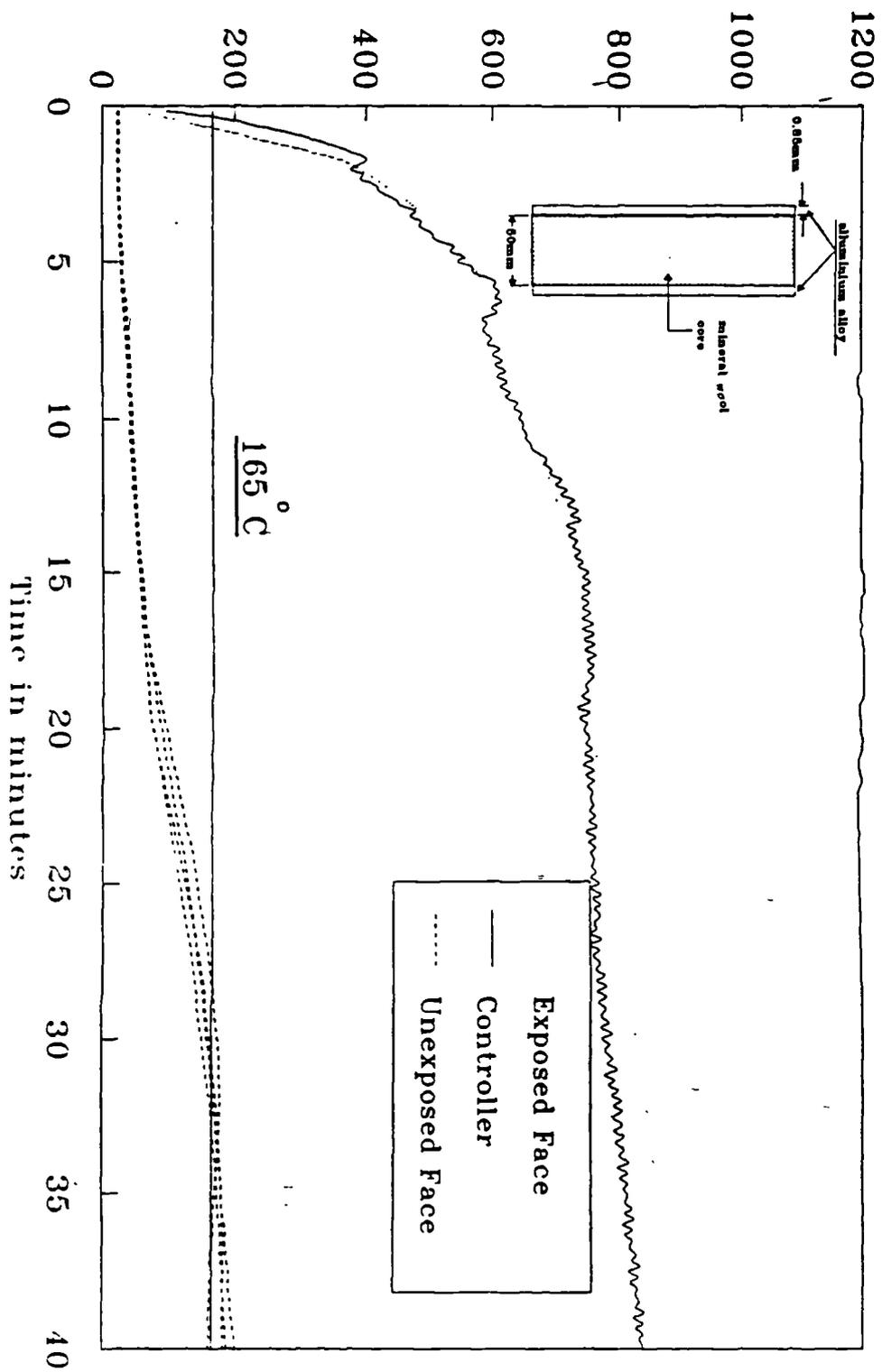
bonded to two 0.6 mm steel face achieved an insulation time of 32 minutes. Replacing the hot face with an 11 mm calcium silicate board (Panel $B_{B.T}$) with 217 Kg/m^3 core density increased the panel insulation time by 14 minutes (see figure 9.6).

Panel X with 50mm thick core and 75 Kg/m^3 core density with two 6mm plywood facing achieved a fire resistance time of 37 minutes in insulation (the core insulation failed after 15 minutes). Reinforcing the cell wall with vermiculite, test panel W (see plate No. 9.5) with a core density of 136 Kg/m^3 achieved a fire resistance time in insulation of 48 minutes (core insulation failed in 30 minutes) see figure 9.7. The core of the tested panel retained it's structure after the termination of the fire test due to burning of the plywood on the cold side. Plate No. 9.6 shows that the core of the tested panel has retained it's structure and is still capable of carrying some load.

Table 9.3B show the results for filled honeycomb core impregnated with sodium silicate.

Panel $C_{B.T}$ with two 0.6mm steel and 25mm thick core with a density of 496 Kg/m^3 with a filler composition of cement, perlite and water (1.5 : 1 : 1.8 by weight ratio) achieved a fire resistance time of 43 minutes in insulation. After close inspection of the tested panels it was found that the honeycomb structure itself burned

Figure 9.6 Cold Face Temperature for panels A and B
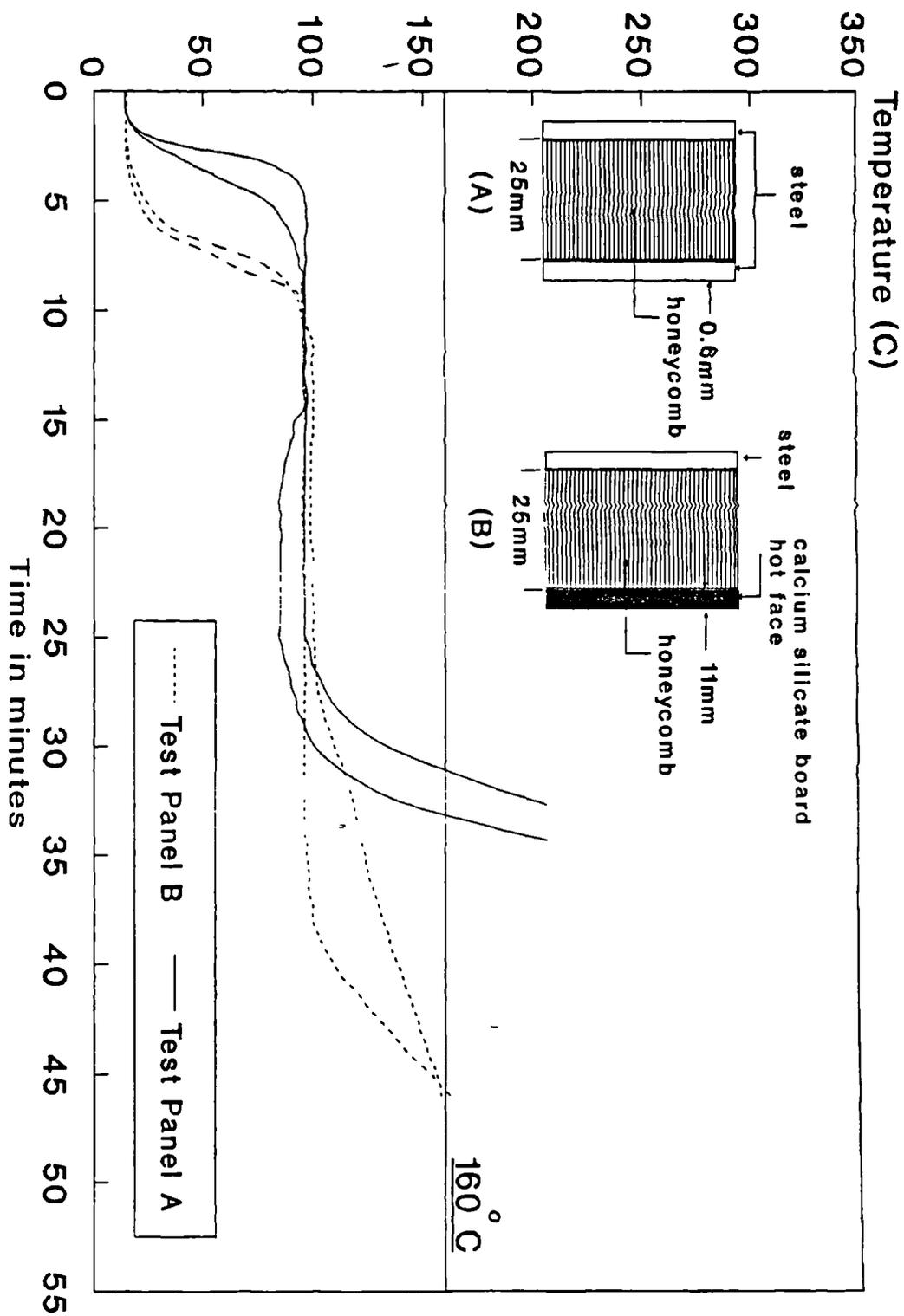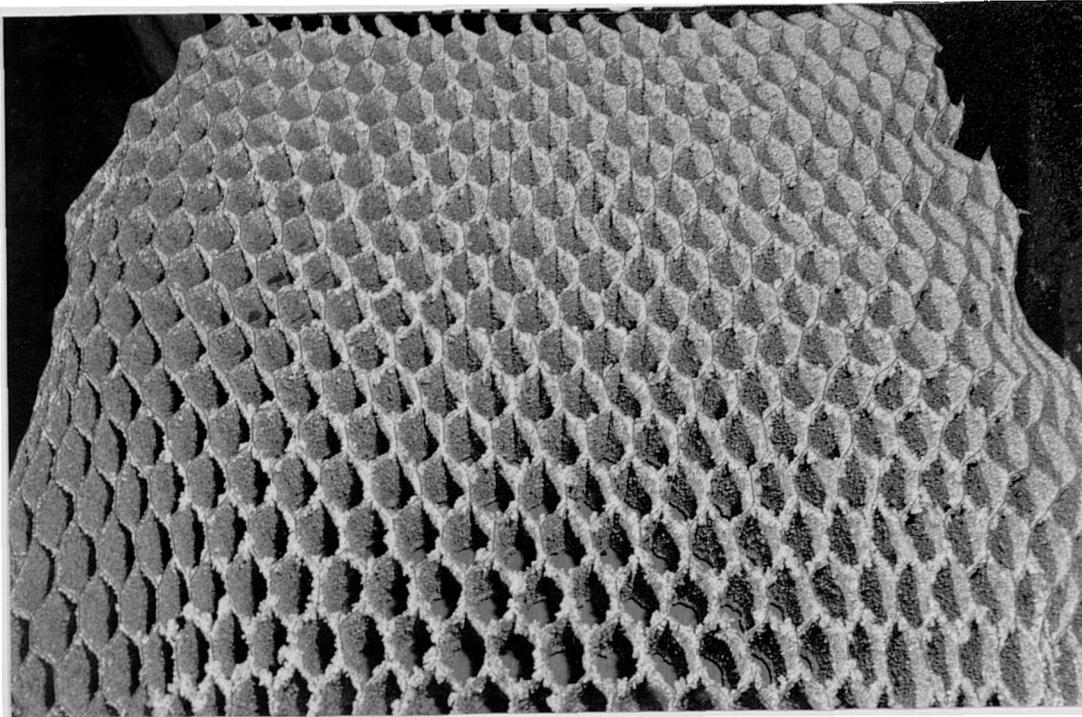
Plate 9.5   Honeycomb core treated With Sodium Silicate and Vermiculite

Plate 9.6   Strength retention at High Temperature of Sodium Silicate and Vermiculite Coating

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Figure 9.7 Test Panels W and X
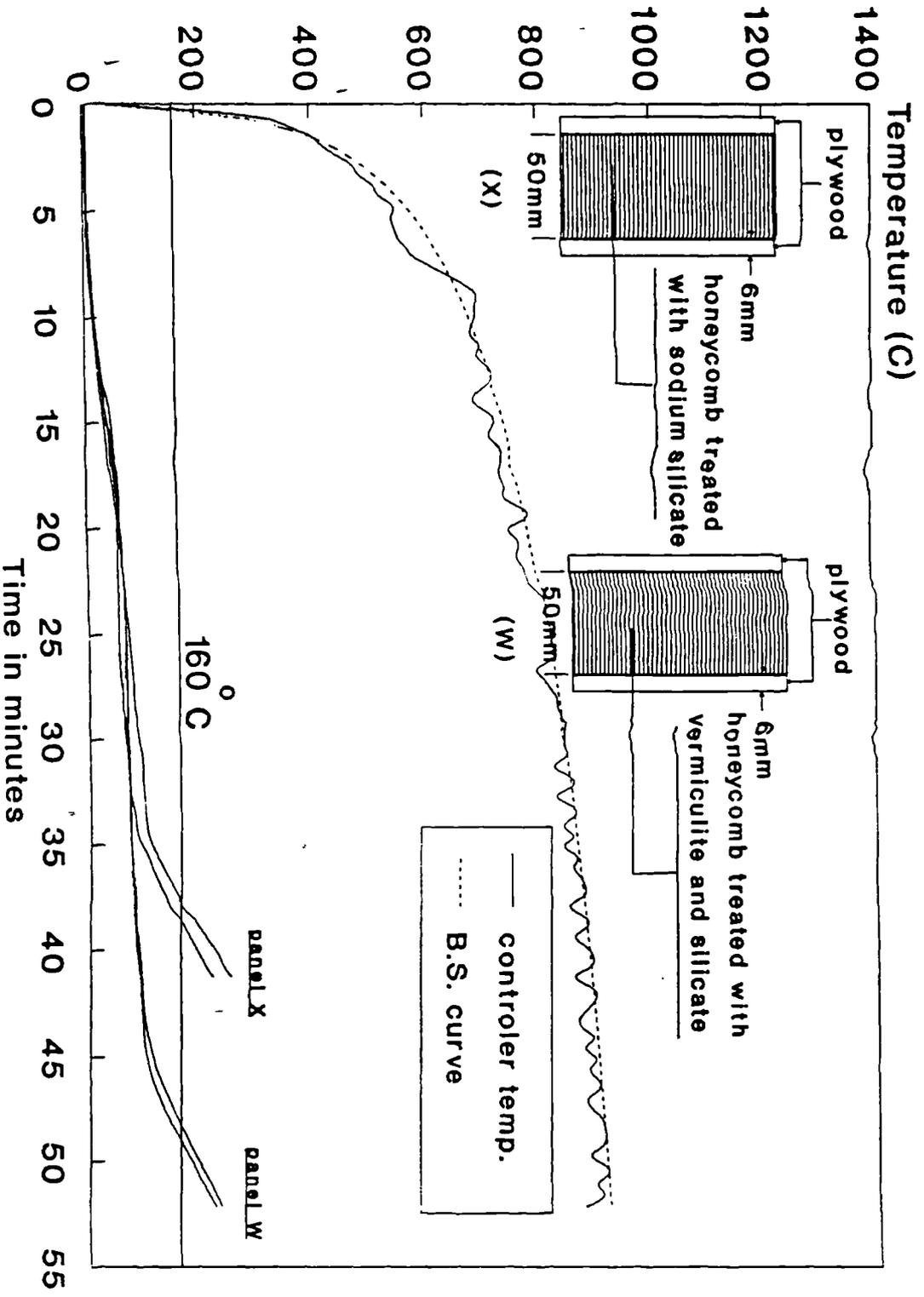
away and the space that it occupied was not filled with the insulation filler resulting in an open voids (see plate No. 9.7).

For the purpose of comparison between perlite and vermiculite as a filler, panel $F_{B.T}$ was divided into four equal quarters. One quarter was filled with loose perlite (46 grams), one quarter was filled with loose vermiculite (79 grams) and the remaining two were left unfilled. To minimise the effect of hot spots on the test specimen silicate boards with 6mm thickness were used for the faces of the panel. The results of the test indicate that the quarter filled with perlite achieved 70 minutes in insulation (core density 159 Kg/m^3) and vermiculite quarter achieved 82 minutes in insulation (core density 273 Kg/m^3). The result of the test is presented in fig.9.8.

Panel T with 50mm thick honeycomb core (density 183 Kg/m^3) filled with lose vermiculite and two 6mm plywood faces achieved 41 minutes core insulation time and 80 minutes panel insulation time. A remarkable improvement of 75% in the core insulation (72 min.) and 31% in panel insulation (105 min.) was obtained by the addition of 20% by weight of dehydrated crushed sodium silicate into the vermiculite filler (panel V). Eighty percent by mass of the hydrated crushed silicate passed through a 2.36 mm sieve.
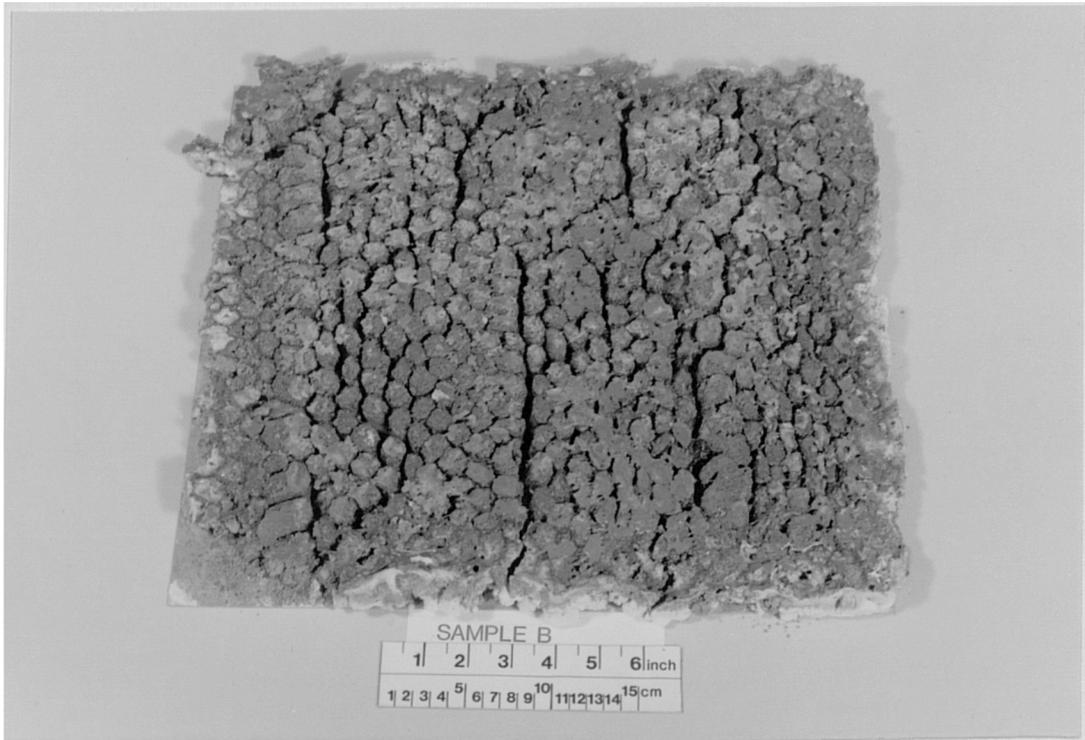
Plate 9.7 Tested Panel C with filler composition of Cement and Perlite Showing the Open voids in the Filler Due to Burning of the Honeycomb Structure

Figure 9.8 Cold Face Temperature for
Test Panel F
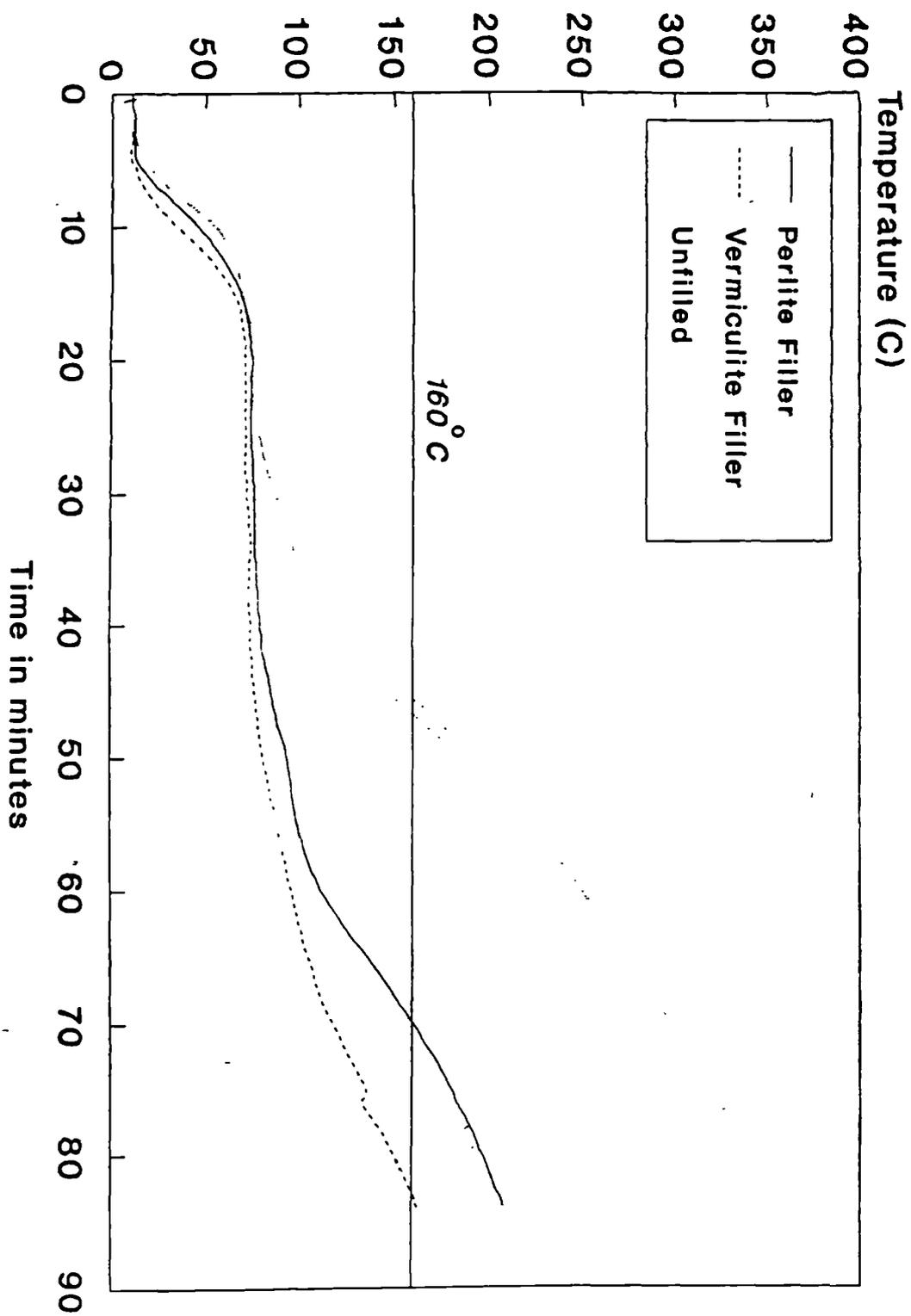
The test of the dehydrated crushed silicate and vermiculite filled specimens indicate that this filler effectively retards the transfer of heat through the panel during the test. This is due to the fact that when dehydrated sodium silicate is subjected to high temperature, it will intumesce to form a hard mass of foam, occupying many times its original volume. As the intumescence takes place, the foam will mix with the loose vermiculite surrounding it. This results in a mixture of sodium silicate intumescent foam and vermiculite which act as a efficient insulant to the substrate. Figure 9.9 shows comparison of the test data for specimens T and V. These two panels were essentially identical except for the presence of dehydrated crushed silicate in vermiculite filler in panel V. The strongly beneficial effects of the filler are evident on inspection of figure 9.9.

The results of the tests on panels with unfilled honeycomb core coated with sodium silicate and ball clay (3:1 ratio by weight) are presented in table 9.4B. Panel G with 25 mm thick core and two 6 mm plywood facing achieved a fire resistance in insulation of 51 minutes and 68 minutes in integrity. Replacing the plywood with 0.6 mm steel faces and with 25 mm core thickness reduced the insulation time by about 27%.

Panel L was tested with one face (exposed face 6 mm

Face Temperature for
Test Panels T and V

Temperature (C)

Time in minutes

Panel T
Panel V

160°C
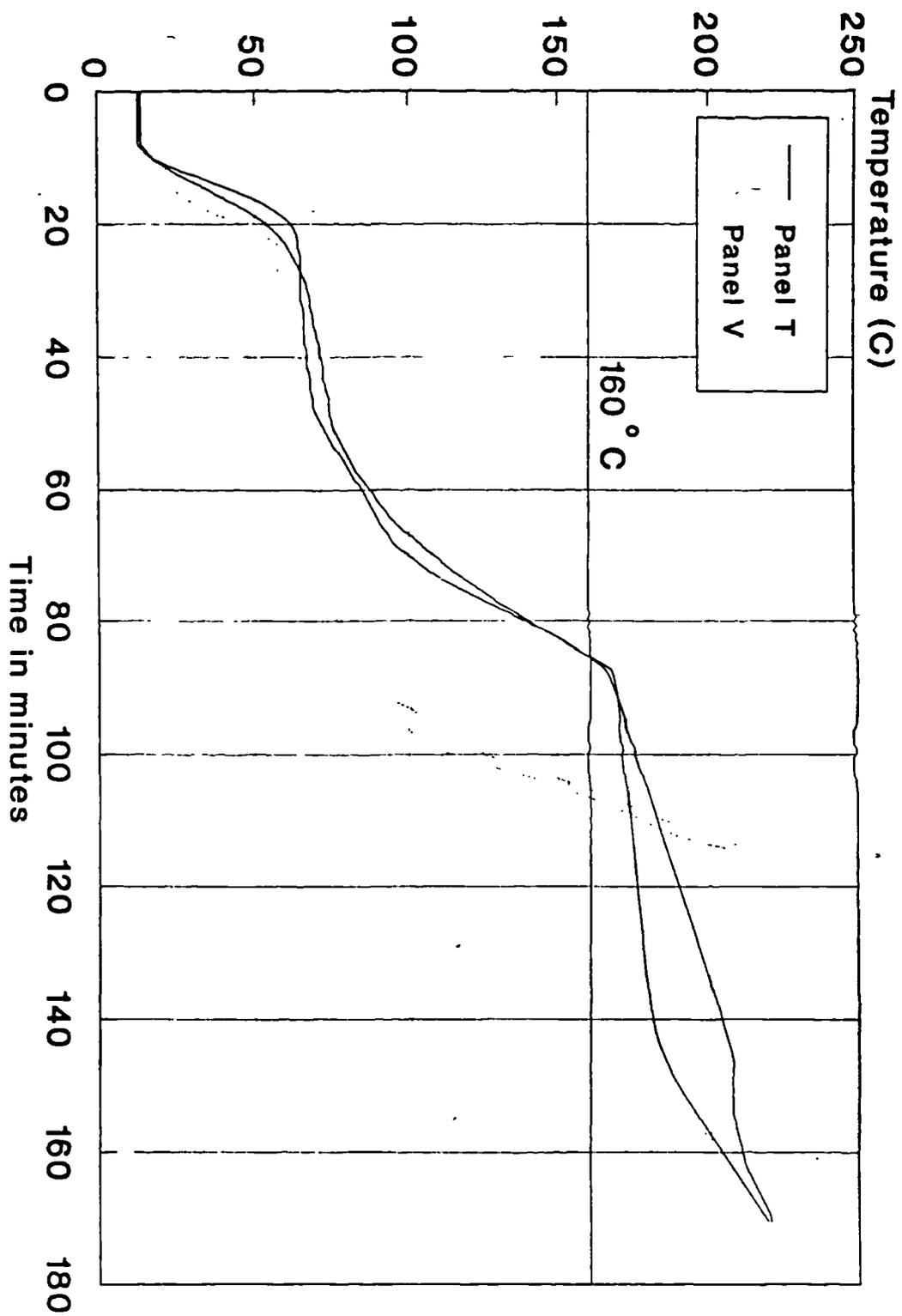
plywood) in order to study the core behaviour when exposed to high temperature. A total of six thermocouples were fixed to the panel. Two were placed at the cold side of the core, two at the middle of the core and two behind the hot face. Observation was made on the general behaviour of the core are as follows :

Time min.	sec.	
3	24	Smoke due to the charring of the plywood.
9	15	Intumescent of the sodium silicate and ball clay used as binder occurred at 110° C measured by the thermocouple placed at the top of this layer.
14	34	Temperature behind the hot face reached 140° C + ambient.
16	00	*The sodium silicate coating on the* honeycomb cell walls started to intumesce at 88° C and 162° C measured at middle and hot face of the core respectively.
34	45	The colour of the sodium silicate intumescent started to go darker at temperature about 92° and 551° C measured at the middle and hot face of the core.
46	00	Temperature at middle of the core reached 140° C + ambient.
50	00	A number of red spots appeared in core at 200° and 714° C measured at the middle and bottom of the core.
58	53	Core failed in insulation.

The result of the test is shown in figure 9.10. The

Figure 9.10 Test result for panel L

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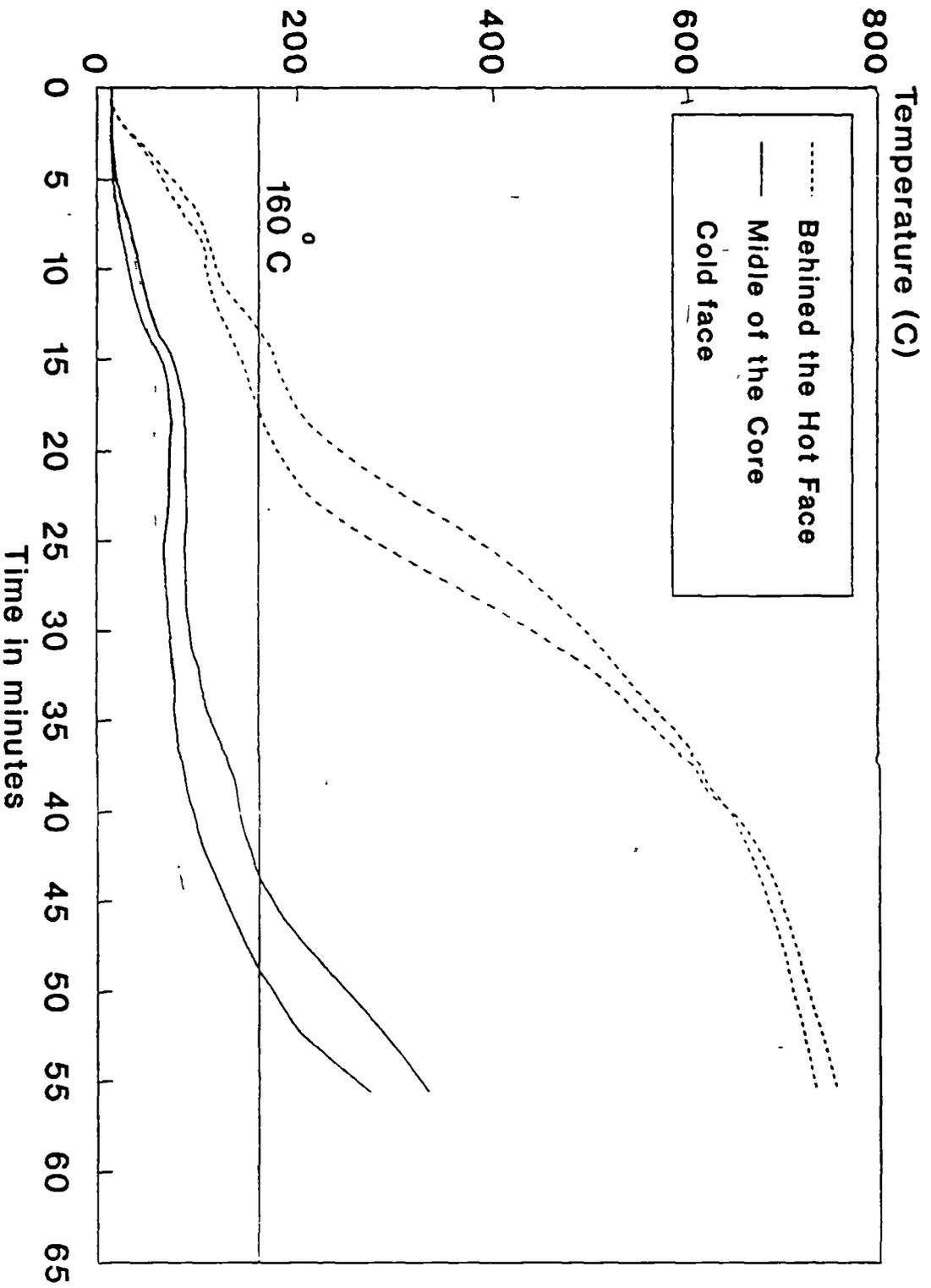
result shows a steady increase of temperature prior to intumescence of the sodium silicate after which no significant rise in temperature was recorded up to the point were the intumescent foam started to shrink.

The result of the tests on filled honeycomb cores coated with a mixture of sodium silicate and ball clay are listed in table 9.5B. Comparing the result of the test for panel M (see table 9.4B) with panel J (table 9.5B) suggest that filling the honeycomb cell with loose vermiculite improved the panel insulation and integrity by 33 minutes and 17 minutes respectively (see figure 9.11).

In order to study the intumescent effect of sodium silicate and ball clay it was desired to test panel P with only one face (6 mm plywood exposed face). This panel was constructed with 20 mm thick core stiffened with sodium silicate and ball clay (see table 9.6A). The following are observations made on the behaviour of the core during the test :

Time		
min.	sec.	
3	51	Smoke due to the charring of the plywood.
7	7	The layer of ball clay and sodium silicate used for binding the core to the hot face started to intumesce at 96° c measured by the two thermocouples situated over the top of this layer.

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12	00	The temperature at the exposed side of the core reached 140° C + ambient.
12	52	The start of sodium silicate intumescence in the core.
15	25	The cell walls of the honeycomb started to expand.
25	19	Temperature at the cold side of the core reached 140° c ambient.
27	7	About 60 % volume of the cells filled by the expansion of the cell walls.
33	00	The colour of the sodium silicate intumescence inside the cells started to darken.
38	14	Expansion of the cell walls . filled about 90 % of the cells volume at about 464° and 600° C measured at the cold side and the hot side of the core.

As explained in section 9.7. the finished core stiffened with silicate and ball clay was finally dipped into the silicate solution in-order to cover the cell wall with a layer of sodium silicate.

From the results and observation of the test it was clear that the intumescence of the sodium silicate layer used for final coating of the core prevented the full expansion of the cell walls. As the intumescent foam of the sodium silicate started to disappears the space that it occupied inside the cell was filled with the expansion of the cell walls as it was released from the compression forces (see plate No. 9.8). But even then the expansion of the cell walls failed to close the cell

Figure 9.11 Comparison of filled and unfilled panels
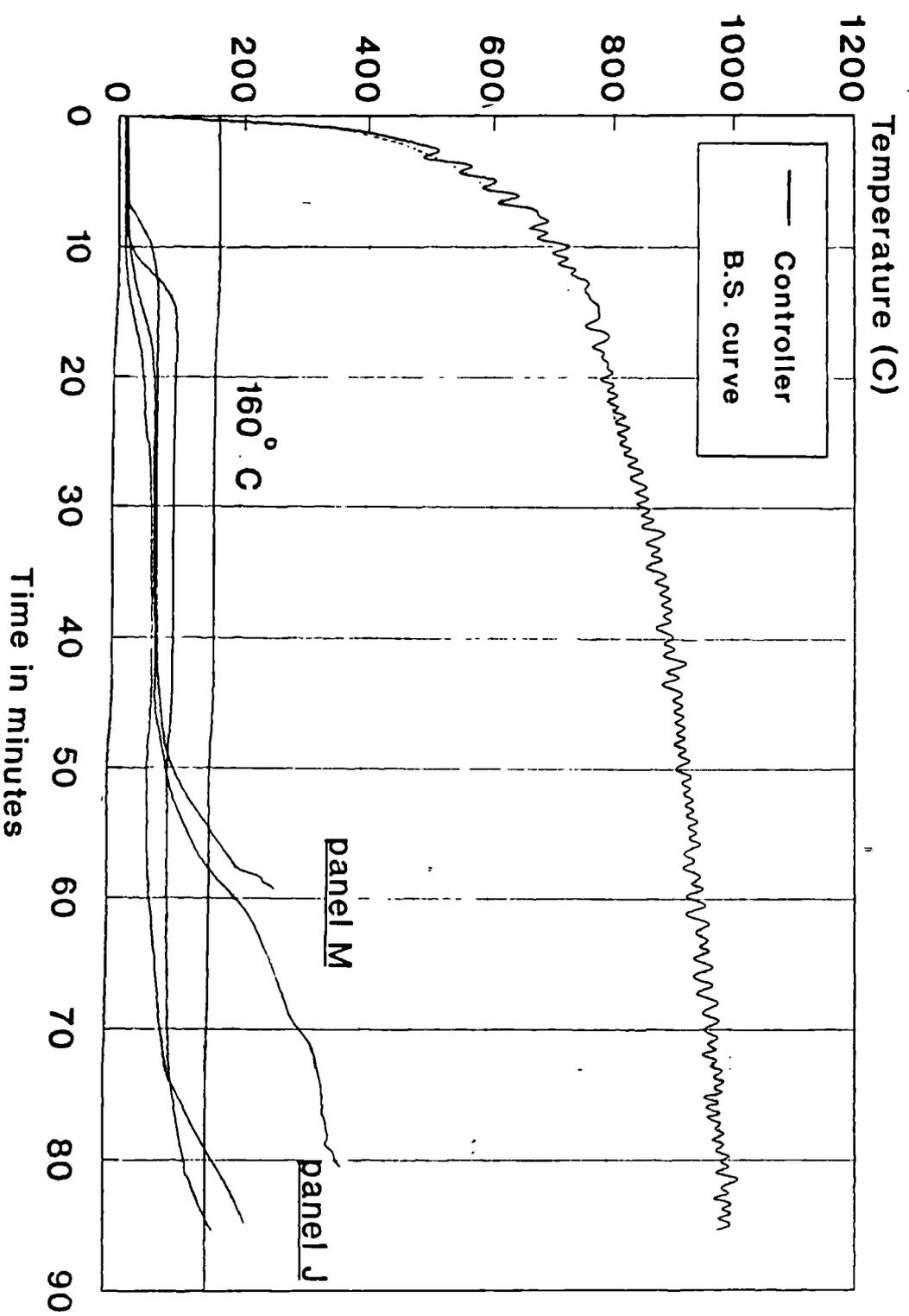
completely. During the test a moisture meter (Protimeter) was used to establish if trapped steam is the cause of cell wall expansion. As the result the protimeter indicated no existence of moisture on the surface of the expanded cell walls but when the steel pins of the Protimeter were pushed into the expanded area the meter indicated a 100% relative humidity and a moisture content of 28% (maximum range of the meter). The output graph is presented in figure 9.12.

Based on these results it was decided to construct a honeycomb core in such a way that small amount of moisture was confined between the last two layers of sodium silicate and ball clay coating. This technique was adopted to assist and increase the cell wall expansion which in turn should result in complete closure of the cells. Panel S with 25 mm thick core and two 6 mm plywood facing was constructed using this moisture entrapment technique. It was also decided not to have the final layer of sodium silicate coating on the honeycomb core so leaving the cell walls free to expand.

The experiment was found to be successful and produced a promising result. The result of this test is presented in table 9.7B. A fire resistance time in insulation of 75 minutes and 105 minutes in integrity was achieved. The time/temperature graph obtained from the test is

Figure 9.12 Test result of panel P (core temperature)
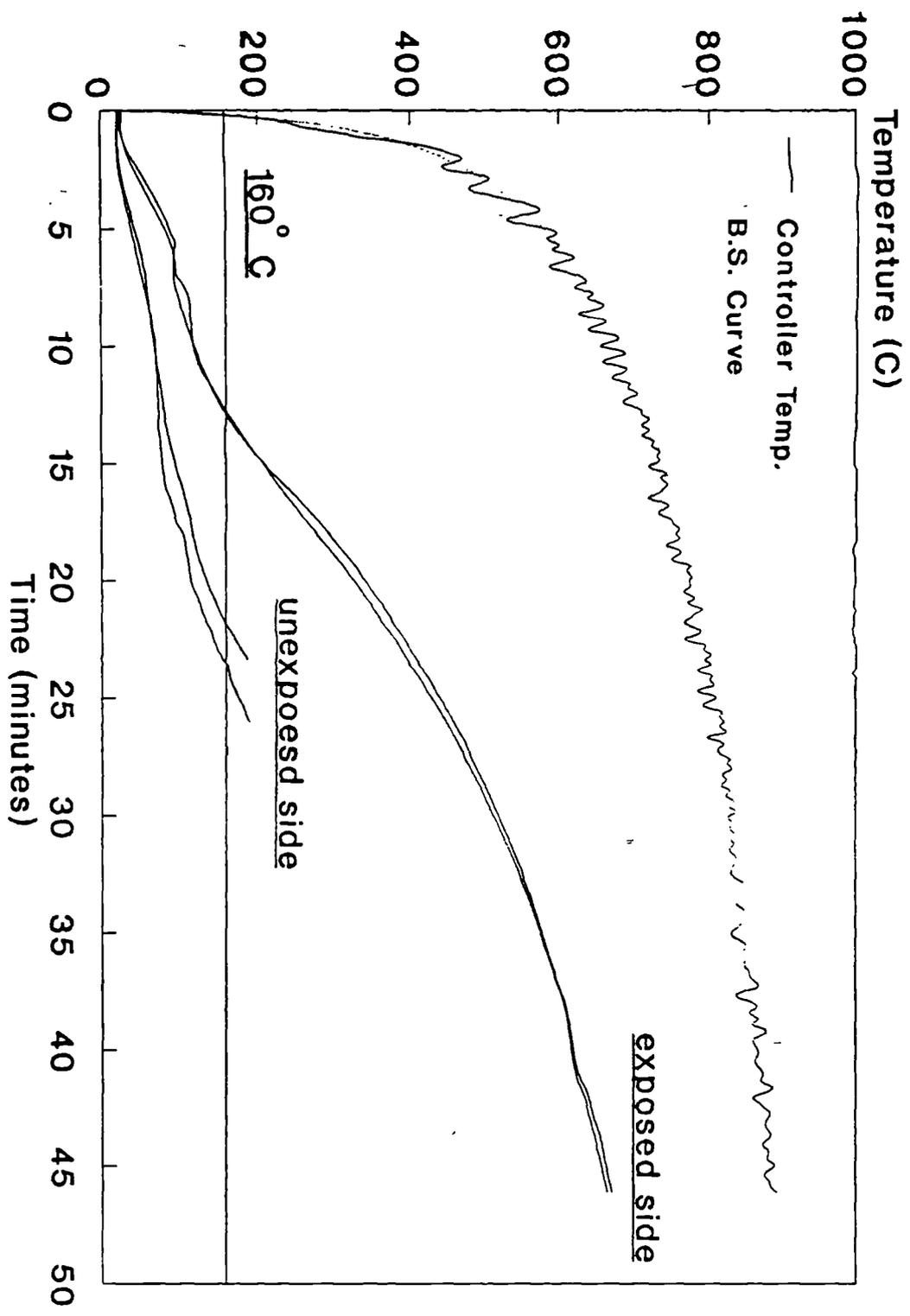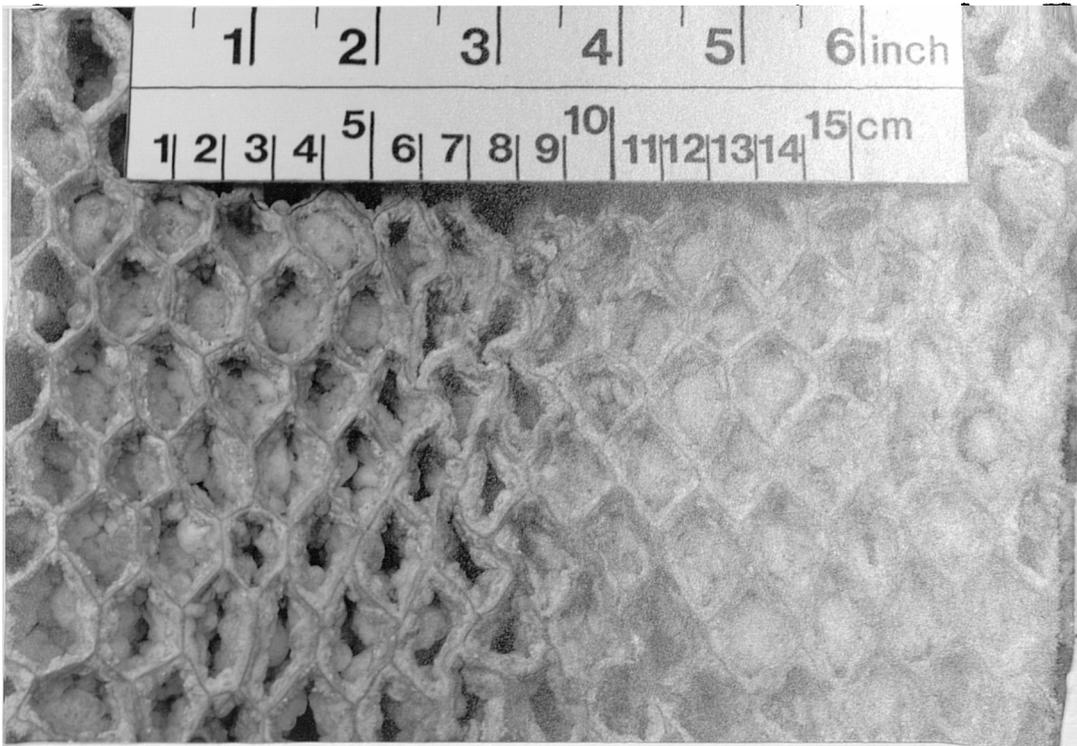
Plate 9.8   Expansion of the Cell Wall Material Replacing the Sodium Silicate Intumescence Foam
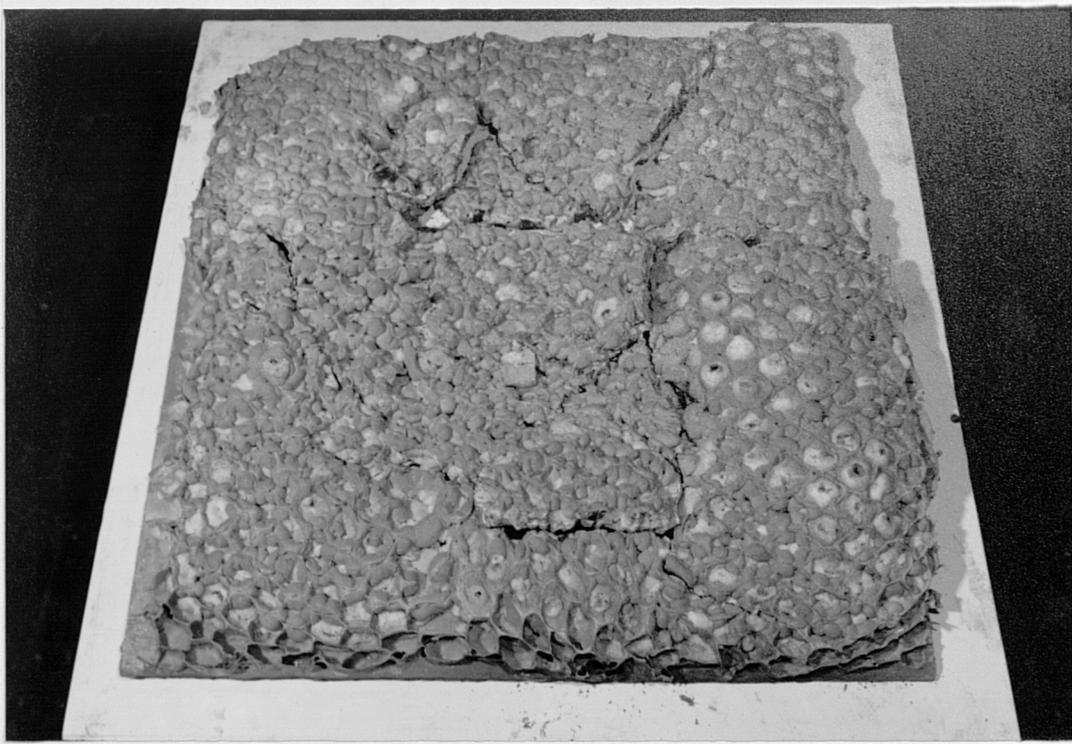
Plate 9.9   The Empty Cells Being Filled by the Expansion of Cell Wall Material

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presented in figure 9.13. The graph indicates a steady rise in temperature of the cold face up to 25 minutes from the start of the test. At this moment the temperature of inside the cell wall was measured at 95° C. After 25 minutes the temperature of the cold face started to drop. This drop in temperature is due to the expanding of the honeycomb cell walls and filling the voids inside the cells. A further reduction in temperature occurs at about 35 minutes as more honeycomb cell voids are blocked and finally reaches to its minimum temperature due to complete closure of the cell voids (see plate No. 9.9).

A similar type of behaviour was observed for panel P which was tested with the hot face only in place (see observation for panel P).

Figure 9.13 Cold face temperature for panel S

cold face temperature
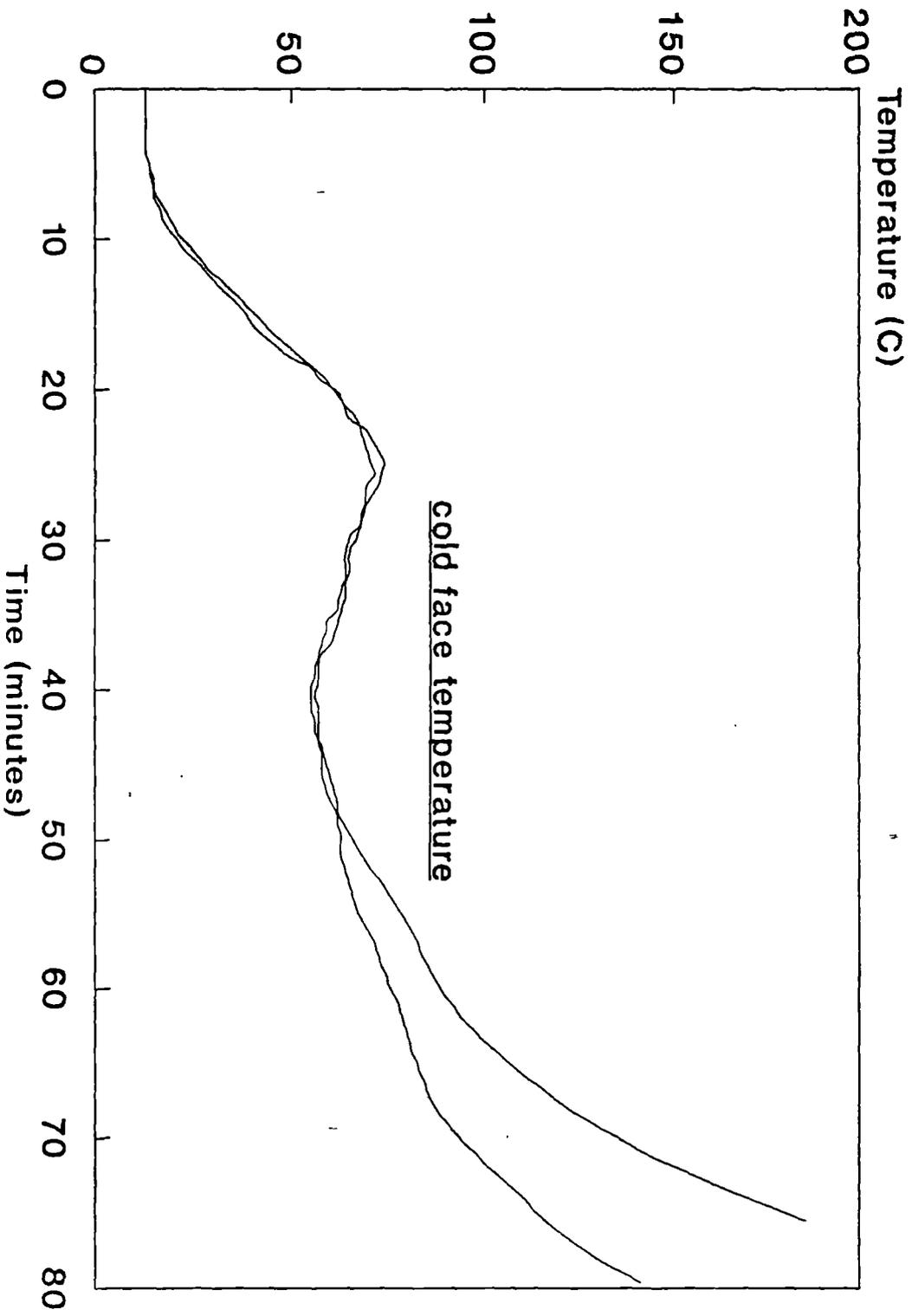
9.9 COMPARISON OF THE RESULTS

In the following, the result of the fire tests on similar developed honeycomb core panels are compared in terms of their fire resistance in insulation to core density and insulation to panel weight ratios.

Table 9.8

Panel No.	Hot Face	Cold Face	Insulation[1] Core density	Insulation[1] Panel Weight
A	steel	steel	0.101	1.814
B	C.B.[2]	steel	0.212	2.013

1 insulation time in minutes
2 calcium board

The above table lists *the results of the tests on panels* with 25 mm thick core treated with sodium silicate. The results indicate a 100 % increase in insulation to core density ratio which can be obtained by replacing the steel face with a calcium silicate board at the exposed side (see figure 9.6).

Table 9.9

panel No.	Hot Face	Cold Face	Filler	Insulation[1] Core Density	Insulation[1] Panel Weight
A	steel	steel	no	0.101	1.814
B	C.B.	steel	no	0.212	2.013
C	steel	steel	yes[2]	0.087	1.955
D	C.B.	steel	yes[2]	0.115	2.00

1 insulation time in minutes
2 core cells filled with cement and perlite (1.5:1)

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Table 9.9 shows the fire tests result on 25 mm thick core panels stiffened with sodium silicate. The results indicate that for this type of panel the introduction of fillers was found to have an adverse effect on the insulation to core density and insulation to panel weight ratios.

Table 9.10

Panel No.	Filler	Insulation[1] Core Density	Insulation[1] Panel Weight
X	no	0.493	2.643
T	yes[2]	0.437	4.44
V	yes[3]	0.493	4.77

1   insulation time in minutes
2   core cells filled with lose vermiculite.
3   core cells filled with lose vermiculite and dried crushed sodium silicate.

Table 9.10 list the fire tests result on 50 mm thick core treated with sodium silicate for both filled and unfilled honeycomb core with plywood facing. The test results for panel X and T indicate an reduction of 11% in insulation to core density when the cells are filled with loose vermiculite. However, in terms of insulation to to panel weight ratio the result shows an increase of 68%. Addition of dried crushed sodium silicate into loose vermiculite filler (panel V) increased the insulation to core density and insulation to panel weight ratios by 12% and 7% respectively.

Table 9.11

Panel No .	Core Treatment	$\dfrac{\text{Insulation}[1]}{\text{Core Density}}$	$\dfrac{\text{Insulation}[1]}{\text{Panel Weight}}$
I	S.S+BC[3]	0.123	1.818
A	S.S.[2]	0.101	1.814

1 insulation time in minutes
2 sodium silicate.
3 sodium silicate and ball clay.

Table 9.11 shows the test results on panels with 25mm thick core with steel facings. The results indicate that an increase of 17% and 0.2% in terms of insulation to core density and insulation to panel weight ratios can be obtained if the core is treated with ball clay and sodium silicate compared to sodium silicate alone.

Table 9.12

panel No.	Core Treatment	$\dfrac{\text{Insulation}[1]}{\text{Core Density}}$	$\dfrac{\text{Insulation}[1]}{\text{Panel Weight}}$
X	S.S.	0.493	2.643
R	S.S.+ B.C.	0.275	2.950

Table 9.12 lists the fire tests results for panels with 50 mm thick core and plywood facings. The results show that a reduction of 44% in insulation to core density ratio and an increase of 12% in insulation to panel weight ratio can be obtained if the core is treated with ball clay and sodium silicate compared to sodium silicate alone.

Table 9.13

Panel No.	Filler	Insulation[1] Core density	Insulation[1] Panel Weight
R	no	0.275	2.950
J	yes[2]	0.225	4.00

1   insulation time in minutes
2   core cell wall filled with lose vermiculite.

Table 9.13 lists the fire tests results on panels with 50 mm thick core treated with a mixture of sodium silicate and ball clay and with plywood facings. The results show that a 18 % $\overset{\text{REDUCTION}}{\vee}$ and 35% increase in insulation to core density and insulation to panel weight ratios can be obtained by filling the core cells with loose vermiculite.

Table 9.14

Panel No.	Core Treatment	Insulation[1] Core Density	Insulation[1] Panel Weight
G	S.S. + B.C.	0.138	3.00
S	S.S + B.C.*	0.186	3.261

*   water entrapment technique.

The above table list the fire tests results on panels with 25mm thick core treated with sodium silicate and ball clay with plywood facing. The result shows panel S which was constructed with a water entrapment technique increased the insulation to core density and insulation to panel weight ratios by 26% and 8% respectively.

9.10 CONCLUSION

1- The developed paper honeycomb core does not release discernible smoke when exposed to fire.

2- A fire resistance of 37 minutes in panel insulation was achieved for an unfilled paper honeycomb core (50 mm thick) impregnated with sodium silicate with 75 Kg/m^3 core density and plywood faces.

3- Reinforcing the cell walls with vermiculite in the sodium silicate coating increased the fire resistance in panel insulation time from 37 minutes to 48 minutes.

4- The tests of the filled specimens indicate that filling the cells with lose inorganic insulation effectively retards the transfer of heat through sandwich panels during transient heating.

5- An high alumina cement/perlite filler was found to have adverse effect on the intumescent properties of the sodium silicate.

6- Vermiculite as a filler increased the core fire resistance in insulation from 10 minutes to *41* minutes for two identical panels (panels X and T).

7- The addition of a small amount of dried crushed sodium silicate increased the core fire resistance

in insulation from 41 to 72 minutes for identical panels (panel T and V).

8- Ball clay and sodium silicate coating of cell walls increased the fire resistance of the core in insulation but with a large increase in core density.

9- The moisture confinement method enhanced the fire performance of the panel in insulation and integrity from 51 to 75 minutes and 68 to 105 minutes respectively for two identical panels. This resulted in only nine percent increase in the core density.

9.11 SUGGESTION FOR FURTHER RESEARCH

1- Further research is required to investigate the water confinement technique. The presence of moisture in the composite may have an adverse effect on the strength of the system.

2- An increase in core fire resistance in insulation may be achieved using several ball clay and silicate layers with moisture confinement.

3- The closure of the cell due to cell wall expansion can be achieved without a large increase in core density. This may be possible by introduction of a coated paper strip in_between the nodes (see figure 9.14). This may improve both the fire resistance and mechanical properties of the core.

4- More research is needed in the effect of different type of inorganic insulation fillers.

5- it would be intersting to investigate the effect of sandwich core of new configurations. Figure 9.15 shows two possible form, (a) a truncated square pyramidal projections with square symmetry, (b) a two-dimensional analog of the corrugated shape. The flat truncated ends of the pyramids not only permit good adhesion to the facings but can be partially filled (rather than being fully filled as in honeycomb) with a intumescent filler (e.g. vermiculite-sodium silicate).
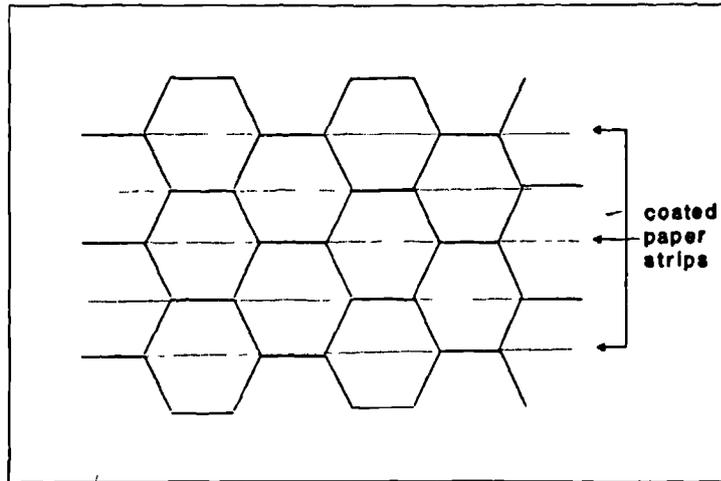
Figure 9.14 Reinforcing the paper honeycomb by adding an
extra coated paper strip in between the nodes

(a)

(b)
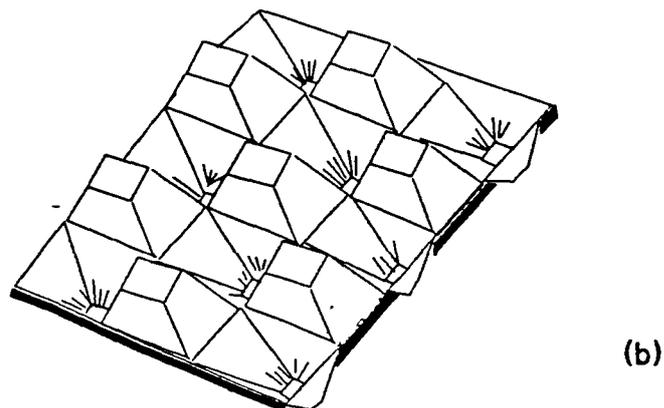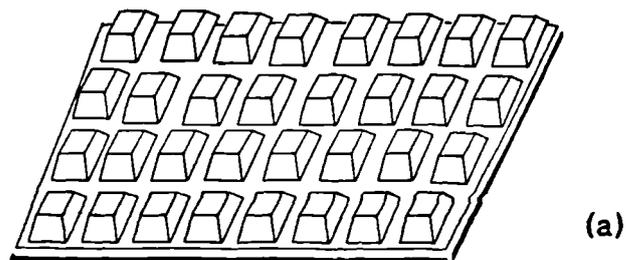
Figure 9.15 Sandwich Ccore with New Configurations

(a) sandwich core consisting of truncayed square pyr-
mitdal projections with square symmetry

(b) two dimentional analog of the corrugated shape

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CHAPTER 10
GENERAL DISCUSSION AND
CONCLUSIONS

10. GENERAL DISCUSSION AND CONCLUSIONS

10.1 DISCUSSION

10.1.1. GENERAL

The research was basically divided into two parts. In the first part the structural analysis of sandwich beams using timber-based facings and plastic rigid foamed cores was studied and the most appropriate theory was identified. In addition timber-based materials suitable for sandwich panel construction were investigated and the most suitable types were identified. The second part of the research was concerned with the development of a new structural fire resistant core material. The new core material was intended to provide a structural function as well as fire resistance at a reasonable density.

The objectives were largely realised. Much information was obtained regarding the accuracy of current standard tests.

An established analytical solution for a simply supported sandwich beam with thick faces of different thicknesses and moduli, with point loading anywhere on the span was represented. The out-of-plane shear modulus and the transverse stiffness of the newly developed core were evaluated. In addition an expression was re-presented for the calculation of shear modulus of the developed core. The fire resistance capacity of the

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core was then evaluated and further improved.

Laboratory test programmes were initiated to test the various material properties within the main study. Analytical solutions were compared with laboratory results in the light of independently obtained material property data. There was a good comparison between the theoretical and experimental results.

10.1.2 MATERIAL PROPERTY TESTS

Considerable background work regarding the test method for rigid foamed core was conducted as the first step. Small scale tests on both facing and core material were required to establish independent values of material property constants for the analysis of sandwich beams. Simple flexural tests on facing materials were considered to be appropriate. In-plane shear properties were required for the core. Considerable background work regarding the test methods for rigid foamed cores was conducted, in particular for the shear test.

On the basis of information gathered from background work the lapped shear test method appears to produces the lowest value of shear modulus. The four point flexural test and joined square test methods are considered to be suitable for the determination of the shear properties of rigid foamed cores. Based on these findings the shear moduli of the foamed cores were obtained by using the joined square shear test method.

10.1.3   TIMBER-BASED FACING MATERIAL

An investigation into timber-based materials suitable for sandwich panel facings was conducted as the first step. A variety of timber-based facings were investigated and national standard methods of testing were discussed. The timber-based materials were compared on the basis of their mechanical and physical properties.

The computer program written for the analysis of sandwich beams was utilised in the examination of the suitability of the timber-based materials under investigation. Computer-modelled beams were created using the mechanical properties of proposed materials which enable the behaviour of each beam to be studied.

The overall flexural rigidity of the modelled beams were calculated and the modelled beams were compared in terms of their stiffness to weight ratio.

10.1.4   SANDWICH BEAM

The concept of timber as a an orthotropic material with three principal axes of symmetry, and its widely different properties along and across the grain makes it a complicated material in structural analysis. Employing timber-based materials to form the facings of sandwich panels would therefore complicate things more from the view point of mathematical treatment. It was therefore appropriate to study the behaviour of sandwich panel

beams using timber-based facings and foamed plastic cores and to identify the most appropriate theory. As a result the Stamm and Witte[30] theory was identified to be the most appropriate theory. Their solution approach was considered the most relevant and applicable form of continuous differential mechanics analysis available for practical situations (i.e. panels of up to three equal spans subject to uniformly distributed and temperature loading). Particular Stamm and Witte solutions for a simply supported panel with different facing thicknesses and modulus and point load anywhere on the span were re-presented. The solutions were then extended for a simply supported sandwich panel with 4-point loading. The analytical method was compared with the results of several laboratory programmes. Corresponding sandwich beam tests were on a range of timber-based skin/core combinations. Finally the analytical solutions were compared with the laboratory results. In addition the calculated failure stresses of the sandwich components were compared with the constituent material strengths.

10.1.5 CORE DEVELOPMENT

The need for a structural fire resistant core material was initially established. The fire tests results on some commercial sandwich panels illustrate that sandwich panels with rigid foamed core materials possess very limited periods of fire resistance.

The related background work illustrated that a considerable amount of work has been carried out by various researchers in trying to improve the fire resistance capacity of plastic rigid foamed core materials. It was concluded that a novel core material was needed with good structural properties at acceptable density, and with adequate fire resistance free from the production of smoke and toxic fumes.

It was decided that the structural requirement could be obtained via a honeycomb with poor heat conduction properties (i.e. non metallic) and the fire resistance requirement can be obtained by filling the cells with non-combustible insulating materials.

Honeycomb core was developed based on a thin absorbent paper stiffened by dipping in sodium silicate and/or potassium silicate solution. This type of honeycomb core was thought to provide a non-combustible, low cost structural core with intumescent properties when exposed to high temperature.

There were two approaches to the core development. The

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first was to develop a material with adequate structural performance and the second was to assess and improve the fire resistance capacity of the core.

1.1.5.1 STRUCTURAL PERFORMANCE

The development work was initiated by detailed investigation into the properties of constituent materials. Initial work on paper stiffened with sodium silicate revealed that the composite posses micro-cracks in the plane of dried sodium silicate due to loss of moisture. Work was then undertaken to investigate the effect of adding inert fillers into the sodium silicate solution to eliminate the cracks. As a result of this investigation, the introduction of ball clay and/or vermiculite appears to produce a crack free composite.

The effect of fillers was further examined by a series of tensile tests on strips of paper stiffened with various coatings. A total of 147 tests were carried out on different paper qualities and a variety of coatings. Based on the test results, the presence of ball clay in the matrix appears to have increased the stiffness and strength of the sodium silicate coating. This may be attributed to the elimination of cracks within the composite and that ball clay contributed an integrity of it's own to the composite.

This investigation gave the opportunity of comparing the effect of different fillers on the tensile properties

of the matrix and the effect of paper quality on the stiffness and strength of the composite as whole. The results of the tensile tests were also required to obtain the elastic constants of the materials which form the cell walls of the developed core for the calculation of honeycomb shear modulus.

The next step in the development work was to investigate the structural properties of the developed core. The compression and shear properties of the developed cores were measured using methods drawn from standard tests.

Since a pure shear test on the developed core was found to be unreliable, the shear modulus was obtained by using a four-point loading test. A total of 39 beams were manufactured and tested using the developed core impregnated with sodium silicate and/or sodium silicate and ball clay.

Three specimens were cut from each tested beams for compression test.

The result of the tests illustrate that the developed core has excellent structural properties in shear as well as in compression. It also shows that not much benefit arose from creating excessive cell wall thickness. The shear modulus of the developed core was not found to be dependent solely on the density of the core but on the product of the ratio of cell wall thickness to single wall length and the elastic constant

of the cell wall material (i.e. $t/l.E_s$).

The shear modulus of the developed core was also calculated using the expression presented by Ashby and Gibson[35]. The authors formulated the upper and lower bound shear moduli by calculating the strain energy associated first with a strain distribution which allows compatible deformation and, second with a stress distribution which satisfies equilibrium.

In order to calculate the shear modulus of the developed core the core cell geometries of the tested beams had to be measured. Measurement were taken randomly for each core tested. The average of ten measurements was used for the characteristic dimensions of each core. The results were found to be more scattered for developed cores impregnated with sodium silicate and ball clay particularly in the measurement of the cell wall thickness and cell diameter.

A comparison was made between calculated and measured core shear modulus. In the case of sodium silicate impregnated cores the calculated shear moduli agreed well with the test values. The arrangement was found to be poor for sodium silicate and ball clay impregnated cores. The discrepancy may be be related to the irregularity of the honeycomb cell walls and shape. The hexagonal shape of the sodium silicate impregnated core was found to have been distorted after being dried.

Better agreement may have been obtained if pure shear tests of the developed honeycomb cores in isolation had been feasible. Since the test on the developed core had to be carried out in the form of a sandwich, the test results are therefore affected to a greater or lesser degree by the properties of the faces and core face bond.

10.1.5.2 FIRE PERFORMANCE

The work was initiated by establishing a base line behaviour of some commercial sandwich panels. The behaviour of the panels containing extruded polystyrene, expended polystyrene and mineral wool cores with steel or aluminium alloy skins was established. The results of the fire tests show that these panels achieved a limited fire resistance time in insulation. Sandwich panels with mineral wool core produced better results, but performance of these panels was adversely effected by the method of manufacture. This resulted in the shrinkage of the mineral wool strip which caused opening up of the joints between each strip and, through these openings, heat penetrated to the cold face of the panel. Finally fire tests were conducted on small sandwich panel systems containing the developed cores. A total of 17 tests were carried out on. Each provide a different test condition by impregnation of the developed core with sodium silicate, and/or sodium silicate and ball

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clay and/or sodium silicate and vermiculite, by having cells empty or filled and by using different face materials. The assessment of fire resistance of the developed cores has been based on the insulation and integrity criteria. The assessment of the fire resistance of the developed core has been carried out in idealised conditions as explained in section 9.5 (small panel without joints).

As anticipated the test results show that with the correct balance of cell size and sodium silicate wall coating thickness, the coatings expand and block the cell. This delayed the passage of heat from hot face to the cold face of the panel. However, based on the test observation, the intumescence foam appeared to have shrunk back from the hot face at temperature around 550° C (Measured on the hot side of the core) and at this point the intumescent foam ceased to provide sufficient thermal insulation. Filling the cells with good insulant sufficiently delayed the passage of heat through the core. A 72 minutes core insulation time was obtained for a 50mm core of this this type using a loose vermiculite and dried sodium silicate fillers.

Impregnating the core with sodium silicate and ball clay provided a core with strength retention at high temperature. A panel of this type with loose vermiculite filler achieved a fire resistance in panel insulation of

88 minutes. Although this type of core retained it's structure at high temperature, it only obtained a limited fire resistance insulation time when tested without any filler. This was due to the shrinking back of the sodium silicate intumescent foam which was used as a final coating. To overcome this problem the water entrapment technique was developed which causes intumescence of the cell wall to occur (i.e. intumescence of the sodium silicate and ball clay) which blocked the cells. This had the advantage of retaining blockage at high temperature.

Based on the fire test results, the developed cores provide adequate fire resistance time, free from the production of smoke and toxic fumes.

10.2 CONCLUSIONS

The main objectives of the project have been realised. Investigation into the test methods for the determination of material property values of core materials have been successful in themselves, and have also been used to underpin later examination of sandwich beam analysis.

Laboratory tests programmes on a selection of sandwich beams were used to verify sandwich beam analysis for timber-based material facings.

Laboratory test programme were also undertaken on the newly developed honeycomb core for the determination of the desired mechanical properties. In particular shear test results were used to examine the accuracy of the theory used to calculate the shear modulus of the developed core. Fire tests were carried out on the sandwich panel systems containing the developed core to assess their fire resistance capacity. The main conclusion are as follows.

1- The most appropriate theory for sandwich beams using timber-based facings and foamed plastic core was identified. The basic equations and solution are presented for simply supported sandwich beams of this type subject to point loading. The solution of the point loading is extended for the case of four point loading.

The author has programmed these solutions coded in Fortran language. The program calculates mid span deflection and the stresses for each element of the sandwich at any given cross-section.

2- Tests on simply supported sandwich beams with semi-thick timber based facings and rigid plastic foamed core subjected to four point loading have been conducted. The experimental and the theoretical load deflection curves were presented. The agreement between the theoretical and experimental result is good with regard to midspan deflection and the calculated stresses at failure.

3- Based on the information gathered from background work the joined square and the four point shear tests were considered to be the most suitable test methods for the determination of core shear properties of rigid plastic foamed cores. The lapped shear test method appears to produce the lowest value of modulus.

4- A variety of timber-based materials were investigated and those most suitable for sandwich panel construction were identified. The comparison was made, based on the mechanical and physical properties of timber-based material considered in this work and on the test results of computer modelled beam tests. Plywoods appeared to be the

most suitable timber based facings for sandwich panel construction.

5- Development work on a new structural fire resistant core material was performed. Coated paper honeycomb cores were chosen for this study. Combinations of papers and coatings were examined. Based on the comparative tensile test results the untreated paper has a strong influence on the tensile properties of the coated paper. There was not much benefit obtained from creating excessive coating thicknesses

A sodium silicate and ball clay coating appear to be the most effective in terms of stiffness and strength.

6- The calculation of honeycomb core shear modulus has been presented. The shear moduli of the developed cores have been measured by using the four point shear test. Shear moduli as high as 70 N/mm^2 were obtained. The calculated and measured shear moduli of the developed core were compared and the agreement between the experimental and theoretical results was generally good.

7- Introduction of ball clay into the matrix overcame the problem of micro-cracks which had been observed when coating with sodium silicate . This particular coating combination proved to be

effective in terms of stiffness, fire resistance, freedom from micro cracking and produced cores which retain their structure at high temperature.

8- As a result of this investigation a non-combustible core with excellent strength and adequate fire resistance was developed. The following sum up broadly the findings of the test programme on the developed core.

Shear modulus of the core ranged in between 4-70 N/mm^2 for a density range of 23-240 Kg/m^3.

The core fire resistance value in insulation range between 10-72 minutes for a density range of 75-239 Kg/m^3.

The fire resistance value in insulation of the panel core systems ranged between 37-105 minutes and the fire resistance value in integrity ranged between 42-164 minutes for a panel weight range of 14-22 Kg/m^2.

A P P E N D I X   A

C O M P U T E R   P R O G R A M   A N D

T Y P I C A L   O U T P U T

COMPUTER PROGRAMME WRITTEN FOR THE ANALYSIS OF SIMPLY SUPPORTED SANDWICH BEAMS WITH THICK FACINGS

```
C STAMM2 IS FOR DIFFERENT KINDS OF OUTPUTS FORCES OR
     STRESSES
     OPTIONS (DREAL)
     DOUBLE  PRECISION
     I1,I2,L,LANDA,MS,NS,LS,MM,MMS,MMD,MD,LD,ND,M,
    + LD1,LD2,ND1,ND2,MD1,MD2,MMD1,MMD2,MMAX1,MMAX2,MMAXS,
    + T1,T2,B1,EP,
     COMMON/A/ EP
C  STIFFNESS PARAMETRES
        DO 500 I=1,20
        READ(5,*)
C  ICASE=1  STREESES, 2 DEFLECTION AND  FORCES  ONLY
        READ (5,*)ICASE,a
        print*,'******** icase=',icase,'**********'
        write(6,10)icase,a
   10   format(//,5x,'ICASE=',I2,5X,'TEST NO.',F20.1)
        IF(ICASE.LT.0)GO TO 600
        EP = 0
        READ(5,*)
        READ(5,*)B1,T1,EF1,C1
        A1=B1*T1
        I1=(B1*T1**3)/12.
        READ(5,*)
        READ(5,*)T2,EF2,C2
        A2=B1*T2
        I2=(B1*T2**3)/12.
        READ(5,*)
        READ(5,*)D,DC,G
        BR=B1
            READ(5,*)
            READ(5,*)L,P1,P2,Z1,Z2
            WRITE (6,'(3X,''L='',F10.4,3X,''P1='',F10.3,3X,
    +       ''P2='',F10.3,3X,''Z1='',F10.3,3X,''Z2'',F10.3)
    +       ')L,P1,P2,Z1,Z2
C           CALL SUBGC(L,EF1,BR,DC,T1,G)
        WRITE(6,2000)
        DO 100 IEP=1,51
        WW= 0.0D0
        MM= 0.0D0
        MMS= 0.0D0
        MMD1=0.0D0
        MMD2=0.0D0
        MMD=0.D0
        QQD=0.D0
        QQ=0.D0
        QQS=0.D0
        MD=0
        MS=0
```

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```fortran
      DO 50 IL=1,2
      BS=EF1*A1*EF2*A2*D**2/(EF1*A1+EF2*A2)
      BD1=EF1*I1
      BD2=EF2*I2
      BD=BD1+BD2
      B=BS+BD
      ALFA1=BD1/BS
      ALFA2=BD2/BS
      ALFA=BD/BS
      GEFF=G*D/DC
      A=BR*DC
      BETA=BS/(A*GEFF*L**2)
      LANDA=SQRT((1+ALFA)/(ALFA*BETA))
C     DIMENSION LOAD POSITION FACTORS
      e1=Z1/L
      e2=Z2/L
      IF(IL.EQ.1)THEN
      P=P1
      e=e1
      ELSE
      P=P2
      e=e2
      ENDIF
C     CALCULATION OF DEFLECTION PROFILE
      U=(P*L**3/B)*((1-e)*EP*(2*e-e**2-EP**2)/6+(1-e)
     + *EP/(ALFA*LANDA**2)-SINH(LANDA*(1-e))*SINH(LANDA
     + *EP)/(ALFA*LANDA**3*SINH(LANDA)))
      V=(P*L**3/B)*(e*(1-EP)*(-e**2+2*EP-EP**2)/6+e*(1-
     + EP)/(ALFA*LANDA**2)-SINH(LANDA*e)*SINH(LANDA*(1-
     + EP))/(ALFA*LANDA**3*SINH(LANDA)))
      IF(EP.GT.e)THEN
      W=V
      ELSE
      W=U
      ENDIF
      WW=WW+W
C     CALCULATION OF BENDING MOMENTS
      LS=P*L/(1+ALFA)*((1-e)*EP-SINH(LANDA*(1-e))*(SINH
     + (LANDA*EP))/(LANDA*SINH(LANDA)))
      NS=P*L/(1+ALFA)*(e*(1-EP)-SINH(LANDA*e)*SINH
     + (LANDA*(1-EP))/(LANDA*SINH(LANDA)))
      LD1=P*L*ALFA1/(1+ALFA)*((1-e)*EP+SINH(LANDA*(1-e)
     + )*(SINH(LANDA*EP))/(ALFA*LANDA*SINH(LANDA)))
      ND1=P*L*ALFA1/(1+ALFA)*(e*(1-EP)+SINH(LANDA*e)*
     + (SINH(LANDA*(1-EP)))/(ALFA*LANDA*SINH(LANDA)))
      LD2=P*L*ALFA2/(1+ALFA)*((1-e)*EP+SINH(LANDA*(1-e)
     + )*(SINH(LANDA*EP))/(ALFA*LANDA*SINH(LANDA)))
      ND2=P*L*ALFA2/(1+ALFA)*(e*(1-EP)+SINH(LANDA*e)
     + *(SINH(LANDA*(1-EP)))/(ALFA*LANDA*SINH(LANDA)))
      LD=LD1+LD2
      ND=ND1+ND2
      IF(EP.GT.e)THEN
```

```
          MS=NS
          MD=ND
          MD1=ND1
          MD2=ND2
            ELSE
           MS=LS
          MD=LD
          MD1=LD1
          MD2=LD2
            END IF
          M=MS+MD
          MMS=MMS+MS
          MMD1=MMD1+MD1
          MMD2=MMD2+MD2
          MMD=MMD+MD
          MM=MM+M
C         CALCULATION OF SHEAR FORCES
          PS=P/(1+ALFA)*(1-e-SINH(LANDA*(1-e))*COSH(LANDA
     +    *EP/(SINH(LANDA)))
          RS=P/(1+ALFA)*(-e+SINH(LANDA*e)*COSH(LANDA*(1-
     +    EP))/(SINH(LANDA)))
          PD=P*ALFA/(1+ALFA)*(1-e+SINH(LANDA*(1-e))*COSH
     +    (LANDA*EP)/(ALFA*SINH(LANDA)))
          RD=P*ALFA/(1+ALFA)*(-e-SINH(LANDA*e)*COSH(LANDA
     +    *(1-EP))/(ALFA*SINH(LANDA)))
          IF(EP.GT.e)THEN
          QS=RS
          QD=RD
            ELSE
          QS=PS
          QD=PD
          END IF
          Q=QS+QD
          QQS=QQS+QS
          QQD=QQD+QD
          QQ=QQ+Q
    50    CONTINUE
          IF(IEP.EQ.26)THEN
          MMAX1=MMD1
          MMAX2=MMD2
          MMAXS=MMS
          ENDIF
          IF(ICASE.EQ.1) CALL STRESS (A1,A2,I1,I2,BR,D,MMD1
     +    ,MMD2,MMS,QQS)
          IF (ICASE.EQ.2)
     WRITE(6,1000)EP,WW,MMS,MMD,MM,QQS,QQD,QQ
    100   EP=EP+0.02
          CALL STRESS
     (A1,A2,I1,I2,BR,D,MMAX1,MMAX2,MMAXS,QQS)
          IF(ICASE.LT.0)GO TO 600
    500   CONTINUE
    600   STOP
```

```
1000 format(1x,f4.2,2X,f5.2,1x,3f11.2,3F9.2)
1001 FORMAT(8F12.3)
2000 FORMAT(//2X,'EP',4X,'WW',10X,'MMS',
     +9X,'MMD',6X,'MM',6X,'QQS',8X,'QQD',5X,'QQ')
     END
     SUBROUTINE STRESS (A1,A2,I1,I2,B,e,MD1,MD2,MS,qs)
     DOUBLE PRECISION I1,I2,MD1,MD2,MS,EP
     COMMON/A/ EP
     WRITE(6,'(//,''***** STRESS CALCULATION****'',/)')
     T1=A1/B
     T2=A2/B
     Sx1=(MD1*T1/2.0)/I1+MS/(E*A1)
     SX2=-(MD2*T2/2.0)/I2-MS/(E*A2)
     TS=QS/(B*E)
     WRITE(6,1000)SX1,SX2,TS
1000 FORMAT(5X,'STRESS IN THE TOP FACE',F20.5,/,5X,'
    + STRESS IN THE','BOTTOM FACE',F20.5,/,5X,'SHEAR
    + STRESS  IN CORE',F20.5)
1001 FORMAT(4F12.3)
     RETURN
     END
C SUBROUTINE TO CALCULATE G VALUE FROM THE DEFLECTION
FOR SANDWICH PANELS
C  WITH THIN FACES (EQUAL THICKNESS)
     SUBROUTINE SUBGC(L,E,B,H,T,GC)
     DOUBLE PRECISION L,E,IT,B,H,T,GC,P,DT,DS,DB,TC
     READ(5,*)
     READ(5,*)P,DT
     IT=2.0*(B*T**3/12.0)+2.0*(B*T*((H+T)/2.0)**2)
     DB=23.0*P*L**3/(648.0*E*IT)
     DS=DT-DB
     GC=P*L/(3.0*DS*B*(H+T))
     TC=P/(B*(H+T))
C      WRITE(6,100)GC,P,TC
100    FORMAT(1X,'SHEAR MODULUS OF THE CORE=',F6.2,'SHEAR
       STRESS AT',
     +'LOAD LEVEL ',F6.3,'IS',F10.5)
     RETURN
     END
```

EXAMPLE OF THE COMPUTER OUTPUT

ICASE= 2   **TEST NO.   1.0** (Failure Load)

L = 710.0000,   P1 = 3330.000,   P2 = 3330.000,

Z1 = 236.660,   Z2 = 473.330

EP	WW	MMS	MMD	MM	QQS	QQD	QQ
0.00	0.00	0.00	0.00	0.00	3078.74	251.31	3330.0
0.02	0.77	43704.35	3582.32	47286.67	3075.83	254.22	3330.0
0.04	1.53	87325.70	7247.63	94573.33	3067.02	263.03	3330.0
0.06	2.30	130778.59	11081.41	141860.00	3052.04	278.00	3330.05
0.08	3.05	173972.51	15174.16	189146.66	3030.46	299.59	*3330.05*
0.10	3.80	216809.22	19624.11	236433.33	3001.61	328.44	3330.05
0.12	4.54	259179.81	24540.18	283720.00	2964.64	365.40	3330.05
0.14	5.27	300961.47	30045.19	331006.66	2918.45	411.59	3330.05
0.16	5.99	342013.78	36279.55	378293.33	2861.66	468.38	3330.05
0.18	6.69	382174.55	43405.45	425579.99	2792.57	537.47	3330.05
0.20	7.37	421254.95	51611.71	472866.66	2709.12	620.93	3330.05
0.22	8.03	459033.91	61119.42	520153.33	2608.82	721.23	3330.05
0.24	8.66	495251.47	72188.52	567439.99	2488.66	841.39	3330.05
0.26	9.25	529601.07	85125.59	614726.66	2345.07	984.98	3330.05
0.28	9.81	561720.34	100292.98	662013.32	2173.75	1156.30	3330.05
0.30	10.32	591180.32	118119.67	709299.99	1969.59	1360.46	3330.05
0.32	10.78	617472.62	139114.04	756586.66	1726.49	1603.55	3330.05
0.34	11.18	640002.85	148086.27	788089.12	1442.63	-1442.58	0.05
0.36	11.50	658578.74	129511.05	788089.79	1180.18	-1180.14	0.05
0.38	11.77	673686.74	114403.72	788090.45	952.98	-952.94	0.05
0.40	11.99	685778.00	102313.12	788091.12	754.24	-754.19	0.05
0.42	12.16	695213.59	92878.20	788091.79	578.02	-577.97	0.05
0.44	12.29	702275.27	85817.18	788092.45	419.05	-419.01	0.05
0.46	12.38	707173.91	80919.21	788093.12	272.61	-272.56	0.05
0.48	12.44	710055.79	78038.00	788093.78	134.30	-134.25	0.05
0.50	12.45	711006.94	77087.51	788094.45	0.00	0.05	0.05
0.52	12.44	710055.74	78039.37	788095.12	-134.30	134.35	0.05
0.54	12.38	707173.79	80922.00	788095.78	-272.61	272.66	0.05
0.56	12.29	702274.98	85821.47	788096.45	-419.07	419.12	0.05
0.58	12.16	695213.01	92884.11	788097.11	-578.04	578.09	0.05
0.60	11.99	685776.95	102320.83	788097.78	-754.28	754.32	0.05
0.62	11.77	673685.00	114413.45	788098.45	-953.04	953.09	0.05
0.64	11.50	658576.03	129523.09	788099.11	-1180.26	1180.31	0.05
0.66	11.18	639998.80	148100.98	788099.78	-1442.74	1442.78	0.05
0.68	10.78	617467.02	139098.32	756565.34	-1726.59	-1603.36	-3329.95
0.70	10.32	591173.57	118106.44	709280.01	-1969.66	-1360.30	-3329.95
0.72	9.81	561712.84	100281.84	661994.68	-2173.79	-1156.16	-3329.95
0.74	9.25	529593.13	85116.21	614709.34	-2345.09	-984.86	-3329.95
0.76	8.66	495243.36	72180.64	567424.01	-2488.66	-841.29	-3329.95
0.78	8.03	459025.86	61112.82	520138.67	-2608.80	-721.15	-3329.95
0.80	7.37	421247.15	51606.19	472853.34	-2709.10	-620.86	-3329.95

```
0.82  6.69 382167.16   43400.85 425568.01 -2792.54 -537.41 -3329.95
0.84  5.99 342006.94   36275.74 378282.67 -2861.62 -468.33 -3329.95
0.86  5.27 300955.28   30042.06 330997.34 -2918.41 -411.55 -3329.95
0.88  4.54 259174.36   24537.65 283712.00 -2964.59 -365.36 -3329.95
0.90  3.80 216804.57   19622.10 236426.67 -3001.55 -328.40 -3329.95
0.92  3.05 173968.73   15172.61 189141.34 -3030.39 -299.56 -3329.95
0.94  2.30 130775.72   11080.28 141856.00 -3051.98 -277.97 -3329.95
0.96  1.53  87323.77    7246.90  94570.67 -3066.95 -263.00 -3329.95
0.98  0.77  43703.38    3581.96  47285.33 -3075.76 -254.19 -3329.95
1.00  0.00      0.00       0.00      0.00 -3078.67 -251.28 -3329.95
```

****** STRESS CALCULATION ******

STRESS IN THE TOP FACE   **19.25378**

STRESS IN THEBOTTOM FACE   **-19.24611**

SHEAR STRESS IN CORE   **-0.50590**

APPENDIX B
DETAILED TEST RESULTS FOR
DETERMINATION OF MATERIAL
PROPERTIES

Table b1 shear test results for the core in the tested beams[*].

core type	sample No.	shear modulus (N/mm^2)	average shear modulus (N/mm^2)	shear strength (N/mm^2)	average shear strength (N/mm^2)
Styrofoam	1	9.98		0.39	
	2	10.63		0.45	
	3	12.49	10.6	0.42	0.44
	4	10.60		0.55	
	5	9.28		0.41	
Expanded polystyrene	1	4.29		0.10	
	2	3.66		0.14	
	3	4.45	4.5	0.09	0.11
	4	4.58		0.12	
	5	5.43		0.08	

* The results have been obtained from a joined square test.

Table b2 compression test results for EXP. polystyrene.

Core type	Sample No.	Load N	Defl. mm	Stress N/mm^2	Strain N/mm^2	Comp. Mod. N/mm^2
Expanded Polystyrene	1	145	1.08	0.06	0.022	2.73
	2	149	1.03	0.06	0.022	2.73
	3	145	1.28	0.06	0.026	2.31
	4	158	1.18	0.06	0.024	2.5

Table b3 Flexural test results of Timber Baesd Facings.

Beam No.	Sample No.	Young's modulus (N/mm²) thin face[2]	thick face[2]	Average Young's modulus (N/mm²) thin face	thick face	Modulus of rupture (N/mm²) thin	thick	Average modulus of rupture (N/mm²) thin	thick
1-3	1	2763.9				22.47			
	2	2827.5		2795.7		21.96		22.35	
4-6		4500.0[1]				8.0[1]			
7-10	1	6019.09	2951.94			26.4	24.5		
	2	5915.70	3540.20			25.1	19.6		
	3	5875.80	3357.09	5930.94	3279.50	27.7	22.6	26.4	25.11
	4	5913.25	3268.80						
11-13	1	12020.90				43.20			
	2	15280.00				46.80			
	3	14551.58		14419.02		43.20		45.90	
	4	13952.80				49.68			
	5	16289.80				46.80			
14-15	1	6391.30				32.92			
	2	8271.10		7491.32		39.00		36.10	
	3	8271.10				36.40			

1 qouted values by the manufacturer.
2 beams No. 7-10 were manufactured with facings of different thickness.

APPENDIX C

TENSILE TEST RESULTS ON

TREATED PAPER STRIPS

Figure C1. Load Elongation Curve for Stiffened Telephone Directory Paper

Load (N)

Legend:
- — sodium silicate(S.S)
- ·+· S.S and ball clay
- —*— S.S and Latex
- ·□· Potassium silicate
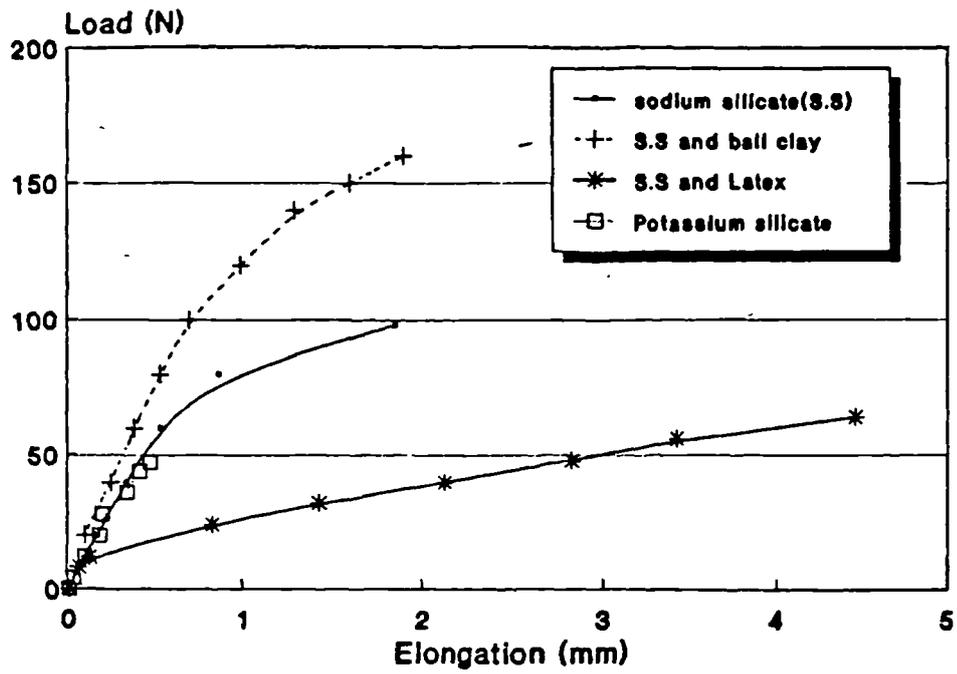
Elongation (mm)

Figure C2. Load Elongation Curve for Stiffened Kraft Paper

Load (N)

Legend:
- — sodium silicate(S.S)
- —+— S.S and ball clay

Elongation (mm)

300
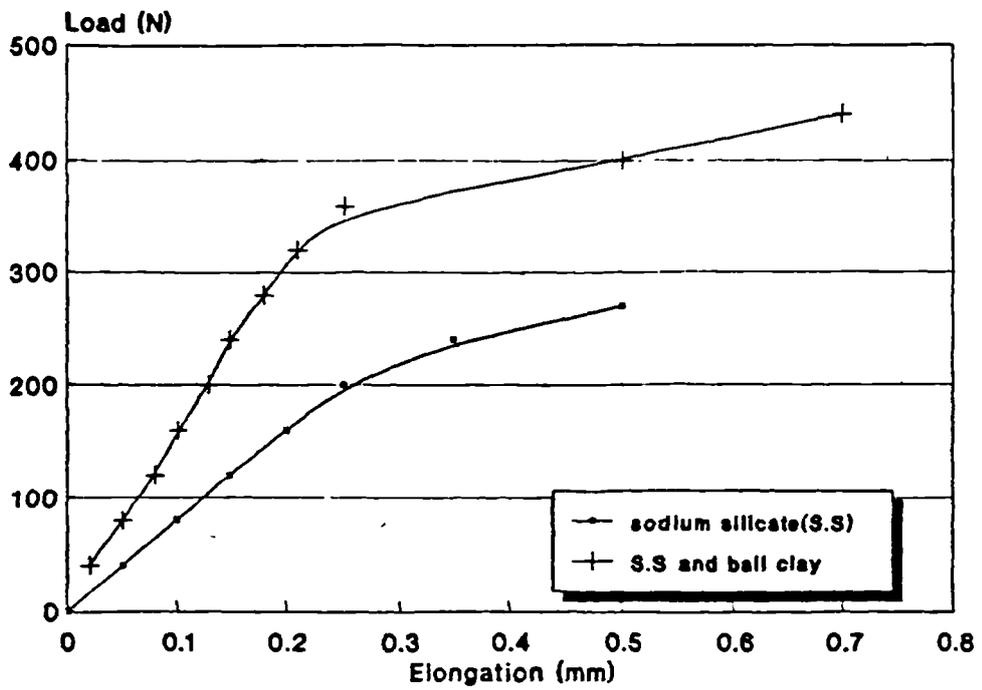
Table C1.   Paper Treated With Potassium Silicate

Test No.	Number of Dipping	Paper Grammag (g/m^2)	Strip Thickness (mm)	Elastic Modulus (N/mm^2)	Tensile Strength (N/mm^2)	Fail-ure Load
1p	once	112.9	0.1	2293.91	6.8	17
2p	once	105.5	0.11	2294.66	8.15	22.4
3p	once	116.0	0.09	2555.5	8.71	19.6
4p	once	130.7	0.11	2996.98	9.82	- 27.0
5p	once	110.9	0.13	2215.33	8.74	28.4
mean		115.2	0.11	2471.28	8.44	22.8
6p	twice	222.2	0.17	2027.64	7.95	33.8
7p	twice	259.2	0.16	2950.0	8.4	33.6
8p	twice	247.4	0.17	2128.87	7.15	30.4
9p	twice	244.9	0.17	1859.44		
mean		343.4	0.175	2241.49	7.83	32.6
10p	3 times	498.9	0.34	1661.65	5.46	5.46
11p	3 times	526.4	0.32	2149.45	5.79	46.3
12p	3 times	528.4	0.34	2368.63	6.17	52.4
mean		517.9	0.33	2059.91	5.81	48.4
13p	4 times	661.1	0.38	2386.0	4.63	44.0
14p	4 times	591.8	0.32	2797.72	5.45	43.6
15p	4 times	653.4	0.33	2693.55	6.545	54.0
16p	4 times	591.8	0.38	2268.56	4.56	46.4
mean		624.5	0.36	2536.46	5.31	47.0

Table C2. Paper Treated With Sodium Silicate

Tets No.	Number of dipping	Paper Grammag (g/m^2)	Strip Thickness (mm)	Elastic Modulus (N/mm^2)	Tensile Strength (N/mm^2)	Failure Load
1s	once	_	0.12	3840.0	6.27	18.8
2s	once	_	0.13	2186.91	4.49	14.6
3s	once	_	0.13	3590.78	8.86	28.8
4s	once	_	0.12	2845.42	8.2	24.6
5s	once	590.5	0.18	2650.77	13.11	59.0
6s	once		0.3	823.89	4.0	30.0
7s	once	609.5	0.21	1065.73	13.33	70.0
8s	once	590.5	0.3	1166.25	5.87	44.0
mean		590.5	0.28	2477.98	9.27	40.84
9s	3 times	1038.1	0.67	530.7	4.72	79.0
10s	3 times	1382.9	0.9	441.22	_	_
11s	3 times	1333.3	0.83	582.55	4.35	90.0
12s	3 times	1628.6	1.01	462.73	3.71	94.0
mean		1345.7	0.85	504.3	4.28	87.67
13s	4 times	1714.3	0.84	1319.24	5.14	70.8
14s	4 times	1798.1	0.93	822.99	4.22	98.0
15s	4 times	1800.0	0.89	788.59	4.58	102.0
16c	4 times	2000.0	0.95	829.13	3.71	88.0
mean		1828.1	0.9	939.98	4.39	99.0

Table c3. Paper Treated with Sodium Silicate and Glass Fiber

Test No.	Number of Dipping	paper Grammag (g/m^2)	Strip Thickness (mm)	Elastic Modulus (N/mm^2)	Tensile Strength (N/mm^2)	Fail-ure load
1sf	twice	1923.8	1.35	389.47	2.58	87
2sf	twice	1276.2	0.86	936.96	5.16	111
3sf	twice	1200.0	0.63	563.64	6.79	107
4sf	twice	1257.1	.0.74	820.30	4.92	91
mean	twice	1414.3	0.89	677.59	4.71	99

Table C4. Paper treated With Sodium Silicate and Vermiculite

Tets No.	Number of Dipping	Paper Grammeg (g/m^2)	Strip Thickness (mm)	Elastic Modulus (N/mm^2)	Tensile Strength (N/mm^2)	fali-ure Load
1sv	–	–	1.99	464.09	1.4	70.0
2sv	–	–	1.66	711.89	1.69	70.0
3sv	–	–	2.15	253.33	–	–
4sv	–	–	1.84	539.40	1.67	100.0
5sv	–	–	2.39	–	–	–
mean			1.83	571.79	1.59	80.0

Table C5. Paper Treated with sodium Silicate and Ball Clay with 2:1 Ratio

Test No.	Number of Dipping	Paper Grammage	Strip Thickness (mm)	Elastic Modulus N/mm2	Tensile Strength N/mm2	Failure Load (N)
1sb	once	1190.5	0.61	2720.0	6.29	96
2sb	once	1125.7	_	_	_	_
3sb	once	1430.5	0.64	2876.11	2.00	_
4sb	once	1321.9	0.75	1943.15	4.48	_
5sb	once	1121.9	0.57	2140.00	6.88	98
mean		1238.1	0.64	2419.82	6.59	97
6sb	twice	2245.7	1.07	1362.52	3.06	82
7sb	twice	2059.0	0.95	2513.84	7.72	184
8sb	twice	2281.9	_	_	_	_
9sb	twice	_	1.19	1097.74	4.30	128
10sb	twice	2476.2	1.27	1331.09	4.35	138
mean		2265.7	1.12	1576.29	4.86	133

Table C6. Paper Treated with Sodium Silicate and Ball Clay With 4:1 Ratio

Test No.	Number of Dipping	Paper grammage (g/m2)	Strip Thickness (mm)	Elastic Modulus N/mm2	Tensile Strength N/mm2	Faliure load (N)
11sb	once	1035.6	0.64	1155.25	3.06	_
12sb	once	1156.2	0.74	938.7	6.70	116
13sb	once	1137.1	0.76	882.36	9.47	130
14sb	once	805.7	0.53	1238.62	7.43	105
15sb	once	1165.7	0.67	1026.9	10.63	178
16sb	once	992.4	0.6	1201.55	9.47	142
mean		1048.8	0.66	1073.28	8.84	134
17sb	twice	2169.5	1.25	932.95	4.86	152
18sb	twice	2076.2	1.52	864.56	4.86	152
19sb	twice	1508.6	1.23	770.34	4.23	130
20sb	twice	2007.6	1.01	1317.39	6.26	158
21sb	twice	2011.4	1.21	937.00	4.49	136
mean		1954.7	1.24	964.45	4.94	1456
22sb	3 times	2887.6	1.70	575.73	3.62	154
23sb	4 times	2695.2	1.55	1084.06	4.59	128
24sb	4 times	2860.9	1.48	1410.07	3.62	134
25sb	4 times	-	1.87	_	3.34	156
26sb	4 times	3180.9	2.08	672.0	_	_
mean		2906.2	1.74	1023.29	3.94	138

Table C7. Paper Treated With Sodium Silicate and Ball Clay + Glass Fiber

Test No.	Number of Dipping	Paper geammage (g/m2)	Strip Thickness (mm)	Elastic Modulus N/mm2	Tensile Strength N/mm2	Failure Load
1sbf	twice	2800.0	1.51	1389.5	5.77	218
2sbf	twice	3158.1	1.59	1238.4	5.89	234
3sbf	twice	2613.3	1.62	2528.9	6.07	246
4sbf	twice	2958.1	1.38	1765.2	7.13	246
mean		2882.3	1.53	1728.0	6.22	236

Table C8 Paper Treated With Sodium Silicate and Latex With 1:1 Ratio

Test No.	Number of Dipping	paper Grammage (g/m2)	Strip Thickness (mm)	Modulus of Elastisity (N/mm2)	Tensile Strength N/mm2	Failure Load (N)
1sl	once	500.9	0.49	903.5	4.7	57.6
2sl	once	525.4	0.55	831.1	5.24	72.0
3sl	once	483.3	0.53	953.1	6.34	84.0
4sl	once	600.0	0.64	751.6	3.15	50.4
5sl	once	480.0	0.46	762.6	5.43	62.4
6sl	once	—	0.75	871.1	4.09	76.8
7sl	once	—	0.71	347.8	3.16	56.0
mean			0.59	774.4	4.59	65.0
8sl	twice	1264.0	1.17	482.49	3.89	114.0
9sl	twice	1207.9	1.16	640.4	4.59	106.0
10sl	twice	1140.3	1.16	—	—	—
11sl	twice	1107.5	1.13	—	—	—
mean		1179.9	1.16	561.4	3.79	110.0

Table C9 Paper Treated With Sodium Silicate and Latex With 2:1 Ratio

Test No.	Number of Dipping	paper Grammage (g/m2)	Strip Thickness (mm)	Modulus of Elastisity (N/mm2)	Tensile Strength (N/mm2)	Failure Load (N)
12sl	once	580.3	0.45	1265.15	5.62	63
13sl	once	698.0	0.46	1667.19	5.77	66
14sl	once	623.7	0.45	1947.56	6.76	76
15sl	once	623.2	0.47	1443.4	6.06	71
mean		631.3	0.46	1580.80	6.05	69
16sl	twice	1308.7	1.33	654.99	2.50	83
17sl	twice	1290.7	1.12	921.18	3.33	93
18sl	twice	1080.6	0.98	1170.28	3.64	89
19sl	twice	1218.6	1.11	813.49	3.01	84
20sl	twice	1218.6	1.12	858.02	3.46	96
mean		1223.4	1.13	883.59	3.19	89
21sl	3 times	1801.0	1.51	401.81	2.33	88
22sl	3 times	1522.3	1.41	476.22	_	-
23sl	3 times	1595.9	1.62	474.36	3.36	106
24sl	3 times	1647.7	1.48	507.20	2.24	83
mean		1641.7	1.51	464.89	2.61	102

APPENDIX   D
TYPICAL   CALCULATION   OF
HONEYCOMB   CORE   SHEAR   MODULUS

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Calcualtion of Honeycomb Core Shear Modulus

The shear modulus of the developed honeycomb core were obtained by means of flexural tests under four point loading as discribed in section 3.3.2.1. the test arrangment and the method of applying the load are shown in figure 5.4 in the chapter 5.

Deformations of the beam tested were measured at the center and at the points were the beam rested on the support. The deformation of the beam had two components, shear and bending. By measuring thr total deformation and subtracting, the bending component, the shear deformation may obtained, and the shear modulus was calculated using the following formula:

$$d_b = \frac{23 \ P.L^3}{648 \ E.I}$$

$$d_s = d_t - d_b$$

$$G_c = \frac{P. \ L}{3 \ d_s.b(h+t)}$$

where

L = beam span	(mm)
d_b= deflection due to bending	(mm)
E = elastic modulus of the face	(N/mm^2)
I = moment of inertia of the sandwich	(mm^4)
d_s= deflection due to shear	(mm)

d_t= total deflection (mm)

b = width of the beam (mm)

t = thickness of the faces (mm)

h = thickness of the core (mm)

p = point load (N)

G_c= core shear modulus (N/mm^2)

EXAMPLE

Test NO. 2

span of the beam	L = 600.0	mm
elastic modulus of the facings	E = 203x10^3	N/mm^2
thickness of the facings	t = 0.52	mm
width of the beam	b = 100	mm
thicknees of the core	h = 25	mm
point load from the load deflection graph (see fig.D1)	$P = \dfrac{66}{2}$	N
deflection corresponding to load P	d_t= 0.34	mm

(1) calculation of moment of inertia of the sandwich

$$I_s = 2 \times \frac{b.t^3}{12} + 2(b.t)\left[\frac{h+t}{2}\right]^2$$

$$I_s = 2 \times \frac{100 \times 0.51^3}{12} + 2(100 \times 0.52)\left[\frac{25 + 0.52}{2}\right]^2$$

$$I_s = 16935.37 \quad (mm^4)$$

(2) calculating_deflection due to bending

$$d_b = \frac{23 \times 33 \times 600^3}{648 \times 203000 \times 16935.37}$$

$$d_b = 0.0736 \quad (mm)$$

(3) calculating deflection due to shear

(4) calculating the core shear modulus

$$G_C = \frac{33 \times 600}{3 \times 0.2664 \times 100(25 + 0.52)}$$
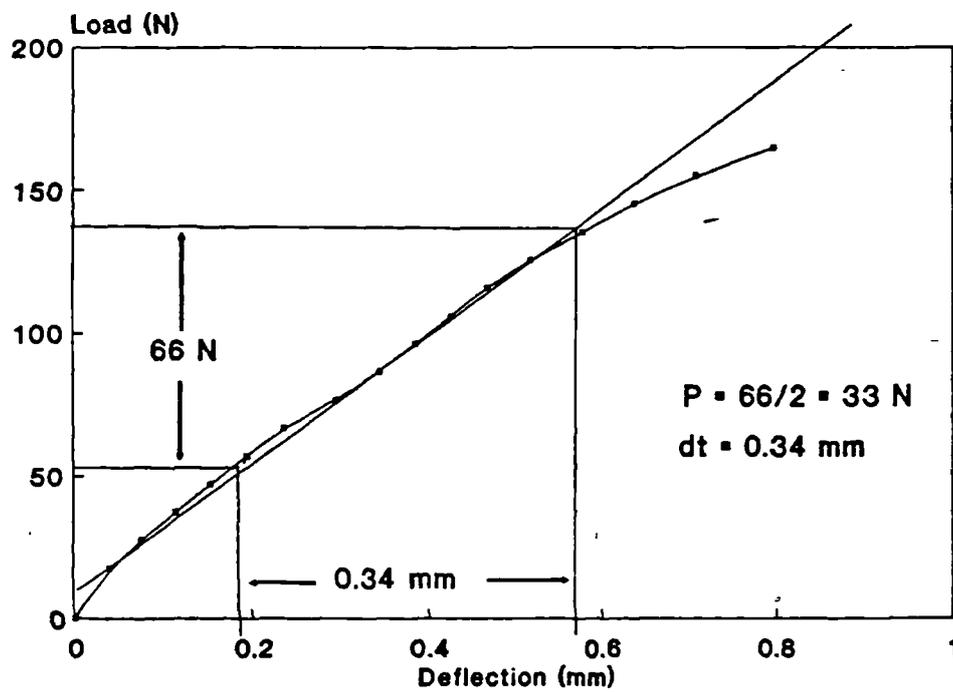
$$G_C = 9.83 \quad N/mm^2$$

Figure D1
Load Deflection curve for Test No. 2

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