# Experimental study of timber-timber composite beams using welded-through wood dowels

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## Abstract

This paper presents exploratory research related to novel full-scale multi-layered timber beams with composite action achieved with welded-through wood dowels. Different multi-layer beam designs, where the timber layers were interconnected with welded wood dowels providing interlayer shear resistance, were tested in bending with different dowel densities. The main originality of this study is the achievement of dowel welds through greater depths of sections than has previously proved possible. The practical difficulties encountered in constructing deeper multi-layer beams, and the successful solutions arrived at, are discussed. The significance of the research reported is the demonstrated ability to produce multilayered timber sections which are structurally efficient and do not require non timber based joining agents such as nails or adhesive.

**Keywords:** wood dowels, timber-timber composite, analytical modelling, timber connections

## 1. Introduction

Glue laminated timber, glulam, has been used in Europe since the end of the 19th century [1]. Glulam technology finds extensive applications in timber construction due to its flexibility and the advantages it offers in terms of different shapes and forms in final assembled systems. Also, where possible, its use is often favoured as timber is recognised as being more environmentally friendly, and often more aesthetic, when compared to traditional materials such as steel and concrete. In addition to adhesive joining technologies, metallic fasteners and plates, between constituent timber components, have been, and continue to be widely used, to achieve composite action and connectivity between multiple components, for example in connections between glulam beams and supporting columns. However, the manufacture and the use of glulam beams, and other structural timber products, have been shown to be very energy intensive, thereby leading to significant levels of undesirable emissions to the environment. Life Cycle Inventory (LCI) studies [2], examining the energy requirements, and resulting emissions to the environment, associated with the production of glulam and other structural timber products, have identified the need to optimise the utilization of natural materials, and particularly the manner in which they are used [3] so as to maximise the environmental accruing from them.

In addition to being less environmentally friendly other disadvantages manifest themselves when traditional (adhesive and metallic fastener based) joining technologies are used. Wood working, planning and cutting, is incompatible with the presence of metal fasteners in wood. Fire fighter experience and studies of the performance of metallic connectors have shown that early failure can be attributed to the presence of metallic connections in an otherwise timber structure. As a result, stringent requirements for fire-proofing of metallic connectors have been introduced. These have severe implications on cost, simplicity of construction and environmental impact, since most insulating materials are made from non-renewable sources. Gluing is also extensively used today, but is associated with both real and perceived pollution costs. At manufacture the deposits on the glue-applicators and subsequent cleaning of the work area and safe disposal of the excess adhesive is costly and incompatible with an otherwise environmentally friendly product. Adhesives also experience problems in environments susceptible to thermal change. The glass transition temperature of adhesives is greatly influenced by temperature, and thus glulam stiffness decreases drastically before its timber has experienced any major temperature effects. Thus in a fire situation the adhesive tends to be the weakest component of the composite system.

To address these concerns, an original joining alternative, which uses wooden dowels to replace metallic fasteners, connectors, and the traditional poly (vinyl acetate) (PVAc)-adhesive, is advanced. The process of achieving a natural weld between the dowels and the timber components to be joined is high speed dowel rotation welding [4-5]. If the economic cost and mechanical performance of dowel-welded structural joints can be shown to be at least comparable to that achieved by nailing or adhesives then this novel joining solution will be attractive on two fronts, firstly as it will result in an entirely organic, and thus more environmentally friendly, composite system and secondly as it will result in a more sustainable structural performance during fire. The idea to use wood fasteners in the construction industry is not new, but research in this area has been limited by the widespread use of nails since the beginning of the 20$^{th}$ century. The use of wooden dowels is generally limited to the furniture industry and the interior joinery and the do-it-yourself markets. However, with the rise in steel and petroleum, and hence energy, costs there is a stronger than ever incentive to investigate cheaper, more sustainable and more environmentally friendly solutions.

In this regard Pizzi et *al.* [4] and Kanazawa et *al.* [5], among others, have studied the performance of timber assemblies made with welded wood dowels as connecting elements rather than traditional poly (vinyl acetate) (PVAc)-glued dowels and nailing. Guan et *al.* [6] and Jung et *al.* [7] studied timber joint systems using compressed wood fasteners and plates in place of steel fasteners. While, Hassel et *al.* [8] have investigated the performance of a wooden block shear wall assembled with compressed wood dowels. Bocquet et *al.* [9] undertook studies on small-scale and full-scale two-layer timber beams joined with welded wood dowels. The relations between the applied load and deflection, as well as the load carrying capacity of two-layer timber beams, were measured. The results showed clearly the role of the wood dowels in carrying shear stresses that would otherwise have been transferred through the adhesive. All of these works concluded that joint systems made with wood dowels perform well with good initial stiffness and load carrying capacity compared to traditional joining methods using bonded wood dowels or metallic fasteners (nails or screws). Despite these significant advances further research and investigation is needed, primarily on large scale structural applications, so as to enable this joining technique to penetrate the structural engineering market.

This paper focuses on the structural response of 2.2m laminated timber beams, in which, two and four, timber laminates are joined using wood welded dowels. Specifically the study evaluates the efficiency of the composite action and the resulting flexural behaviour. In order to estimate the efficiency of the composite beams, the simplified design method, also called "$\gamma-$method", related to the Möhler's model [10], is used in the case of two-layer beam system by considering fully composite and fully non-composite actions. In addition a solution identified, to weld multi-layered beams at much greater depths than previously achieved [9], is presented.

## 2. Assessment of Efficiency

The use of welded-wood dowels to transfer shear forces between the timber layers leads to a composite beam with semi-rigid connections, and hence partial composite action, between the individual layers. The structural response of such a beam system will be bound between that of a layered beam (with no inter connectivity) and a layered beam with fully rigid (no slip) interfaces between the individual layers. On this basis, and as suggested by Gutkowski et *al.* [11], the efficiency of the welded-wood dowel connection can be evaluated as:

$$Eff = \frac{D_n - D_i}{D_n - D_c} . 100 \quad (1)$$

Where:

$D_n$ is the theoretical composite beam deflection with fully composite connections,

$D_c$ is the theoretical composite beam deflection without interlayer connections,

$D_i$ is the theoretical composite beam deflection with semi-rigid interlayer connections.

Using the "$\gamma-$method", which can be found in Eurocode 5 [12], it is possible to approximate the effective bending stiffness of a simply supported composite beam, composed of two layers (Fig. 1), as follows:

$$EI_{eff} = E_1 I_1 + \gamma E_1 I_1 \, e_1^2 + E_2 I_2 + E_2 I_2 \, e_2^2 \quad (2)$$

The shear coefficient $\gamma$, of the semi-rigid connexion, and the distances $e_1$ and $e_2$ are given by:

$$\gamma = \frac{1}{1 + \frac{\pi^2 E_1 A_1 \, s}{k \, L^2}} \quad (3)$$

$$e_1 = \frac{h_1 + h_2}{2} - e_2 \quad (4)$$

$$e_2 = \frac{\gamma E_1 A_1 (h_1 + h_2)}{2\gamma E_1 A_1 + E_2 A_2} \quad (5)$$

Where $I_i$, $A_i$ and $E_i$ represent the second moment of inertia, area and modulus of elasticity of the timber layers, $s$ is the regular spacing between wood dowels, $L$ represents the length of the beam, $k$ is the slip modulus of the dowel, $h_i$ is the layer thicknesses.

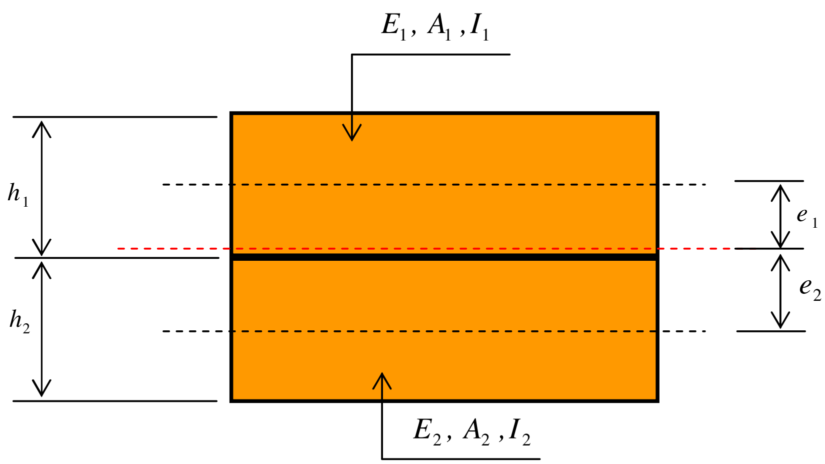


**Fig. 1:** Cross-section of a two-layer beam with wood dowel connection

In the above equations, $\gamma=1$ indicates a fully bonded system (fully composite connections) while $\gamma=0$ indicates no shear transfer between layers.

According to equations (2) to (5), the normal stresses in the composite section for each timber layer, at mid-span, and the shear force in the dowels can be calculated by the following:

$$\sigma_i = \frac{\gamma E_i e_i}{EI_{eff}} M_d \quad (6)$$

$$\sigma_{m,i} = \frac{E_i h_i}{2EI_{eff}} M_d \quad (7)$$

$$w_{max} = \frac{5qL^4}{384\, EI_{eff}} \quad (8)$$

$$F = \frac{\gamma E_i A_i e_i s}{EI_{eff}} V_d \quad (9)$$

Where $q$ is the uniformly distributed load, $w_{max}$ is the mid-span deflexion, $\sigma_i$ and $\sigma_{m,i}$ are the stresses at the centroid and the flexural component of the stresses in the timber layers, $F$ is the shear force acting in the wood dowel, $M_d$ is the maximum bending moment and $V_d$ is the shear force in the cross-section of interest.

## 3. Experimental Study

In this study a series of multilayered beams were constructed and tested under four point bending. The number of laminates and density of wood welded dowels was varied.

### 3.1. Construction process of multi-layered beams

C16 Irish Spruce was used to construct the multi-layered beams. The individual layer dimensions were 140 x 38 x 2200 (mm). Commercially fluted beech dowels of 10mm of diameter were used in the assembly of the multilayer beams. Two series of multi-layered beams were constructed; namely two-layer and four-layer beams. All multi-layered beam systems had one row of wood dowels inserted at 45°, with respect to the plane of the layers as indicated in Fig.2, in the two-layer beams, and at 60° in the four-layer beams.

#### *3.1.1. Construction of the two-layer beams*

In the first stage of the study, the earliest work done on rotational wood dowel welding for a two-layer beam [9] was replicated in order to gain first hand experience of constructing multi-layered beams before attempting a greater number of layers, and hence dowel insertion depths. The number of dowels used for the two-layer beam was 56. The dowels used were 130mm long and, at 33mm centres, were distributed evenly along the 2m simply supported length of the beam. (Fig. 2). It was found that all 56 dowels, each of 10 mm diameter, could be successfully inserted at 45° and welded into 9mm holes through the two-layers.

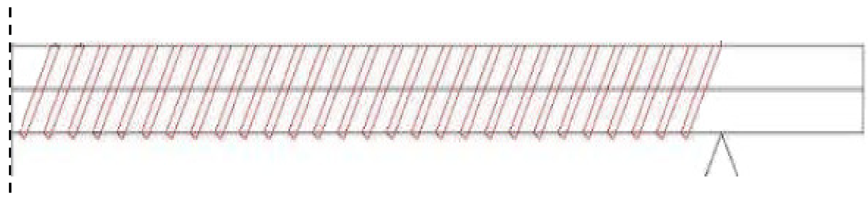

**Fig. 2:** Dowel arrangement in the two-layer beam (one half beam)

#### *3.1.2. Construction of the four-layer beams*

The success of the two-layer beam construction led to a decision to consider constructing four-layer beams, the challenge being the increased insertion depth, arising from an increase in beam depth from 76mm to 152mm, required during rotational welding. For these four layered beams the dowels used were 10mm diameter and 200mm long. The insertion process used for the two layer system did not prove as effective with the dowels splintering at their bases (Fig.3). This splintering generally occurred when the dowels passed a depth of two layers and was attributed to the greater insertion force required for deeper insertion lengths through four layers.

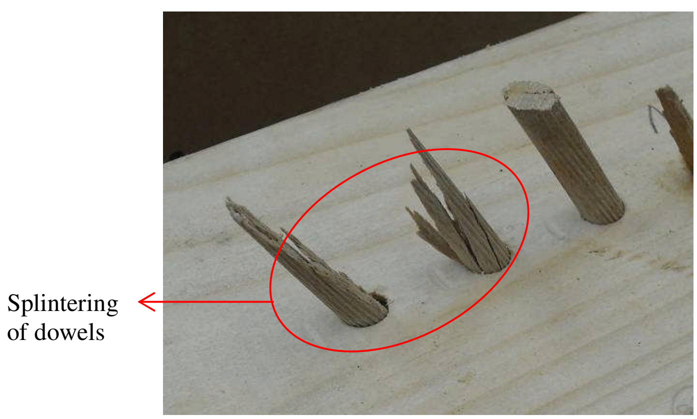


**Fig. 3:** Splintering of dowels during beginning of four-layer beam construction.

Two options were considered to prevent this occurrence of splintering. The first was to increase the diameter of the dowel holes in the layers; a further potential benefit of this approach was considered to be the reduction in insertion force, as the mismatch between hole and dowel diameters would be reduced. This approach did not prove effective. The increase in hole diameter required to prevent splintering was such that the dowel was able to pass quite freely through the hole. Using this approach little or no friction existed between the dowel and substrate resulting in not enough heat being generated during the weld process to cause melting of the lignin nor enough mechanical resistance to aid entanglement. The second option considered was the use of plasticising compounds, such as water, petroleum jelly, vegetable oil, and sunflower oil [5] to aid insertion. Eventually Sunflower oil was chosen as the plasticiser to be used as its effects on the tensile capacity of the joint, although slightly negative, had been documented in previous research [5]. The dowels were soaked for ten minutes in sunflower oil to a depth of 160mm (Fig. 4). The top 40mm was not soaked for two reasons, it was not entering into the layers and it was being held in the drill and so the sunflower oil would have hampered the drill's grip on the dowel. Trial tests, with the soaked dowels, also showed that adjusting the rate of dowel insertion, on a dowel-by-dowel basis, lead to an increase in the number of successful insertions without splintering.

**Fig. 4:** Dowels soaking in sunflower oil

Finally, with this construction process proving successful, a total of seven four-layer beams were constructed (Fig.5). The number of dowels in each beam was varied in order to evaluate their effect on the stiffness of the beam, from which the composite action could be assessed. In total three pairs of beams, with 56, 44, and 32 dowels respectively, and one final beam with 20 dowels were constructed.

**Fig. 5:** Four-layer beam held in clamps during construction

### 3.2. Bending tests and measurements

The experimental program consisted of four point bending tests (Fig.6) of each of the multi-layered beams, assembled with different number of wood dowels. The load was applied using an Instron 8500 series load cell. A steel jig consisting of two 80mm and 90mm box sections and two half cylindrical load pads were used to convert the one point load of the Instron load cell to two point loads acting on the beam. Two series of beams systems were tested, namely the two layers and the four layer doweled beams.

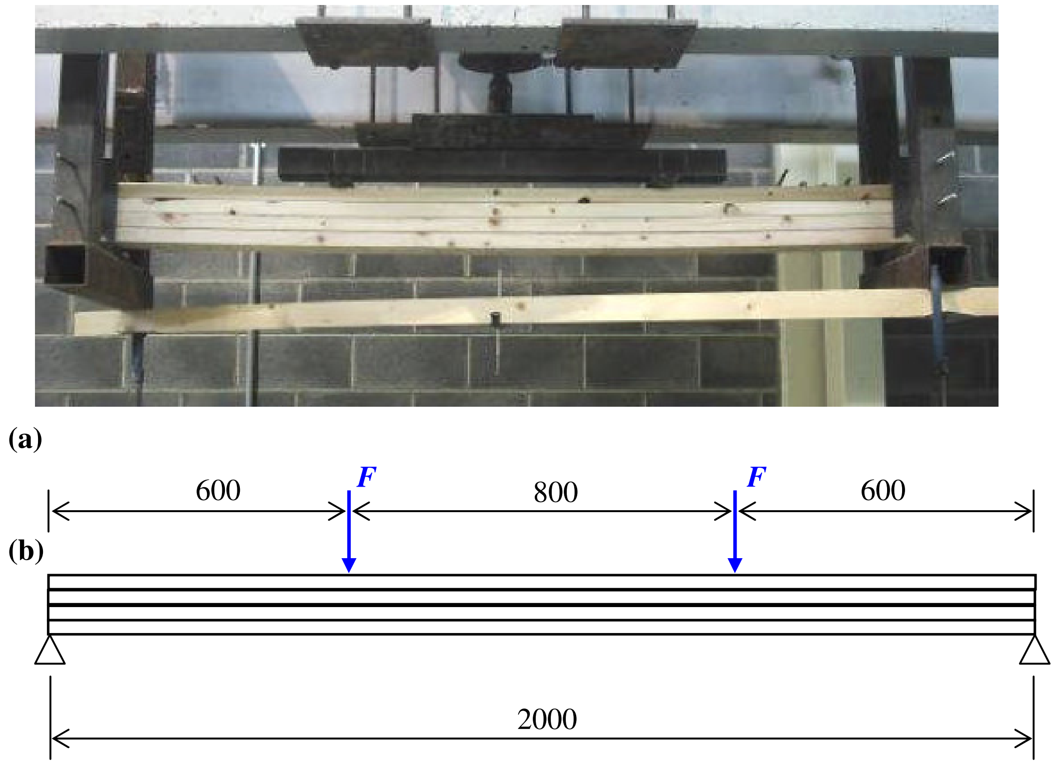


**Fig. 6:** Four-point bending tests: (a) four- layer beam during test, (b) test arrangement (in mm)

Initially the two-layer beam systems, with 56 dowels, were loaded to 3.725 KN. The beam was then ramp loaded to failure under controlled displacement. Inspection of vertical sections taken through the beam allowed inspection of the manner in which a welded dowel behaves when working under both shearing and tension forces (induced by bending).

In a second series of tests, the four-layer beams, with different number of dowels: 20, 32, 44 and 56 dowels were loaded up to 7.22 KN. In addition to the dowel welded beams un-joined layered beams (with two and four layers) were also tested to enable the efficiency of the dowel welded beams to be quantified using the theoretical approach described in Section 2. For all tests mid-span deflection was recorded in addition to applied load.

## 4. Results and discussion

### *4.1. Results from the two – layer beams*

Fig. 7 illustrates the comparison between the theoretically calculated (fully composite and full non-composite) and experimentally obtained load-deflection curves for the two-layer beams (with and without the 56 dowels). As expected the dowelled beam response is between the fully composite and non composite beam theoretical solutions. The dowelled two-layer beam performs well with good initial stiffness and exhibits essentially linear load-deflection behaviour up to the final applied load level of 3.725 KN. The non-dowelled beam is slightly stiffer than the theoretical solution; the small additional stiffness is attributed to inter-layer friction in the experiment which is not considered in the theoretical solution.

The efficiency of the 56-dowel two-layer beam is approximately 72% (estimated using equation 1), indicating the capability of wood welded dowels to resist inter-layer shear forces.

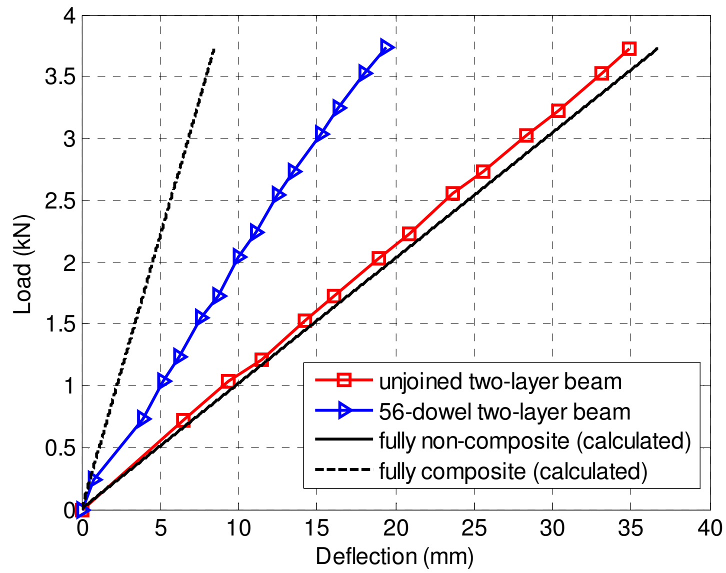


**Fig. 7:** Load – Deflection curves from two – layer beam: comparison between fully composite, fully non-composite and partial composite actions.

For a better understanding of the mode of failure of the welded wood dowels, vertical sections through the two-layer beam are shown in Fig.8. It can be seen that the dowels are not working only in shearing but primarily receive the upward tensile force caused by the layers wanting to separate vertically due to flexure.

**(a)** **(b)**

**Fig. 8:** Vertical sections of the two- layer beam: (a) Left support, (b) Right support

### *4.2. Results from the four – layer beams*

The load–deflection responses obtained for the four-layer beam systems with varying numbers of dowels (20, 32, 44 and 56) are plotted in Fig. 9. The 56-dowel and 44-dowel beams were found to be of similar efficiency (stiffness) and obviously more efficient than the other beam sets. The 32-dowel beam was the next most efficient (stiff) while the lowest efficiency (stiffness) was obtained for the 20-dowel beam. The estimated efficiencies of the different beams were: 74%, 71%, 63% and 49% for 56-dowel, 44-dowel, 32-dowel and 20-dowel beams, respectively. Hence it is demonstrated that efficiency increases with increasing number of dowels. However, beyond a certain number of dowels the incremental increase reduces until such point as it becomes negligible, as evidenced by the similar efficiencies achieved for the 56 and 44 dowel beams.

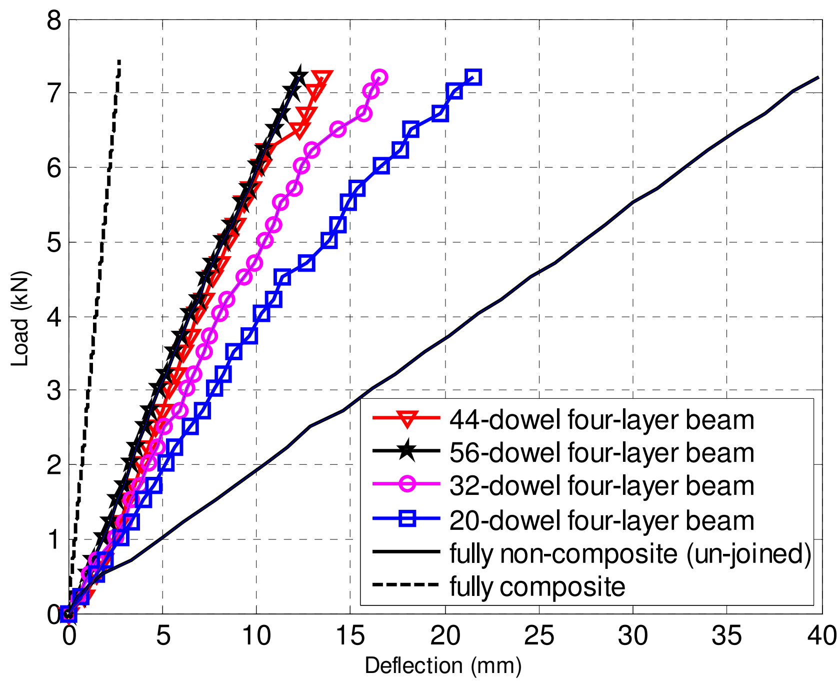


**Fig. 9:** Load – Deflection curves from four – layer beam as a function of number of dowels.

To evaluate the ultimate load of these multi-layer beams, selected beams were loaded, in four-point bending, to failure. The 44-dowel beam, at failure, is shown in Fig.10; other beams behaved similarly. Failure occurs in the bottom layer in the constant bending moment region. The mode of failure was consistently tensile fracture of the bottom layer at locations of knots (imperfections) in the timber. The load–deflection responses, for the beams loaded to failure, are plotted in Fig. 11. Initial stiffness, ultimate load attained and deflection at failure for the four layered beams, with different number of dowels, are summarized in Table 1. Note that stiffness values of all beams were calculated in the linear region of the load-deflection curves shown in Fig. 11.

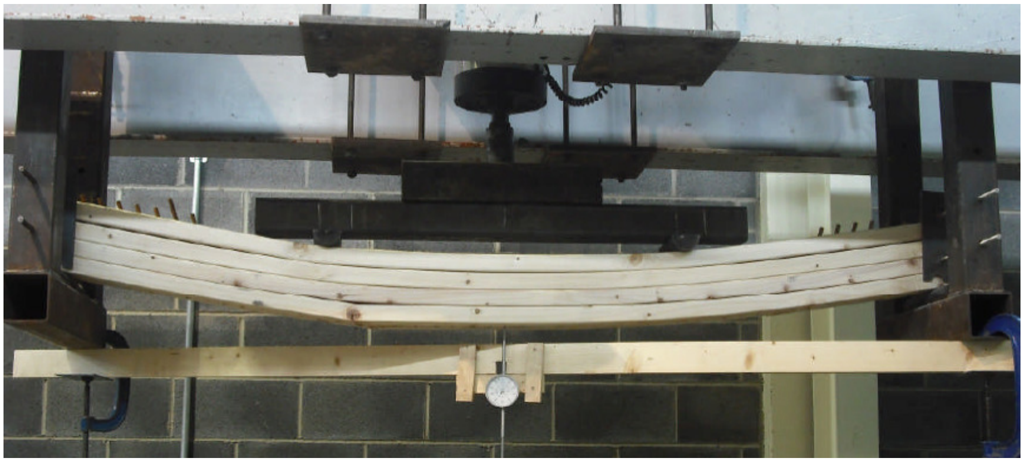

**Fig. 10:** Four – layer 44-dowel beam at failure

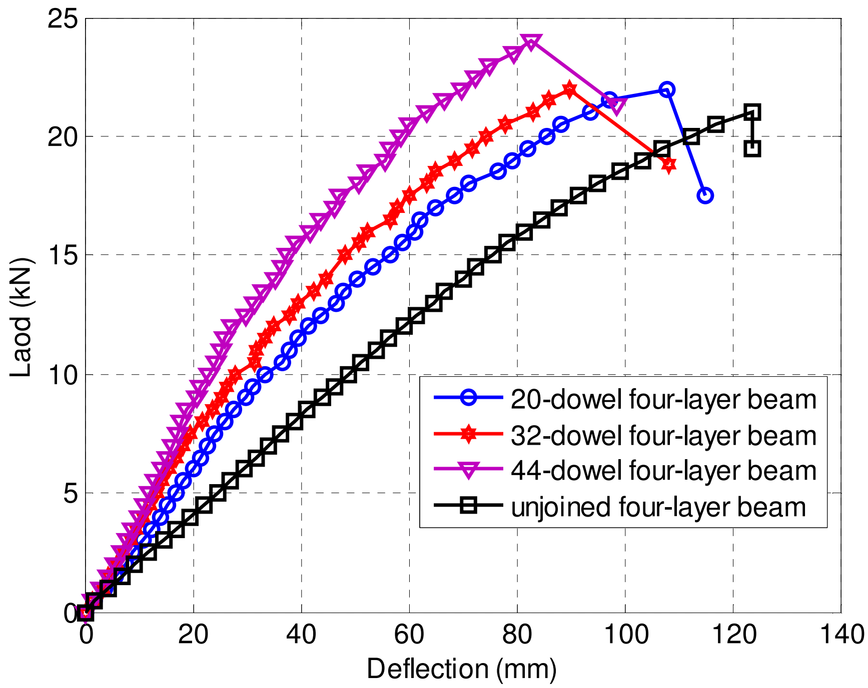


**Fig. 11:** Load – Deflection curves from four – layer beam loaded up to failure.

For the four beams tested to failure the ultimate load varied between 21kN for the unjoined system to 24kN for the 44-dowel beam (with the 20-dowel and 32-dowel beam lying between these in sequence). The impact on strength is thus not that significant, approximately 14% for the 44-dowel beam, relative to the unjoined one. This is in contrast to the more pronounced difference in stiffness in the dowelled beams relative to the unjoined one; the 44-dowel beam is just over twice as stiff as the unjoined one to load levels up to approximately 10-12.5kN. The relatively small increase in strength is attributed to progressive dowel weld failure (there was no indication of actual dowel failure) as load is increased. This hypothesis is supported, in part, by examination of the various load deflection responses. The unjoined system response is smooth and essentially linear to approximately 15kN at which load some softening of the response is evident as the ultimate load is approached. In contrast the dowelled system responses are characterised by small discrete step changes, notably around the 10kN load level in the 32-dowel and 20-dowel systems. In the 20-dowel system the post 10kN stiffness is similar to the unjoined system, while it is almost 66% stiffer below this load level. This drop in stiffness is also evident, but less pronounced in the 44-dowel system, as load is increased. Hence at increasing loads the stiffness tends to that of the unjoined system. As there is no evidence of actual dowel failure it is believed that it is failure of the welds between the dowels and the layers that contribute to this effect. The ultimate load is thus similar to that of the unjoined system. However, increased numbers of dowels result in decrease of deflection, which reaches 20% in the case of 44-dowel beam compared to the deflection of the unjoined one.

**Table 1:** Initial Stiffness, Ultimate Load and Maximum Deflection for Beams tested to failure

| Type of beam | Initial Stiffness (KN/mm) | Ultimate Load (KN) | Maximum Deflection (mm) |
|---|---|---|---|
| 44 dowels | 0.565 | 24.00 | 98.70 |
| 32 dowels | 0.465 | 22.75 | 108.15 |
| 20 dowels | 0.400 | 22.00 | 115.04 |
| Un-joined | 0.180 | 21.00 | 123.57 |

## 5. Conclusion

In this paper a novel full-scale multi-layered beam has been presented where the timber layers were interconnected via welded wood dowels to form a timber-timber composite element. A manufacturing process, whereby dowels are submerged in sunflower oil for a period of ten minutes prior to being used as part of the rotational welding technique, allow wood welded dowels to be used over greater depths of composite sections than has previously been achieved.

The experimental results demonstrate that it is possible to achieve a high degree of composite action using wood welded dowels as shear connecting elements. Increased numbers of dowels result in increased stiffness with the efficiency of composite action, measured using stiffness relative to a fully composite system, being between 49% and 74% for the beams tested. This degree of efficiency could be further enhanced for even more competitive performance by using more dowels in multiple rows. The strength increase was more modest and was attributed to progressive failure of the welds between dowels and individual layers as load increased. Clearly multiple dowel rows would reduce the stress on any individual weld and potentially manifest itself in more substantial strength increases; further investigation in this regard is needed.

In conclusion wood welded dowel systems do offer potential as viable load bearing systems in structural applications and coupled with their environmentally friendly footprint further research into these systems is both justified and required. Reliable methods for measuring and quantifying the precise strength of the welds produced are required. Equally investigations of their hydro-thermo-mechanical and creep/relaxation behaviour deserve attention.

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