International Journal of Engineering & Technology, *3 (2) (2014) 129-136*
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www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v3i2.2140
Research Paper

Numerical simulation and analytical study of glulam timber beams

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Abstract

Glulam beams or glued-laminated beams consist of sawn lumber laminations (timber) bonded with an adhesive material. This paper, through the mathematical description of the contact conditions that apply at the interfaces of glulam beams and the development of two three-dimensional finite element models by the use of the ANSYS software package, studies the flexural properties of unreinforced (UGB) and reinforced (RGB) glulam beams. The first computational model presents an unreinforced glulam beam that has been produced by three wood laminations of dimensions 6 by 3.6 by 176 cm. The latter one describes a reinforced glulam beam, which has been produced by gluing a 0.15 cm thick steel plate at the bottom edge of the previously described beam. The computational analysis indicates that the two glulam beams have significantly different bearing capacities under the same load and support conditions. The failure mode of the UGB is brittle whereas the one of the RGB is ductile. The numerical results of both models are in close agreement with experimental ones from the international literature.

Keywords: *Glulam Timber Beams, Numerical Simulation, Contact.*

1. Introduction

For many centuries, wood has been considered as the predominant building material. This natural material has been used in a variety of constructions. The main advantages of wood are its lightweight, the ease to manufacture wood parts and the environmental friendliness. The main disadvantages of wood are its vulnerability to fire and humid climate conditions. Nowadays, wood remains a key construction material thanks to its engineered products. These wood products have advanced mechanical properties and are available in a range of grades [1]. Composite lumber, glulam and sandwich are the most common glued engineered members [2], [3].

2. Glulam timber beams

2.1. Definition

Glulam beams are structural glued-laminated beams that consist of two or more layers of lumber (timber) with the grain of all layers, which are known as laminations, parallel to the length. The laminations are firmly bonded by using adhesives such as Phenol Resorcinol Formaldehyde (PRF) or Melamine Urea Formaldehyde (MUF) [4]. It is an engineered, stress-rated product that is widely used in wooden floors, trusses and roofs. The glulam beam can be reinforced by gluing- using a construction adhesive- steel, plastic or carbon fiber to an exterior surface. Epoxy, polyurethane and other isocyanate-based construction adhesives are capable of bonding, with a high degree of structural integrity, wood to rigid metals and plastics [3], [4].

2.2. Construction and mechanical properties

In order to construct a glulam beam, the lumber is joined end-to-end, edge-to-edge and face-to-face. Therefore, the size of glulam beams depends only on the manufacturing and transportation capabilities available. The length of a glulam beam is usually between 1.5 and 5 m and the thickness 5 to 12 cm [3], [5]. Manufacturing companies use high quality lumber near the exterior surfaces of the glulam beam (regions of higher stresses under flexural loads) whereas lumber of lower quality is placed at the center [1, 3]. Species can also be varied to comply with the structural requirements of the laminations [4]. In general, the longitudinal direction of a glulam beam has significantly more strength than the transverse one [5]. The moisture content of glulam is in the range of 12 to 15 % [6]. The average mechanical properties of the unreinforced glulam beam and the natural wood used for the production of the laminates are presented in Table 1 [1], [6].

Table 1: Mechanical Properties of Unreinforced Glulam Beam and Natural Wood.

	Unreinforced Glulam Beam	Wood
Bending resistance f_b	22 MPa	10.22 MPa
Tensile resistance parallel to grain f_t	18.12 MPa	12.16 MPa
Compressive resistance parallel to grain f_c	7.25 MPa	5 MPa
Shear resistance f_v	2.8 MPa	1.1 MPa
Density ρ	360 Kg/m^3	380 Kg/m^3
Modulus of Elasticity E	13.5 GPa	12.65 GPa

3. Mathematical approach

3.1. Mathematical description

The multi-layered glulam beams can be considered as composite members. The composite behaviour of glulam beams is achieved through various contact bonds at the interface of the laminations. Therefore, in order to simulate -in an accurate way- a glulam beam, the contact conditions that are present at the interface of the laminations have to be investigated. In the case of reinforced glulam beams, where a layer made from a different material (such as steel or plastic) is glued to the other layers, the composite behavior can more easily be recognized. The physical properties of the bond between the lumbers (case of UGB) or between wood and steel (case of RGB) have been the key factors to the design of the numerical model presented in the following sections of this paper.
The contact regions at the interface of glulam beams are not a priori known, resulting in a Unilateral Contact Problem [7], [8].

3.2. Unreinforced glulam beam

When an unreinforced glulam beam is loaded, the interaction between wood layers and the adhesive material forms a shear bond at the wood-adhesive interface. When the loading exceeds the tensile strength of the adhesive, the shear bond is broken and this leads to failure of the glulam beam. It must be noted that the friction forces, between wood and adhesive material, have not been taken into account. The failure mode of the unreinforced glulam beam, as described above, is brittle.
For an UGB, unilateral contact conditions -relations (1) and (2)-have been applied at the normal direction to the interface between wood and adhesive [8].

$$\text{If } \bar{u}_N > 0 \text{ then } S_N = 0 \tag{1}$$

$$\text{If } \bar{u}_N = 0 \text{ then } S_N \geq 0, \tag{2}$$

where: $\bar{u}_N$ is the quantity $u_{N1} + u_{N2} + h - u_0$, u_{N1} is the displacement of the first body (wood), u_{N2} is the displacement of the second body (adhesive), h is the distance between the two bodies and u_0 is the relative displacement of the bodies due to rigid body motion (rigid body displacement). Moreover, S_N is the normal contact (or delamination) force at the interface of the two bodies?
In the direction tangential to the wood-adhesive interface, a nonmonotone contact law should be applied, of the form depicted in Figure 1 [9].
As depicted in Figure 1, there is a sudden decrease of the shear forces, developed at the interface of the glulam beam, at the time when the maximum value of the shear strength is reached. This decrease denotes the sudden interface delamination after exceeding the tensile strength of the adhesive.

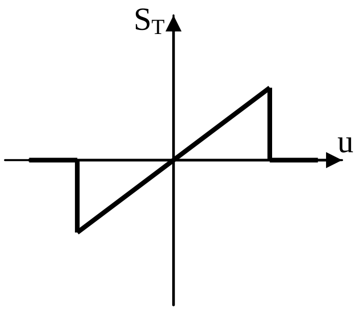

Fig. 1: No monotone Contact Law for Unreinforced Glulam Beam.

3.3. Reinforced glulam beam

When a reinforced glulam beam is loaded, the interaction between wood and steel, gives rise to friction forces that form a shear bond at the wood-adhesive and adhesive-steel (for simplicity reasons wood-steel) interface. Friction forces absorb the initial loads but as the loading continues to be applied, the adhesive material is left alone to cope with the external forces. When loading exceeds friction forces, the shear bond due to friction is broken and sliding occurs at the interface of the two layers. Further loading of the beam leads to failure of the glulam beam due to interface delamination. The failure mode of the reinforced glulam beam, as described above, is ductile. This type of contact problem is called Unilateral Contact problem with friction [8].

In the normal direction to the interface between steel and wood, unilateral contact conditions, as in the case of unreinforced glulam beams have been applied.

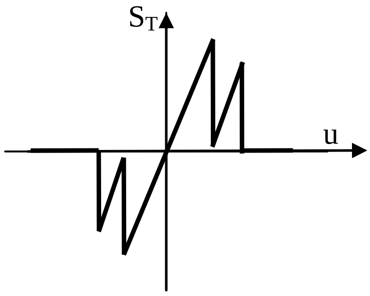

Fig. 2: Nonmonotone Contact Law for Reinforced Glulam Beam.

In the direction tangential to the wood-steel interface, a nonmonotone friction material law should be applied, of the form depicted in Figure 2 [9].

As depicted in Figure 2, there is a sudden decrease of the shear forces, developed at the interface of the glulam beam, at the time when the maximum value of the shear strength is reached. These vertical 'softening' branches of the friction law denote that the friction bond has been broken and the adhesive material has been weakened. The last vertical branch of the law denotes the delamination at the interface of the glulam beam has occurred.

4. Finite element model

4.1. Description

Two finite element models have been created using the ANSYS software program. Different mesh sizes have been tested in order to get better accuracy in the numerical simulation.

The first finite element model describes the case of an unreinforced glulam beam, which contains three layers made from the same wood. The mechanical properties of this material have been described in the previous paragraph. The dimensions of the laminations are 6 by 3.6 by 176 cm and the dimensions of the glulam beam are 6 by 11 by 176 cm [1]. The cross-section of the UGB is depicted in Figure 3.

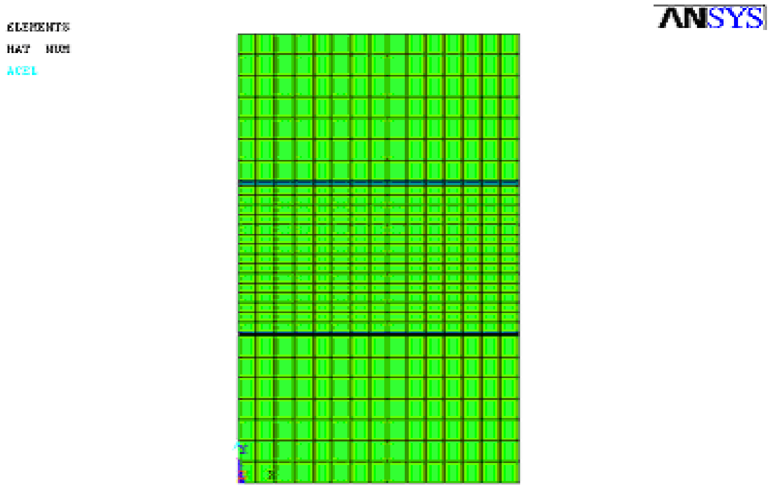

Fig. 3: Finite Element Model Grid of the Cross-Section of Unreinforced Glulam Beam.

A three-dimensional eight-node isoparametric structural element has been selected for the wood laminations. The hexahedron form of the finite element consisting of eight nodes with three degrees of freedom (displacements towards the x, y, and z axes) in each node has been chosen. The middle lamination has been meshed finer in order to achieve better connectivity with the two adhesive layers of the glulam beam.

The adhesive layers have been modelled using a three-dimensional eight-node interface element. It is defined by eight nodes, having three degrees of freedom at each node: translations in the nodal x, y, and z direction. The adhesive layers have been glued with the laminations (using an ANSYS design tool) before meshing. This is an essential step for the analysis, in order to prevent delamination of the glulam beam at low load.

The second finite element simulation describes the case of a reinforced glulam beam. A steel plate of 0.15 cm in thickness has been glued at the bottom surface of the lower wood lamination of the glulam beam, which is described in the first simulation. The wood laminations have been glued together without adhesive layers using an ANSYS feature, prior to the attachment of the steel plate. The wood-steel interface (found only in the second simulation) has been modelled with three-dimensional contact surface to surface elements in order to achieve composite action. The wood and the steel surface have both been assumed to be deformable but the steel one has been considered significantly stiffer. The contact elements overlay the elements used for the simulation of the wood laminations and the steel plate. However, it is not easy to obtain accurate results using ANSYS when different types of contact are found; therefore the adhesive layers of the first model have not been implemented in the second simulation. The cross-section of the RGB is shown in Figure 4.

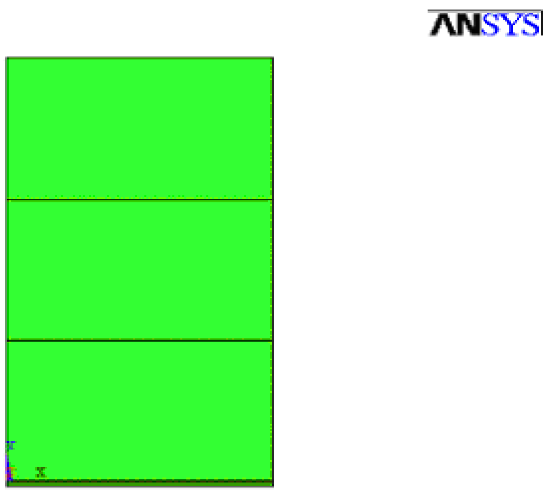

Fig. 4: Unmeshed Cross-Section of Reinforced Glulam Beam.

The steel plate exhibits very small thickness compared to its other dimensions and is therefore considered as a thin-walled element [10]. The chosen three-dimensional eight-node shell element has six degrees of freedom (three displacements and three rotations towards the x, y, and z axes) in each node and its characteristics include plasticity, ability to develop great deformations and displacements, creep and hardening. Further, the shell element thickness has been selected equal to the steel plate's thickness [7].

The analysis performed is geometrically nonlinear with stress stiffening, large deflections and small strains characteristics [7], [11]. ANSYS uses the Newton-Raphson method as an incremental-iterative solution process [10].

4.2. Wood, steel and adhesive material laws

The constitutive material law selected for steel has been bilinear elastoplastic-strain hardening using the von Mises stress yield criterion. Steel has been assumed to be homogenous [11]. The yield stress for the steel in tension has been determined at 320 MPa and the modulus of elasticity at 210 GPa. The density of steel has been determined at 7850 Kgr/m3. The material law is depicted in Figure 5 [12].

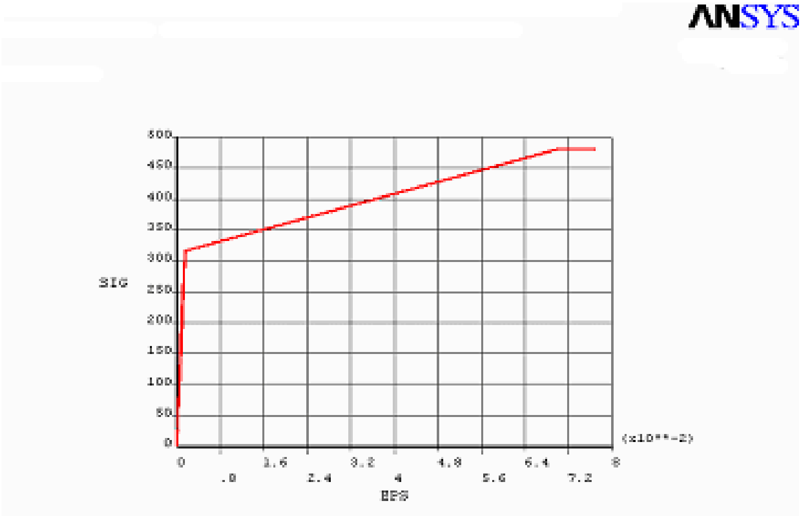

Fig. 5: Material Law for Steel.

For the wood laminations and the adhesive layers of the glulam beam, a non-linear material law (ANSYS feature) has been used. The bending strength has been determined at 22 MPa and the modulus of elasticity at 13.5 GPa. The ultimate tensile stress has been determined at 18.12 MPa [1]. The resistance in compression and in shear has been applied as 7.25 MPa and 2.8 MPa, respectively. The density of wood has been determined at 360 Kgr/m3. The Poisson ratio for steel has been assumed as 0.3 [11].
For the contact elements, at the interface between wood and steel, a material law similar to the one of the wood has been used but the material properties of an epoxy have been applied. The ultimate tensile stress has been determined at 27 MPa and the modulus of elasticity at 10 GPa. The density of the adhesive has been determined at 1700 Kgr/m3. The Poisson ratio has been assumed as 0.38 [11], [13].
The friction which develops in the steel-wood interface has been deemed non negligible; a constant friction coefficient of 0.3 has been considered [12], [13]. ANSYS uses the Coulomb friction model, which is adequate for our problem [5].

4.3. Support and loading conditions

The glulam beam, in both cases, has been assumed as simply supported. The load has been applied to act as two static line loads distributed across the width of the glulam beam at L/3. The support and loading conditions coincide with those of the experimental work [1]. The support and loading conditions of a reinforced glulam beam are shown in Figure 6.

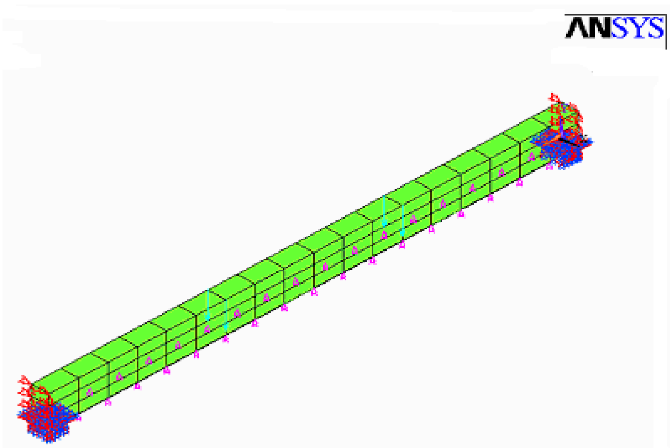

Fig. 6: Support and Loading Conditions of the Finite Element Model.

4.4. Results

The following Figures 7 to 11 present the computational results. Figure 7 that depicts the deformation of the glulam beam under load is common for both finite element models.

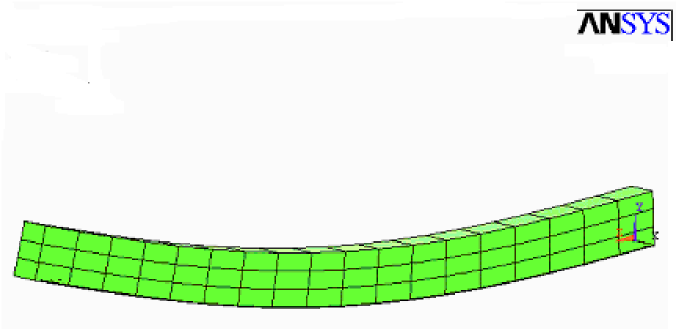

Fig. 7: Deformation of the glulam beam.

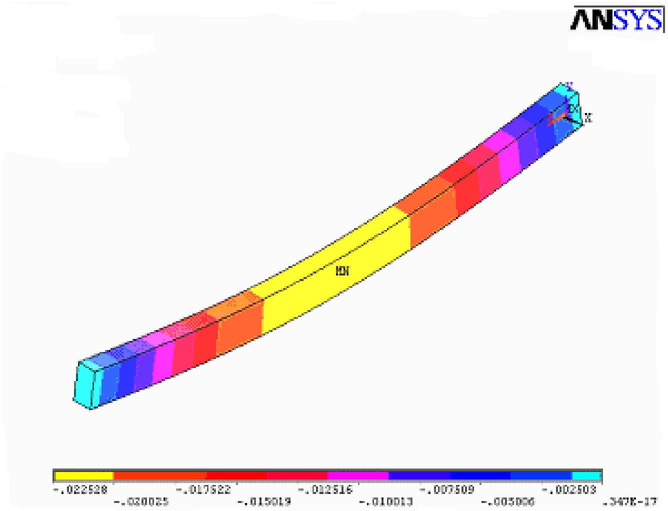

Fig. 8: Deflection of the Unreinforced Glulam Beam under Maximum Load.

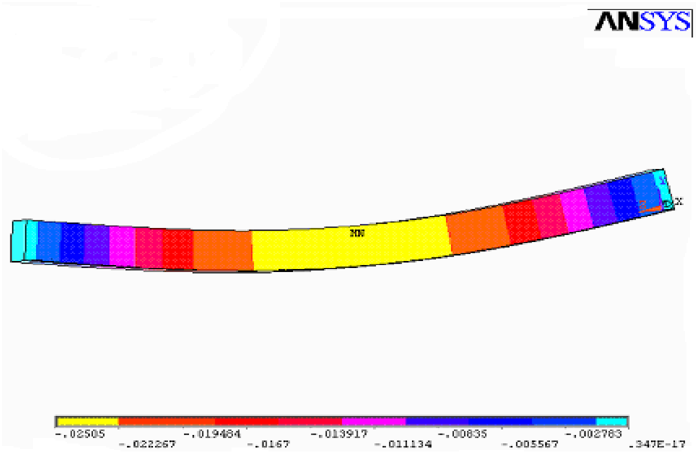

Fig. 9: Deflection of the Reinforced Glulam Beam under Maximum Load.

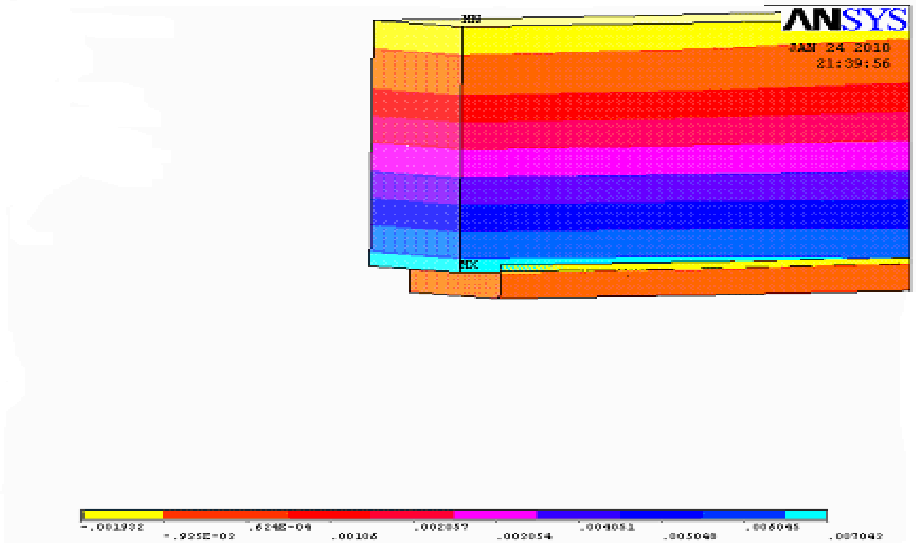

Fig. 10: Relative Slip at the Wood-Steel Interface of Reinforced Glulam Beam.

The maximum load for the unreinforced glulam beam and the reinforced glulam beam has been found equal to 19 KN and 30.4 KN, respectively. The maximum deflection at the middle of the span for the UGB and the RGB has been calculated equal to 22.52 mm (as shown in Figure 8) and 25.05 mm (as shown in Figure 9), respectively. The latter value was measured when the maximum load bearing capacity has been achieved.
The relative slip between wood and steel at the common interface appears in Figure 8. The maximum slip has been found equal to 1.93 mm.

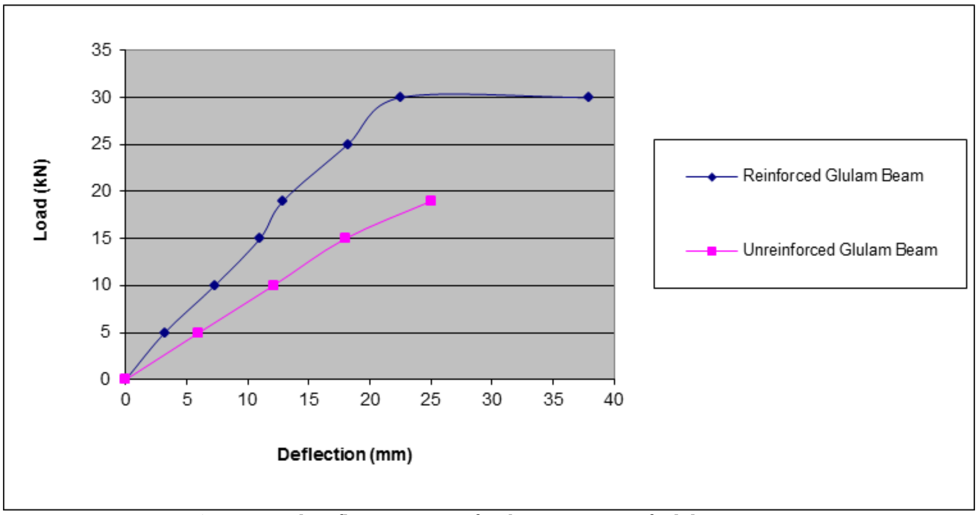

Fig. 11: Load-Deflection Curves for the Two Types of Glulam Beams.

The load-deflection curves for the two types of glulam beam are plotted in Figure 11.

5. Conclusion

The results of the proposed finite element simulation have been compared with experimental ones from the international literature [1].

- The failure modes of the both the computational and the experimental unreinforced glulam beam were brittle. On the contrary, reinforced glulam beams have a ductile failure mode, resulting in excessive deflection before failure occurs. This denotes that the reinforcement plays a major role to the behaviour of the glulam beam.
- Significant slip at the interface of the reinforced glulam beam has been measured during the numerical analysis. The measure of the slip (1.93 mm) can be related with the bonding failure between wood and steel that had been monitored after the end of the experiment.
- The load–deflection curves produced by the numerical approach of the problem, both for the case of UGB and RGB, are in close agreement with the load–deflection curves produced during the experimental study as depicted in Figure 12.

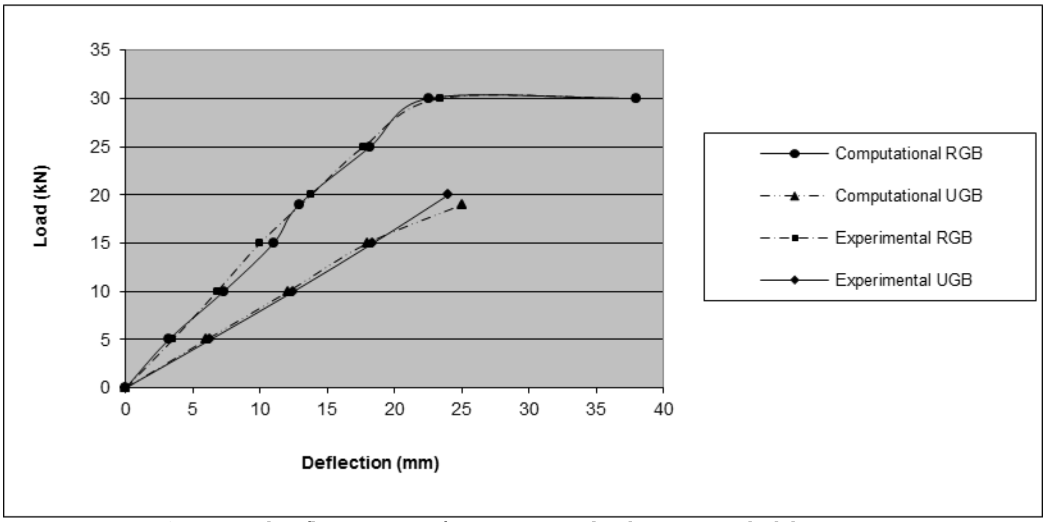

Fig. 12: Load-Deflection Curves for Computational and Experimental Glulam Beams.

- Both in the experimental and the computational analysis the bearing capacity of the unreinforced glulam beam is quite lower than the one of the reinforced glulam beam.
- Both numerical models of glulam beams proposed in this paper are relatively simple and provide accurately results. The numerical simulations are applicable to practice and can be used as an effective design tool for timber constructions.

The use of RGB in construction is highly recommended, due to its mechanical behaviour and strength. Reinforced glulam beams cost less than unreinforced ones, because the application of reinforcement is cheaper than high-grade lumber used for the external laminations [14].

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