EXPERIMENTAL INVESTIGATION OF GLULAM BEAM FABRICATED FROM HDHMR ENGINEERED WOOD

THESIS REPORT

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DEPARTMENT OF CIVIL ENGINEERING
T K M COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

Certified that this report entitled ***“*EXPERIMENTAL INVESTIGATION OF GLULAM BEAM FABRICATED FROM HDHMR ENGINEERED WOOD*”*** is the report of thesis presented by **BINEESH B S, TKM21CESC08** during **2022-2023** in fulfilment of the requirements for the award of the Degree of Master of Technology in Structural Engineering and Construction Management of the APJ Abdul Kalam Technological University.

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DECLARATION

I undersigned hereby declare that the project report, "**EXPERIMENTAL INVESTIGATION OF GLULAM BEAM FABRICATED FROM HDHMR ENGINEERED WOOD**", submitted for the fulfilment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of Mohammed Thowsif, Professor, Department of Civil Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Place: Kollam Bineesh B S
Date: 12-07-2023

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ABSTRACT

The commonly used construction material like cement concrete highly contribute to the global CO_2 emission. The use of timber can reduce these emissions considerably. In recent years, wooden structures have become attractive and popular because of their excellent characteristics. The drawbacks due to the heterogeneous properties of ordinary timber can be solved with the help of manufactured wood product like engineered wood. In this study one such engineered wood named HDHMR (High Density High Moist Resistant) fibre board is used to fabricate a glue-laminated beam. Different configurations of lamination based on the number of layers and adhesive used for bonding are used for fabrication of beam. The characteristics from experimental investigation of this beam specimens are studied and compared.

Keywords: *Engineered wood, glue-laminated beam, flexural strength, polyurethane adhesive*

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LIST OF ABREVIATION

TP	Ten number of layers bonded using polyurethane adhesive
TS	Ten number of layers bonded using instant bond synthetic adhesive
FP	Five number of layers bonded using polyurethane adhesive
FS	Five number of layers bonded using instant bond synthetic adhesive

CHAPTER 1

INTRODUCTION

1.1 General

The wood which is fit for engineering constructions is called timber. The application of wooden structures has a thousand-year history. Many wooden structures, such as palaces, dwellings, and temples, which were built in different historical periods are found around the world. The urban world population surpassed the rural population, more than 70% of all world greenhouse gases (GHG) emissions are produced by cities. Urbanization should increase the chances for sustainable development. Cement concrete, commonly used material, highly contribute to the global CO_2 emission. Timber buildings are a feasible building solution for reducing CO_2 emissions. In recent years, wooden structures have become attractive and popular because of their excellent characteristics, such as being lightweight, comfortable, and environmentally friendly. Although wooden structures are important building forms, timber has natural defects, such as fine cracks, knots, and cross grain that affect the strength. This heterogeneous property of timber made it difficult for understanding the failure behaviour and other mechanical properties. To reduce the drawbacks of ordinary timber, engineered wood is manufactured. Engineered wood is a wood product manufactured by binding strand, particles or fibres of wood. It is a more efficient way of using wood. Engineered wood has enhanced strength and stiffness properties than ordinary timber. One another way of using timber effectively in construction is by using effective strengthening techniques like reinforcements etc.

1.2 Engineered Wood

Engineered wood is a wood product manufactured by binding strand, particles or fibres of wood. It is a more efficient way of using wood. Since it is man-made it can be designed to meet application-specific performance requirement. Engineered wood has enhanced strength and stiffness properties than ordinary timber. It has also reduced the drawbacks of ordinary timber. The different types of engineered wood are:

(i) Plywood
(ii) Oriented strand board (OSB)

(iii) Fiber board
(iv) Particle board
(v) Laminated veneer lumber (LVL)
(vi) Cross-laminated timber (CLT)
(vii) Glue-laminated timber (Glulam)
(viii) Densified wood
(ix) Thermally efficient wood
(x) Transparent wood composites

1.3 HDHMR Fibre Board

HDHMR (High Density High Moist-Resistant) fibre board is a type of engineered wood product manufactured by compressing wood fibres, to increase density, using mechanical press. This timber product is very homogeneous with no grains which makes it a better alternative for ordinary timber. HDHMR panels can be laminated and used for the construction of building members. The use of it can considerably reduce the overall weight of the structure.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Gentile et al., (2002) experimentally studied the flexural behavior of creosote treated sawn Douglas fir timber beams strengthened with glass fiber-reinforced polymer (GFRP) bars. The specimen consists of twenty-two half-scale, four full-scale timber beams strengthened with GFRP and additional unreinforced timber beams as control specimens. The results showed that the proposed experimental technique changed the failure mode from brittle tension to compression failure and an increase in flexural strength. It was found that GFRP reinforcement arrests crack opening, confines local rupture, and bridges local defects in the adjacent timber. And the use of near-surface GFRP bars overcomes the effect of local defects in the timber

Ottenhaus et al., (2018) experimentally studied the behavior of large scale dowelled connections in CLT and a CLT-LVL hybrid material subjected to monotonic and cyclic loading. Two different connection layouts and two different panel layups were considered in the testing. The testing observation concluded that it is advisable to use bolts or threaded dowels with nuts and washers in the end row of a connection to prevent unfavourable delamination of the outer layers.

Tuhkanen et al., (2018) experimentally investigated and discussed the influence of the number and thickness of the lamellas on strength in glued laminated timber (GLT) and cross-laminated timber (CLT). In order to determine the influence of the number of layers, three series of GLT and CLT with a thickness of 100 mm were prepared. The results showed that the strength in CLT is increased by the locking effect of thinner crossed layers.

Gribanov et al., (2019) did an experimental confirmation of the assumptions and suppositions taken as theoretical regarding the complex stress-strain state that occurs in composite wooden structures based on wood and reinforcing materials. The load-strain relation and relative deformation diagrams in the cross section of wood-composite beam specimens are studied. It was concluded that the destruction of the beam structures is plastic in nature and occurs across the standard cross-section in the middle of the span. An increase in strength and decrease in the structure’s deformability in proportion to the modification coefficient was observed

Liu et al., (2020) investigated the behavior of timber beam reinforced with polymer strip. Three lengths of basalt fibre reinforced polymer (BFRP) strips were used to strengthen timber beams made from poplar. Three different strengthening configurations depending on the length of BFRP strip bonded to the beam was developed to observe the failure modes of the control and strengthened specimens, flexural behaviour, ultimate strength, and the relationship of load and defection. It was observed that the unstrengthen beams eventually underwent brittle failure at the ultimate state owing to excessive defection. And full-length BFRP strip bonded to timber beam can effectively and considerably improve flexural performance. The results indicated that the compressive yield point of the wood was substantially lower than the tensile yield point

H. Song et al., (2021) developed Hybrid CLT using Construction oriented strand board (COSB) and spruce-pine-fir (SPF) for the study. The regular SPF CLT and HCLT specimens having different lay-ups and numbers of layers were subjected to low-cycle fatigue bending and shear loading tests. The specimens consist of three-layer CLT and five-layer CLT panels fabricated with the dimensions of the three- and five-layer CLT or HCLT panels as 2440 mm × 1220 mm × 72 mm and 1220 mm × 610 mm × 120 mm, respectively. It was concluded that HCLT showed better bending and shear than regular CLT. The five-layer CLT and HCLT specimens had better fatigue lives than the three-layer specimens. Long-term bending and shear properties significantly improved by using COSB only as transverse layers in CLT. It was also found that due to the rolling shear failure the cracks may extended to the longitudinal layer causing bonding line delamination. So, effective bonding in lamination should be ensured.

Amoruso and Schuetze (2022) developed three sustainable renovation systems for three common building types in the Republic of Korea: residential high-rise (cross-laminated timber system), multi-use (glue-laminated and timber frame system), and residential low-rise (steel and timber frame system) as an alternative to demolishment and construction of new buildings. They also ensured a modular approach using prefabricated assembly.

Jurkiewiez et al., (2022) experimentally analysed the bending behaviour of different configurations of steel-timber hybrid beams. Each component was tested separately to find the material properties and then it was connected and tested up to failure. The observed behaviour shows a limited effect of hybridation in the elastic domain. However, the effect is significant at the ultimate stage. It was concluded the combination of timber and steel elements improves the resistance to lateral torsional buckling and local buckling of the steel beam

Karki et al., (2022) experimentally investigated the load-slip behaviour of connections between CFS and plywood panels constructed with self-drilling screws, coach screws, and nut and bolt. The influence of structural adhesives at the shear interface alongside fasteners was also investigated. The stiffness, ductility and load-carrying capacity of the eight different types of connections were evaluated through a series of push-out tests. It was concluded that nut and bolt connections were demonstrated to be the best choice amongst the shear connectors, followed by self-drilling screws; however, the size of the nuts and bolts should be determined based on the crushing strength of the timber itself. Composite connections with fasteners along with adhesives demonstrated higher stiffness and load-capacity than the fastener alone.

Wang et al., (2022) studied the edgewise bending strength and stiffness of birch plywood. The specimens consist of varying depth, span, face grain angle and moisture content. The specimens from all test series exhibited non-linear load–displacement behaviours before reaching the maximum force, which indicates that yielding in compression occurred prior to the final failure in tension at mid-span. When it comes to the failure mode, all the beams eventually failed in tension.

2.2 Gaps Identified

From the literature survey the following gaps were identified

- Studies are conducted using different engineered wood products but not using HDHMR wood
- Structural stability of HDHMR engineered wood is not studied

2.3 Objectives

- To investigate the ultimate load, load-deflection behaviour and failure characteristics of glue-laminated beam fabricated from HDHMR engineered wood
- To study and compare the beams with varying number of layers glued using commonly used instant bond adhesive and polyurethane adhesive

2.4 Scope

- Study based on experimental analysis of beam fabricated from engineered wood
- Glue-laminated beams with different configuration
- Geometric parameters are kept constant
- To study the load-deflection characteristics of engineered wood as beam
- Long term deflection is not considered in this study
- Durability of the specimen is not considered in this study

CHAPTER 3

METHODOLOGY

3.1 General

This chapter outlines the experimental plan and the materials used to fabricate glulam beam using HDHMR engineered wood. The general outline of the methodology is shown in Figure 3.1.

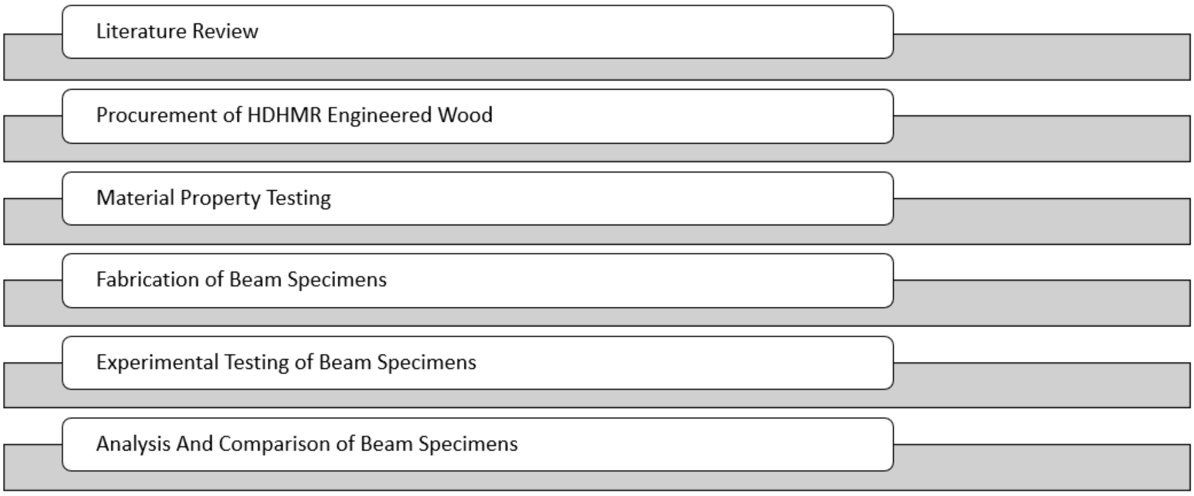

Figure 3.1: General outline of methodology

An extensive literature review is done based on the need and application of engineered wood. Suitable materials are identified and they are procured. Then tests are conducted to find and validate the material properties according to the available standard codes. Then suitable dimensions for the samples are selected. After fixing the dimensions, the HDHMR wood board is cut and laminated using adhesives. An experimental setup is prepared and the specimens are tested. By observing the performance, deflection and failure properties results are compared and conclusion is made.

3.2 Procurement of Materials

The different materials procured are:

- HDHMR engineered wood of 18mm and 9mm thickness
- Polyurethane adhesive
- Commonly used instant bond synthetic adhesive

3.3 Testing of Materials

The different tests done for the material properties are:

- Test for Density of fibre boards as per IS 1658:2006
- Test for Moisture Content of fibre boards as per IS 1658:2006
- Test for Water Absorption of fibre boards as per IS 1658:2006
- Test for Swelling in Thickness After Immersion in Water of fibre boards as per IS 1658:2006
- Modulus of Elasticity and Modulus of Rupture of fibre board as per IS1658:2006
- Test for Tension Parallel to Surface of fibre board as per ASTM D 1037-06a

3.4 Specimen Details

The typical layout and cross-section of glue laminated beam specimen from engineered wood is shown in Figure 3.2.

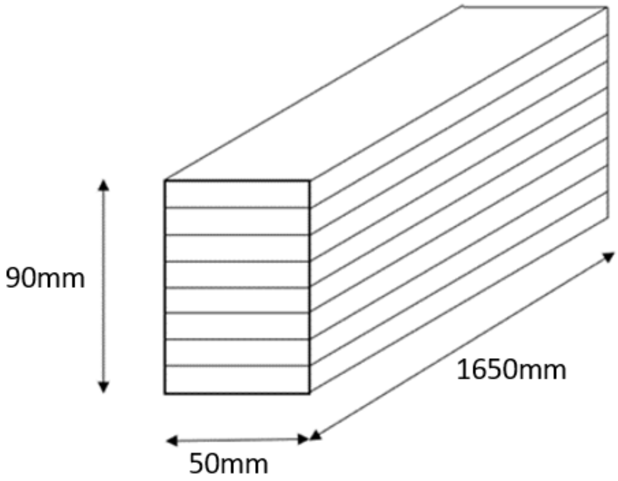

Figure 3.2: Typical layout and cross-section of specimen

The final specimens are required to have a fixed dimension of 1680mm length, 50mm width and 90mm depth. For this, ten number of layers of 9mm thick fibre boards and five number of layers of 18mm thick fibre boards of 1680mm length and 50mm width are laminated using polyurethane based resin adhesive and commonly available synthetic adhesive. Thus, making the specimens differ in number of layers and adhesive used for bonding. The Figure 3.3 shows the cross-section of four different specimen arrangements.

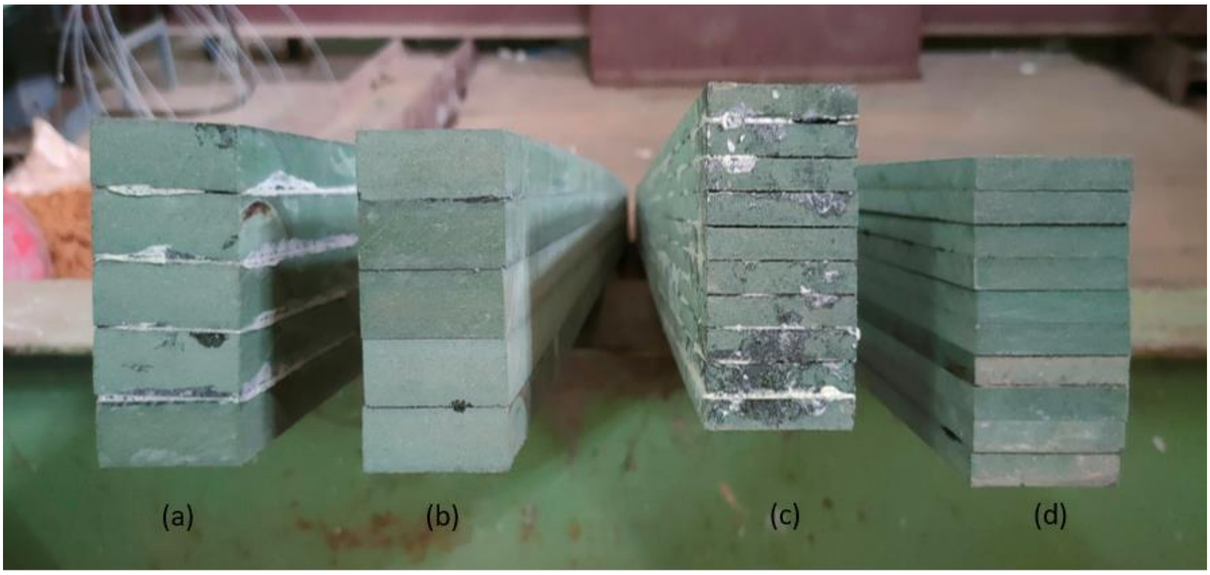

Figure 3.3: Cross-section of (a) 5 layers of fibre board bonded using polyurethane adhesive
(b) 5 layers of fibre board bonded using instant bond synthetic adhesive
(c) 10 layers of fibre board bonded using polyurethane adhesive
(d) 10 layers of fibre board bonded using instant bond synthetic adhesive

3.4 Testing of Specimen

The rectangular beam specimens of glue laminated HDHMR engineered wood will be subjected to a two-point loading test in a 200KN loading frame. This testing setup allow for the study of the behaviour of the engineered fibre board under applied loads. The test setup is shown in Figure

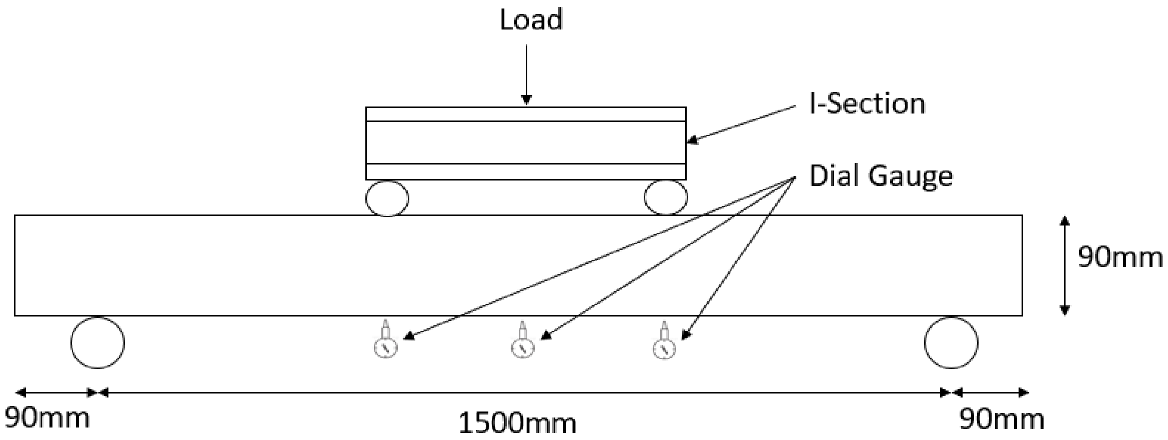

Figure 3.4: Typical representation of Test Setup

During the two-point load test, the beam will be supported at two points and load will be applied near the mid-span of the beam. The load applied on the beam will be measured using a load cell and the deflection of the beam will be measured using dial gauges. These measurements will be used to plot the load-deflection curve, which helps in understanding the structural response and deformation characteristics of the beam under load.

CHAPTER 4

EXPERIMENTAL INVESTIGATION

4.1 General

The HDHMR fibre board is cut into specific dimensions for specific tests. Firstly, material property tests are conducted and then the beam specimens are fabricated to undergo flexural strength testing. The structural responses are analysed to find the effectiveness of using HDHMR engineered wood as a structural member.

4.2 Experimental Test for Material Properties

The following are the material property tests done on HDHMR fibre board.

4.2.1 Test for Density of fibre board

As per IS 1658:2006, for measurement of density of fibre board, three square test specimens of size 100mm is to be cut from the test panel. The edges of the test specimen should be smoothened with sand paper. The length and width of each test specimen is measured to an accuracy of ±1 mm. The thickness of test specimen is measured to an accuracy of 0.05mm. Four readings are to be taken approximately 20mm inside the edges of the test panel, at the centre of each edge. The mean reading is taken as the thickness of the specimen. After that each specimen is weighed to an accuracy of 0.01g. Then the density of the test specimen can be calculated from the following formula:

$$\text{Density} = \frac{\text{Mass of the test specimen,g} \times 10^6}{Le\text{ngth,mm} \times \text{Width,mm} \times \text{Mean thickness,mm}} \ \text{kg/m}^3$$

The average density of each of the specimens shall meet the requirements specified in Table 2 of the code.

4.2.2 Test for Moisture Content of fibre board

As per IS 1658:2006, for determination of moisture content three square test specimens of size 100mm is to be cut from the test panel. Each specimen is weighted to an accuracy of not less than 0.01g. After that the specimen is to be dried in an oven at a temperature of 103±2°C until the mass is constant. Then the moisture content expressed as percentage of oven dry mass can be calculated using the following formula:

$$\text{Moisture content} = \frac{\text{Initial mass} - \text{Oven dry mass}}{\text{Oven dry mass}} \text{ x } 100$$

The average moisture content of the specimens shall meet the requirements specified in Table 2 of the code.

4.2.3 Testing for Water Absorption of fibre board

As per IS 1658:2006, for determination of water absorption three square test specimens of size 100± 1 mm shall be cut from the test panel. The edges of the test specimen are smoothened with sand paper, but not sealed. Each specimen is weighted to an accuracy of not less than 0.01g. Then the specimen is to be submerged horizontally under 25mm fresh clean water for a period od 24hrs. After the period the test specimens is taken out and excess water is wiped off with damped cloth. Then each specimen is reweighed to an accuracy of 0.01g. The water absorption of a test specimen in percentage is calculated using the following formula:

$$\text{Water Absorption} = \frac{\text{Mass after immersion} - \text{Mass before immersion}}{\text{Mass before immersion}} \text{ x } 100$$

The water absorption of each specimen shall meet the requirements specified in Table 2 of the code.

4.2.4 Test for Swelling in Thickness after immersion in water

As per IS 1658:2006, for determination of swelling in thickness after immersion in water, three square test specimens of size 50mm is to be cut from the test panel. The edges of the test specimens are smoothened with sand paper. The thickness at the edge of each test specimen is measured to an accuracy of 0.05 mm at two places along each edge. The points at which the thickness is measured are carefully and indelibly marked. Then the test specimens are immersed in fresh clean water. The top surface of the test pieces should be under 25±5 mm of water throughout the test. After a period of 24 hrs each test specimen is withdrawn from the water, wiped off with damp cloth and allowed to stand at normal room condition for 1 hr. Then the thickness of each test specimen is measured at the same points marked earlier. The swelling in thickness of each specimen expressed as percentage of original thickness is calculated according to the following formula:

$$\text{Swelling in thickness} = \frac{\text{Thickness after immersion} - \text{Thickness before immersion}}{\text{Thickness before immersion}} \text{ x } 100$$

The mean swelling in thickness of the test specimens shall not exceed the value give in Table 2 of the code.

4.2.5 Test for Modulus of Elasticity and Modulus of Rupture

As per IS 1658:2006, for determination of modulus of elasticity and modulus of rupture, rectangular specimens are to be cut. The length of the specimen is to be 20t± 50 mm (where t is the nominal thickness of the test panel) subject to a maximum length of 1050 mm and at minimum length of 100 mm. The width of the specimen is to be 75 ± 1 mm. The thickness is the full thickness of the board. The length and width of each test specimen is measured to an accuracy of ±1mm. The thickness of each specimen is measured to an accuracy of 0.05mm. Span for each test is 20 times the nominal thickness. The supports are to be such that the specimens are not crushed during test. The test piece is placed on the supports with its longitudinal axis at right angle to that of the supports with the centre point under the load. Deflection is measured in the middle of the test piece.

The modulus of elasticity E_m, in N/mm^2 of each test pieces is calculated using the following formula:

$$E_m = \frac{L^3\ (F_2 - F_1)}{4\ bt^3\ (a_2 \text{ x } a_1)}$$

where,

L = distance between the centres of the supports, in mm;
b = width of the test piece, in mm;
t = thickness of the test piece, in mm;
$F_2 - F_1$ = increment of load on the straight-line part of the load deflection curve, in Newtons; and
a_2 x a_1 = increment deflection at the mid length of the test piece (corresponding to $F_2 - F_1$).

The modulus of rupture F_m, in N/mm^2 of each test piece is calculated using the following formula:

$$F_m = \frac{3\ F_{Max}\ L}{2\ bt^2}$$

where,

F_{Max} = maximum load, in Newtons; and
$L, b\ and\ t$ = length, width and thickness of each specimen, in mm.

The Figure 4.1, shows the experimental setup, for finding the modulus of elasticity and modulus of rupture, in a Universal Testing Machine.

Figure 4.1: Test for modulus of elasticity and rupture

4.2.6 Test for Tension Parallel to Surface of fibre board

The tension test parallel to the surface is made to determine the tensile strength in the plane of the panel. The axial stiffness or modulus of elasticity can be determined. As per ASTM D 1037-06a, the test specimen is prepared as shown in Figure 4.2.

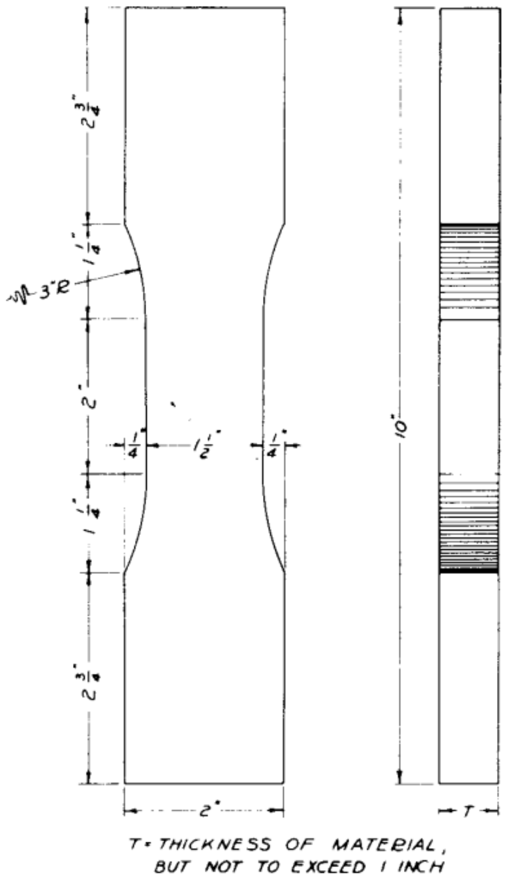

Figure 4.2: Detail of Specimen for Tension Test Parallel to Surface

The minimum width of each specimen at the reduced section is measured to an accuracy of ±3 %. The corresponding thickness is measured to an accuracy of 0.025 mm. The specimen is loaded using self-aligning, self-tightening grips that distribute the force evenly over the grip surface and do not allow slipping, with gripping surfaces at least 50-mm square, to transmit the load from the testing machine to the specimen. Then the load-deformation curve is obtained. The maximum tensile stress and modulus of elasticity is calculated for each specimen using with the following formula:

$$R_t = \frac{P_{max}}{bd}$$

$$E_t = \frac{I_g}{bd}\frac{\Delta P}{\Delta y}$$

where,

b =width of the reduced cross-section of the specimen measured in dry condition, mm,

d =thickness of the specimen measured in dry condition, mm,

E_t =modulus of elasticity in tension parallel to the surface of the panel, MPa,

I_g =gage length or distance between the gage points of extensometer, mm,

$\frac{\Delta P}{\Delta y}$ =slope of the straight-line portion of the load-deformation curve, N/mm,

P_{max} =maximum load, N, and

R_t =maximum tensile stress, MPa.

The Figure 4.3, shows the test specimen shaped according to the specification and the test specimen after undergoing the test.

Figure 4.3: Specimen before tension test and specimen after tension test

4.3 Experimental Setup for Flexural Testing of beam

The glue-laminated HDHMR engineered wood beam specimens are subjected to two-point loading in which the beams are simply supported over a fixer roller support. Steel rollers of 40mm diameter are used as the support. For the test, the position of support, load point, and midpoint are were marked on the beam specimens. The marking is in such a way that the span of the beam is limited to 1500mm thereby giving a clearance of 90mm on both sides. The beam was placed on the supports in the loading frame by following the marked positions. A hydraulic jack with a capacity of 200KN was used for loading the beam. The jack was fixed to the loading frame and the supports of the beam are aligned so that the centre of the jack coincides precisely with the midpoint of the beam specimen. A load cell is placed between the jack and the beam for maintaining loading rate.

For achieving two-point loading configuration, two rollers were used. The two rollers were kept at a distance of 250mm from the midpoint of the beam and with the help of an I-section as the spreader beam, load was transferred from the jack to the rollers. To measure the deflection at each load increment, three dial gauges where placed at two loading points and at the midpoint. The experimental setup including the arrangement of the beam, the supports, the hydraulic jack, the spreader beam, load cell and dial gauge is shown in Figure 4.4.

Figure 4.4: Experimental setup for beam testing

CHAPTER 5

RESULT AND DISCUSSION

5.1 General

The tests were conducted according to the procedures described in the previous chapter. The results and discussions are presented in this chapter.

5.2 Test Results of Material Properties

The tests on density, moisture content, water absorption, swelling in thickness after immersion in water, modulus of elasticity, modulus of rupture and tension parallel to the surface of the HDHMR fibre board is carried out and the results are as follows:

5.2.1 Density of the fibre board

The arithmetic mean of the densities of all the specimens is found to be 831.43 kg/m^3. As per IS specification, density between 350-800 kg/m^3 comes under medium hardboard and 800-1025 kg/m^3 comes under standard hardboard. Thus, the HDHMR engineered wood comes under the category of standard hardboards.

5.2.2 Moisture content of fibre board

The arithmetic mean of moisture contents of all the specimens is found to be 11.3%. As per IS specifications, the moisture content of standard hardboard must be between 5-15%. Thus, the HDHMR engineered wood satisfies the percentage of moisture content.

5.2.3 Water absorption of fibre board

The average water absorption of the test specimens after 24 hr immersion was found to be 17.84%. As per IS specification, the maximum allowable percentage of water absorption after 24 hr immersion for standard hardboard is 20%. Thus, the HDHMR engineered wood satisfies the percentage of water absorption.

5.2.4 Swelling in thickness of fibre board

The arithmetic mean of the results of all the specimens after 24hr immersion was found to be 10.80%. As per IS specification, the maximum allowable percentage of swelling in thickness after 24 hr immersion for standard hardboard is 25%. Thus, the HDHMR engineered wood satisfies the percentage of swelling in thickness after immersion in water.

5.2.5 Modulus of elasticity of the fibre board

The modulus of elasticity of the test specimen was found to be 2793.63 N/mm^2. As per IS specification, the minimum value of modulus of elasticity for standard hardboard must be 2700N/mm^2.

5.2.6 Modulus of rupture of the fibre board

The modulus of rupture of the test specimen was found to be 38.24 N/mm^2. As per IS specification, the minimum value of modulus of rupture for standard hardboard must be 27N/mm^2.

5.2.7 Tension parallel to the surface of the fibre board

The load-deflection curve of the test specimen from Universal Testing Machine is shown in Figure 5.1.

Figure 5.1: Load-deflection curve of the test specimen

By using the load deflection curve, the maximum tensile stress of the test specimen was calculated to be 20.394 N/mm^2. And the modulus of elasticity was calculated to be 0.164 N/mm^2.

5.2.8 Summary of test results

From the tests conducted on material properties, it was concluded that the HDHMR fibre board comes under the category of standard hardboards. It was also found out that the HDHMR fibre board satisfies the minimum requirements of moisture content, water absorption, swelling in thickness, modulus of elasticity and modulus of rupture. In addition to that, the results from the tension test parallel to the surface have helped in finding the maximum tensile stress.

5.3 Test Results of Beam Specimen

The flexural behaviour of glue-laminated HDHMR engineered wood beam was investigated. Static loading was induced throughout the experiment where the specimens were subjected to two-point loading. Deflection was measured at the centre and at the loading points. Observations from the experiment is used to plot load-deflection graphs for understanding the structural response.

5.3.1 Load-deflection characteristics

Using the recorded deflection values obtained at the mid span and loading points, load-deflection graphs were plotted for the four different lamination configurations. These graphs represent the relation between applied load and resulting deflection, thereby showing the beam’s response to bending forces.

The Figure 5.2 shows the load-deflection curve of the beam specimen having ten number of layers laminated using polyurethane adhesive.

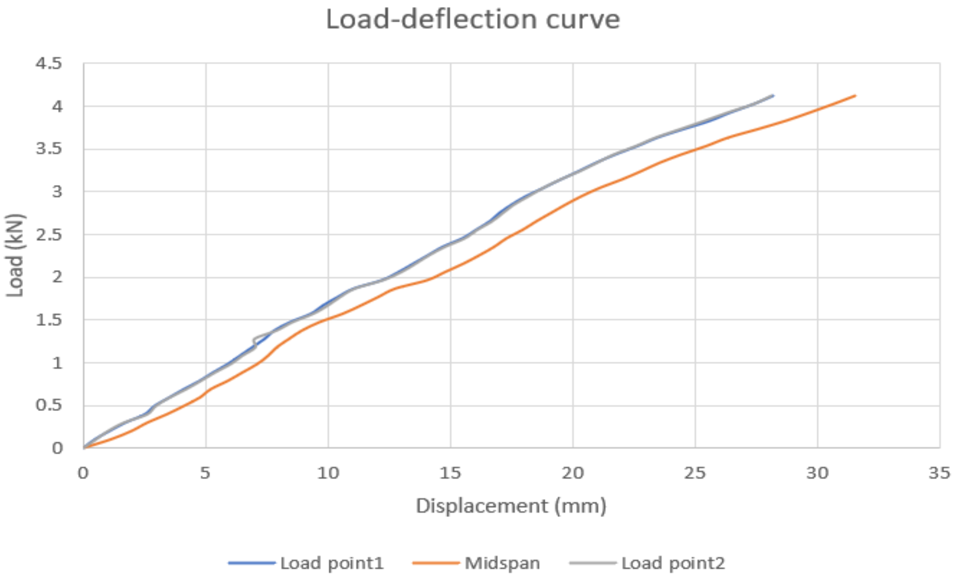

Figure 5.2: Load-deflection curve of TP

The Figure 5.3 shows the load-deflection curve of the beam specimen having ten number of layers laminated using instant bond synthetic adhesive.

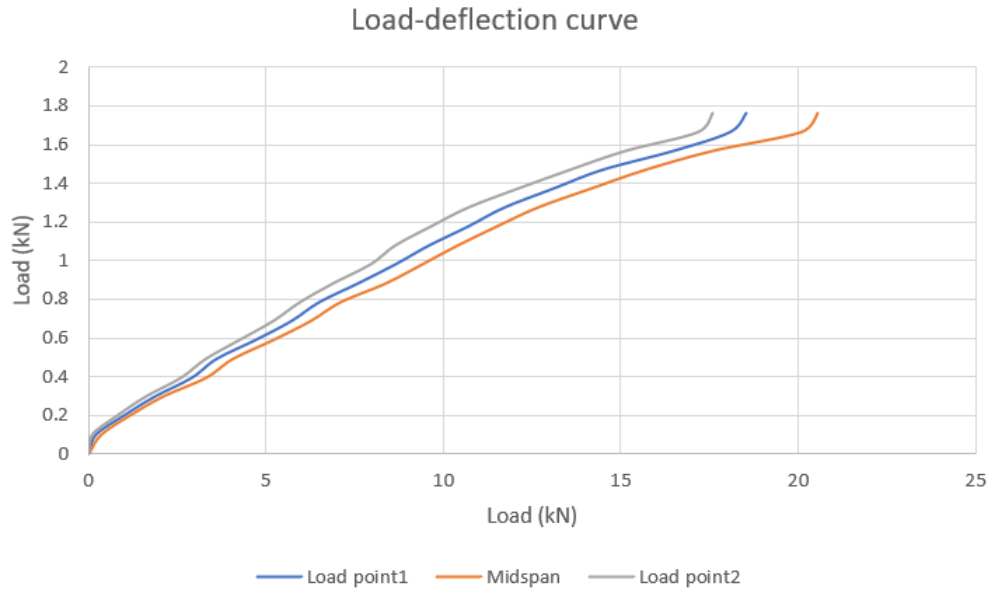

Figure 5.3: Load-deflection curve of TS

The Figure 5.4 shows the load-deflection curve of the beam specimen having five number of layers laminated using instant bond synthetic adhesive.

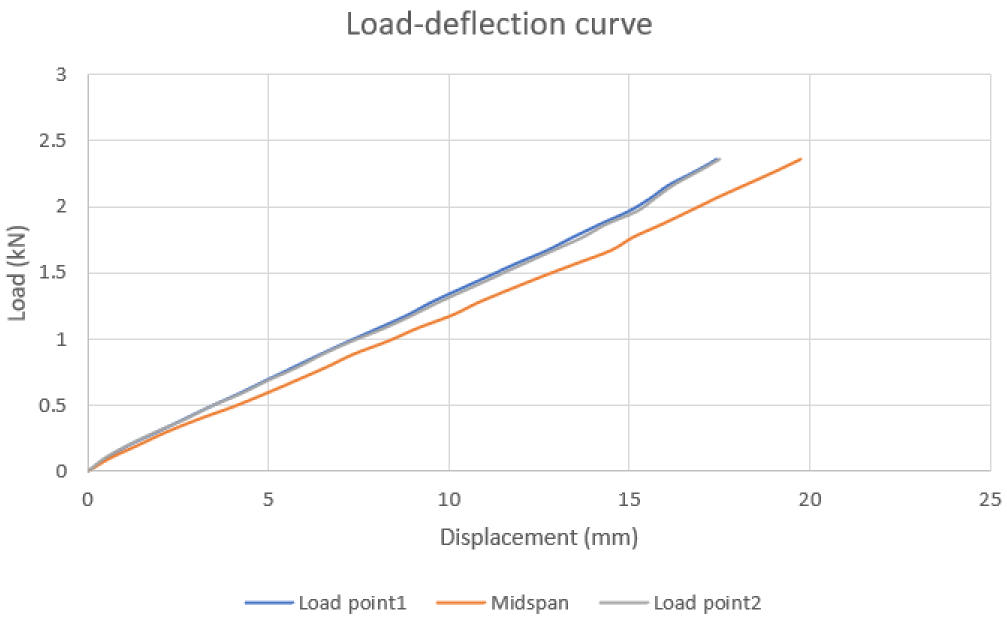

Figure 5.4: Load-deflection curve of FS

The Figure 5.5 shows the load-deflection curve of the beam specimen having five number of layers laminated using polyurethane adhesive.

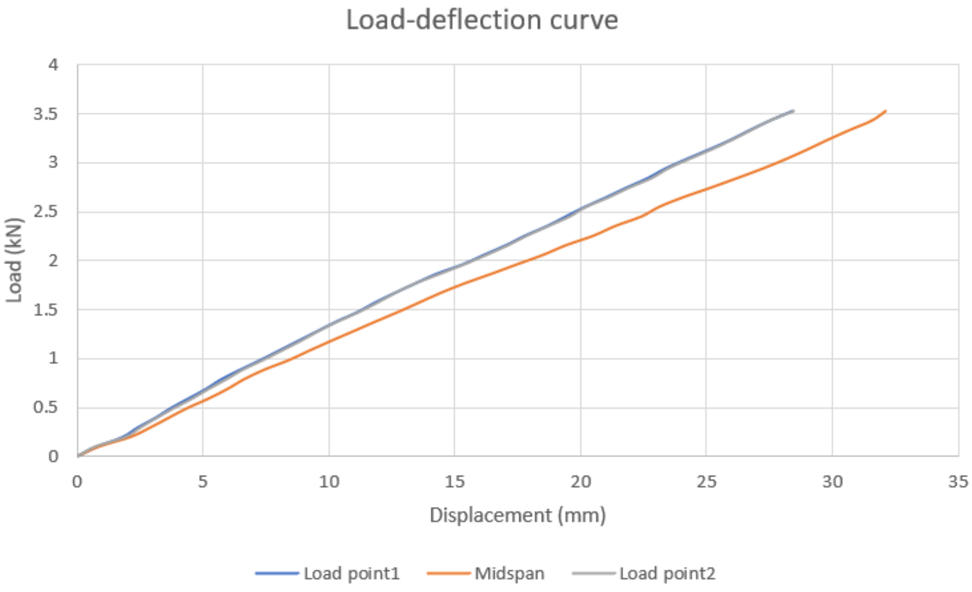

Figure 5.5: Load-deflection curve of FP

The plot shown in Figure 5.6 compares the midpoint deflection of the four different lamination configurations.

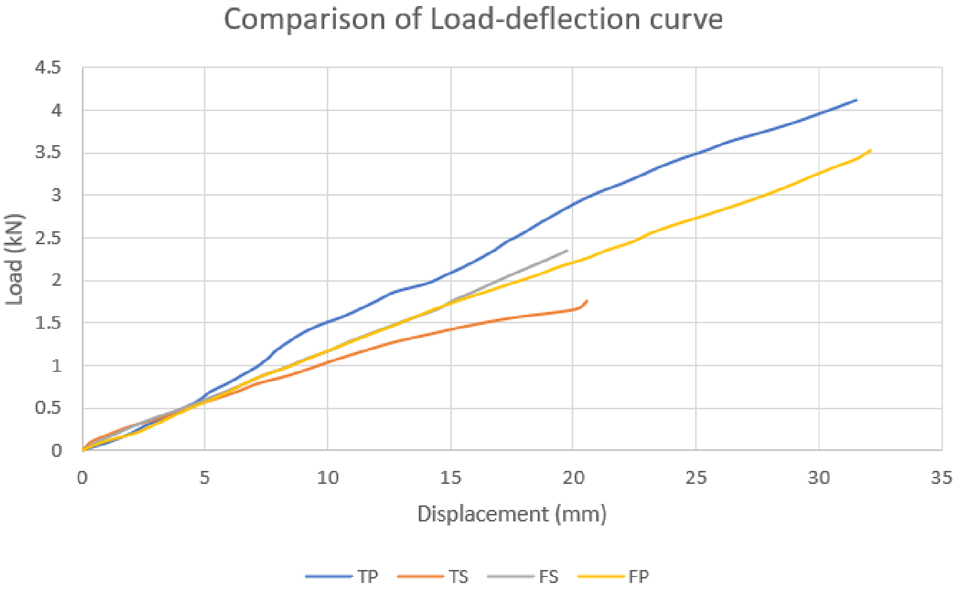

Figure 5.6: Comparison between load-deflection curves

Observations from the comparison of load-deflection curves clearly concludes that polyurethane adhesive have a higher load carrying capacity when compared to the instant bond synthetic adhesive. Polyurethane adhesive provides better ductility to the specimens. The difference in load carrying capacity bonded using synthetic adhesive accounting to the number of layers was not abled to be identified since all the beams failed due to delamination of layers rather than cracking due to tension failure. But from the load-deflection curve of beams bonded using polyurethane adhesive, it can be identified that ten layer laminate can carry more load when compared to five layer laminate. Instant bond synthetic adhesive makes the specimen more brittle in nature.

5.3.2 Crack and Ultimate load

The experimental results from the flexural test shows the difference in load carrying capacity and cracking behaviour of different laminate configurations. When comparing the number of layers, ten layer laminate have greater failure load than five layer laminate. And polyurethane adhesive has greater failure load than instant bond synthetic adhesive. Table 5.1 shows the ultimate load of different specimens and Figure 5.7 shows the variation of ultimate load.

Specimens	Ultimate load in KN
TS1	1.77
TS2	1.86
TP1	4.12
TP2	3.23
FS1	2.35
FS2	2.55
FP1	3.53

Table 5.1: Ultimate load of beam specimens

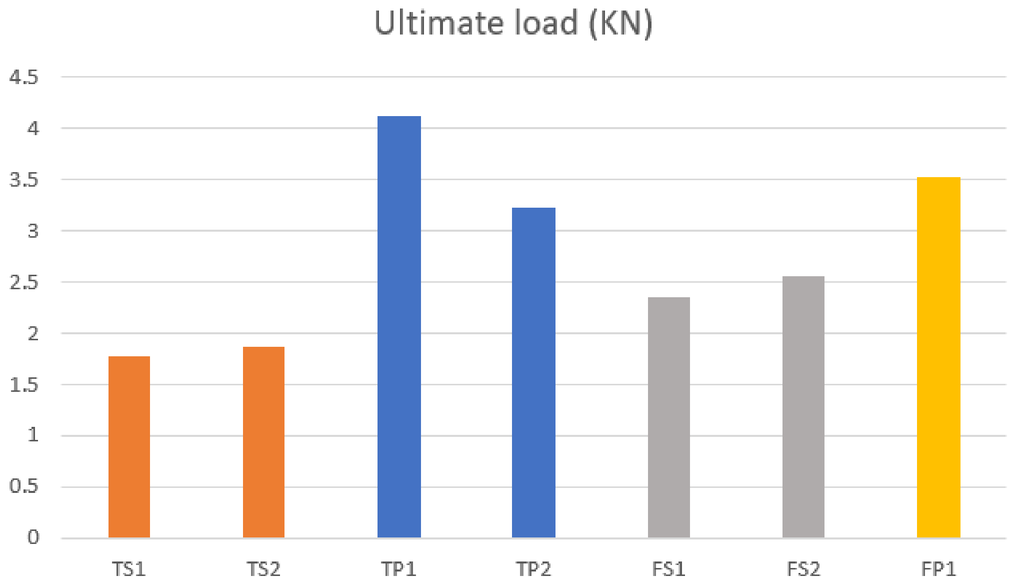

Figure 5.7: Ultimate load of beam specimens

All the beam specimens failed due to the delamination of the layers. This was due to the low shear strength and poor bonding of adhesive. The HDHMR material could not achieve failure thus the load carrying capacity of the material could not be found out. The failure cracks of the beam specimen are shown in the following figures.

Figure 5.8: Failure due to delamination of TP specimen

Figure 5.9: Failure due to delamination of FS specimen

Figure 5.10: Failure due to delamination of TS specimen

Figure 5.11: Failure due to delamination of FP specimen

Delamination mainly occurred to the layers above the neutral axis, as shown in Figure 5.11 and 5.10. Initially delamination occurred near the loading points and then it is propagated towards the supports, as shown in Figure 5.8. The failure pattern observed for all the beam specimens were similar. As the number of layers increase, the probability of occurrence of delamination also increases. Specimen bonded with polyurethane adhesive has contributed less for delamination when compared to instant bond synthetic adhesive. Delamination has also resulted in cracking of inner layers of the specimen as shown in Figure 5.9. However, the beam specimen shown in Figure 5.12 made up of five layers bonded using polyurethane adhesive was not delaminated but the ultimate strength could not be found as the beam has highly deflected and touched the supports, the load at that point was noted to be 5.39 kN.

Figure 5.12: Maximum deflection of the FP specimen

CHAPTER 6

CONCLUSION

6.1 Summary

The main objective of the present investigation is to find out the structural behaviour of glue-laminated beams fabricated using engineered wood. For this, HDHMR engineered wood product was used to make beams which are laminated using two different adhesives. Moreover, different number of layers was also used as a parameter for the study. Their structural behaviour was studied in terms of load-deflection characteristics and failure characteristics.

6.2 Conclusion

- Specimens having ten number of layers could carry more load compared to the specimens having five number of layers
- The observations shows that polyurethane adhesive showed better bonding properties than the instant bond synthetic adhesive
- The specimens boned with polyurethane adhesive could withstand more load and shear when compared to the specimens bonded using instant bond adhesive
- Polyurethane adhesive acts as a layer between two layers of fibreboard thereby providing a ductile property to the specimen whereas instant bond adhesive makes the specimen more brittle
- Since all the specimens failed due to delamination, the ultimate load carrying capacity of the fibre board could not be found out
- The propagation of failure was in such a way that, initially delamination occurred near the loading points and propagated toward the supports
- It was found that as the number of layers increases, the probability of occurrence of delamination also increases

6.3 Future Scope

The following maybe considered as the areas of future potential research

- Experimental studies for finding out the better suitable adhesive for increasing the strength between laminates

- Developing a FEA model using software to the study the behaviour of glue-laminated beams
- Experimental studies on the use of fasteners for connecting the laminates
- Experimental studies on the behaviour of glue-laminated beams under different loading and support conditions

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APPENDIX

Table A1: Experimental observation of TP beam specimen

Load	Load point1	Midspan	Load point2
0	0	0	0
0.098067	0.45	1.1	0.5
0.196133	1.05	1.95	1
0.2942	1.7	2.6	1.65
0.392266	2.5	3.4	2.6
0.490333	2.9	4.1	2.95
0.588399	3.5	4.75	3.52
0.686466	4.1	5.2	4.2
0.784532	4.75	5.9	4.8
0.882599	5.3	6.5	5.38
0.980665	5.9	7.1	6.02
1.078732	6.4	7.55	6.5
1.176798	6.9	7.9	7.03
1.274865	7.4	8.4	7
1.372931	7.8	8.93	7.9
1.470998	8.45	9.65	8.55
1.569064	9.3	10.6	9.4
1.667131	9.8	11.35	10
1.765197	10.4	12.05	10.5
1.863264	11.05	12.75	11.1
1.96133	12.2	14.05	12.25
2.059397	12.9	14.8	13.02
2.157463	13.5	15.55	13.6
2.25553	14.1	16.2	14.15
2.353596	14.7	16.8	14.8
2.451663	15.5	17.3	15.6

2.549729	16.05	17.95	16.1
2.647796	16.6	18.5	16.7
2.745862	17	19.1	17.15
2.843929	17.5	19.7	17.6
2.941995	18.08	20.35	18.2
3.040062	18.8	21.1	18.8
3.138128	19.5	22	19.5
3.236195	20.25	22.8	20.3
3.334261	20.95	23.55	21
3.432328	21.75	24.45	21.7
3.530394	22.65	25.46	22.6
3.628461	23.46	26.35	23.4
3.726527	24.51	27.55	24.4
3.824594	25.6	28.7	25.4
3.92266	26.45	29.7	26.36
4.020727	27.4	30.65	27.4
4.118793	28.2	31.55	28.15

Table A2: Experimental observation of TS beam specimen

Load	Load point1	Midspan	Load point2
0	0	0	0
0.098067	0.2	0.35	0.1
0.196133	0.98	1.15	0.8
0.2942	1.85	2.08	1.6
0.392266	2.9	3.3	2.6
0.490333	3.6	4.06	3.3
0.588399	4.7	5.2	4.25
0.686466	5.71	6.25	5.2
0.784532	6.5	7.1	5.96
0.882599	7.6	8.38	6.9
0.980665	8.65	9.4	7.95
1.078732	9.6	10.4	8.65
1.176798	10.7	11.5	9.65
1.274865	11.72	12.65	10.7
1.372931	13.1	14.15	12.1
1.470998	14.5	15.7	13.58
1.569064	16.5	17.6	15.15

1.667131	18.1	20.1	17.2
1.765197	18.55	20.55	17.6

Table A3: Experimental observation of FS beam specimen

Load	Load point1	Midspan	Load point2
0	0	0	0
0.098067	0.5	0.6	0.45
0.196133	1.12	1.38	1.1
0.2942	1.9	2.15	1.85
0.392266	2.65	3.05	2.68
0.490333	3.4	4.05	3.4
0.588399	4.2	4.93	4.25
0.686466	4.93	5.78	4.98
0.784532	5.7	6.6	5.8
0.882599	6.45	7.35	6.5
0.980665	7.23	8.3	7.3
1.078732	8.05	9.12	8.2
1.176798	8.85	10.08	8.98
1.274865	9.52	10.82	9.7
1.372931	10.3	11.7	10.5
1.470998	11.1	12.6	11.3
1.569064	11.9	13.55	12.1
1.667131	12.75	14.5	12.9
1.765197	13.45	15.1	13.7
1.863264	14.2	15.9	14.35
1.96133	15	16.65	15.2
2.059397	15.6	17.4	15.7
2.157463	16.1	18.2	16.2
2.25553	16.8	19	16.85
2.353596	17.45	19.75	17.5

Table A4: Experimental observation of FP beam specimen

Load	Load point1	Midspan	Load point2
0	0	0	0
0.098067	0.8	0.85	0.7
0.196133	1.8	2.1	1.9
0.2942	2.4	2.9	2.5
0.392266	3.1	3.62	3.15
0.490333	3.7	4.35	3.82
0.588399	4.4	5.2	4.55
0.686466	5.1	5.95	5.2
0.784532	5.7	6.6	5.9
0.882599	6.45	7.4	6.55
0.980665	7.25	8.38	7.35
1.078732	8	9.2	8.1
1.176798	8.75	10.05	8.85
1.274865	9.5	10.93	9.54
1.372931	10.25	11.8	10.3
1.470998	11.1	12.7	11.15
1.569064	11.8	13.55	11.9
1.667131	12.58	14.4	12.6
1.765197	13.4	15.35	13.4
1.863264	14.25	16.42	14.38
1.96133	15.3	17.45	15.35
2.059397	16.15	18.5	16.25
2.157463	17.02	19.4	17.1
2.25553	17.78	20.5	17.85
2.353596	18.65	21.35	18.7
2.451663	19.4	22.4	19.55
2.549729	20.15	23.1	20.2
2.647796	21	24.05	21.1
2.745862	21.8	25.15	21.9

2.843929	22.65	26.2	22.8
2.941995	23.35	27.22	23.45
3.040062	24.2	28.15	24.3
3.138128	25.1	29	25.19
3.236195	25.95	29.8	26
3.334261	26.7	30.65	26.75
3.432328	27.5	31.55	27.5
3.530394	28.4	32.1	28.45