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Cambering of timber composite beams by means of screw fasteners

Wyginanie drewnianych belek kompozytowych z użyciem łączników śrubowych

Keywords: Timber camber beam, Wood camber by screws, Reinforced wooden floors

Słowa kluczowe: drewniana stropnica łukowa, wyginanie drewna za pomocą śrub, wzmocnione podłogi drewniane

1. INTRODUCTION

When rehabilitating historical masonry buildings it is certainly not rare to come to deal with sagged timber floors which cannot be buttressed due to heritage issues. A similar problem occurs when historical buildings are readapted to a new building usage which provides for an increase in floor loads. In this case the timber floors, originally designed to bear low loads, will inevitably show an excessive midspan deflection (serviceability limit state). Therefore the development of a procedure which enables to "lift" a beam by just superposing a "dry reinforcement element", could prove of some interest.

If one considers a composite beam, as in Fig. 1a, where the fasteners forms a 90° angle with the beam axis, it can be seen that without any other external load all the compression forces due to the pressure generated by the screws are in equilibrium and therefore the beam remains undeformed. As soon as a load is applied Fig. 1b, the beam begins to sag and the two component elements exchange a system of forces similar to that in Fig. 1c. On the other hand, if the screws are positioned as in Fig. 1d, in order to reach the equilibrium, the two contact surfaces have to exchange a shear action (Fig. 1e) that is opposite to that in Fig. 1c and consequently the beam rises.

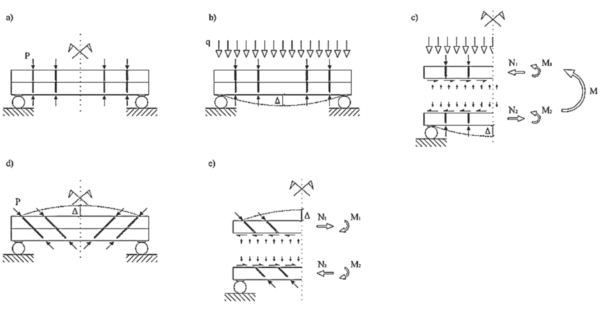

Fig. 1. Cambering principles for a composite beam

2. THE EXPERIMENTAL TESTS

The aim of this paper is to investigate the possibility of cambering a timber beam by simply putting another beam on the top of it and inserting screws inclined at 45° relative to the beam axis. So as to discover it, three tests have been carried out at the Laboratory of the Department of Mechanical and Structural Engineering (DIMS) of the University of Trento. Each specimen is composed by two 0,1 × 0,1 m^2 glulam beams 4 m long, connected by double threaded screws (Fig. 1). The fastener spacing (100 mm), is related to the need of obtaining a clear camber (more than 10 mm) through the connectors at disposal. It is utterly acknowledged that the flexural stiffness of a composite beam is directly related to the fasteners capability of hindering the two contact surfaces from slipping each other. Since the interface slip is maximum at the ends of the composite beam and minimum in the central part, cambering is expected to be more difficult when the screw assembly starts from the outer parts of the beam rather than when it

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starts from the inner part. Consequently tests No. 1 and 3 have been performed inserting the screws from the middle to the ends (Int-to-Ext) and test No. 2 has been carried out from the ends to the middle (Ext-to-Int). Before inserting any mechanical connector, a series of elastic bending tests has been performed in order to determine the MoE of the considered elements (Table 1).

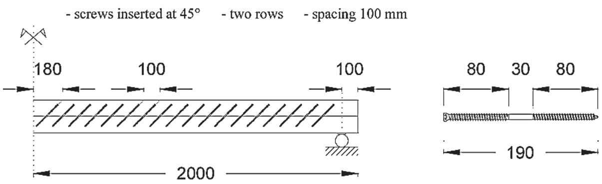

Fig. 2. Test setup

Table 1. MoE of tested elements

Composite Beam	C1		C2		C3	
Element	M1	M2	M3	M4	M5	M6
E [Mpa]	7327	12024	11863	8712	11358	9245

Table 2. Experimental upward camber

	wL/2 [mm]	Screwing pattern
C1	13.39	Int-to-Ext
C2	6.94	Ext-to-Int
C3	14.92	Int-to-Ext

Table 2 shows the results of the cambering procedure. As expected, test No. 2 (Ext-to-Int) exhibits a final value significantly lower than the other tests.

The camber amount (it has been observed an upward deflection of about one three-hundredth of the total beam length) could possibly be increased by reducing the screw spacing or by using fasteners able to generate a greater pressure. In doing so, keen attention should be paid to the magnitude of the internal stress state imposed by the cambering procedure. It is also quite evident that further testing is needed so as to fully understand the behaviour of such a composite beam in the long-term period. For the time being, the three assembled specimens have been monitored for 48 hours, during which no camber loss has been detected.

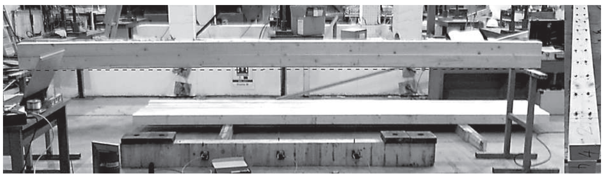
Fig. 3. Composite beam C1 after fastener insertion (starting from the beam centre)

3. THE NUMERICAL MODEL

A numerical model has been developed through the finite element software SAP2000. In particular, as to reproduce the act of inserting the screws one after the other, the nonlinear staged-construction function has been employed [1]. The choice of not utilizing the structure symmetry is due to the impossibility, during "real" assembly, of inserting the fasteners on symmetric positions simultaneously. However in that case, a slightly lower value of the final camber would have been reached since at the application of the screw pressure, the connector stiffness is already in place (other solutions have been tested but have led to excessive values of upward camber). Both the fasteners and the wood elements have been modelled as linear elastic materials. The stiffness of the screw couple K_c has been determined in accordance with [2] (K_c = 26303 N/mm) and has been reproduced by means of two crossed rods (inclined at 45°) whose axial stiffness is equal to K_c itself. The screw pressure has been introduced as a system of two inclined forces acting at the screw nodes. In addition, inextensible rods have been used to keep locked the distance between the barycentre lines of the wood elements.

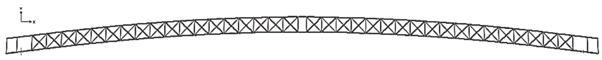
Fig. 4. The F.E. model

So as to determine what sort of pressure is to be assigned to the screw couple, some tests have been performed, relying on the setup showed in Fig. 5. Many parameters have been pried (e.g. screw angle with respect to the grain direction, initial pressure, head penetration length, threaded part length, connector typology, wood density, time-dependence) and further testing has already been started. A resultant pressure value of 4.4 kN for the single screw has been deemed as acceptable.

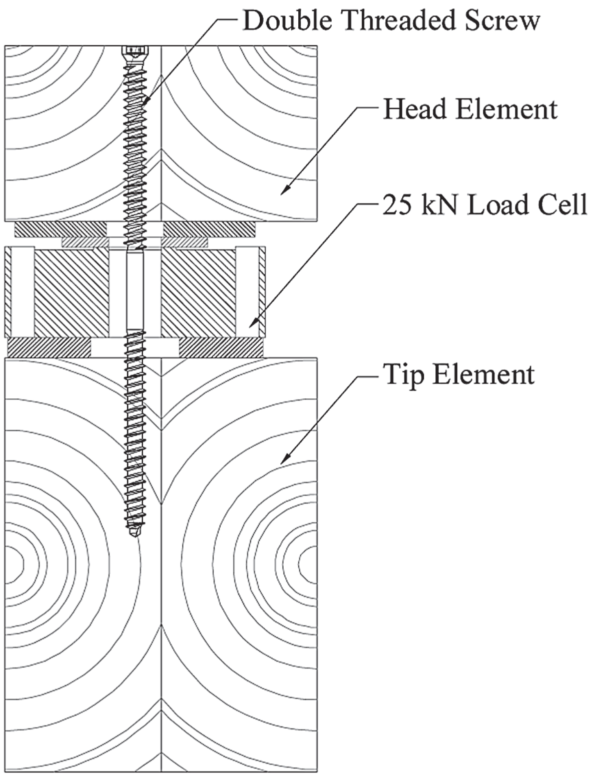

Fig. 5. Screw pressure test setup

The results obtained from the numerical model are given in Table 3 Regarding specimens C1 and C3, it could be seen that the numerical model reproduces the experimental behaviour with sufficient precision for both the tested screwing patterns (Int-to-Ext and Ext-to-Int). An underestimation of the camber value has been observed for specimen C3.

Table 3. Experimental data Vs. Numerical values [mm]

	Experimental	Numerical	Err. %
C1	13.39	13.78	2.91
C2	6.94	7.40	6.63
C3	14.92	12.52	16.09

4. THE ANALYTICAL FORMULA

Starting from equilibrium considerations [3] and taking into account the static scheme of Fig. 6, if one assumes the absence of the external bending moment, it is possible to obtain Eq. (1) and consequently Eq. (2):

$$N_{1,i}''(x) - \alpha^2 N_{1,i}(x) = 0, \text{ with } N_{1,i}''(0) = 0,\ N_{1,i}(si) = T \qquad (1)$$

$$N_{1,i}(x) = \frac{T \sinh(\alpha x)}{\sinh(\alpha si)} \qquad (2)$$

where:

- $N_{1,i}$ is the axial force in the upper element of the composite structure (the beam length is equal to *si*);
- $N_{1,i}''$ is the second derivative of $N_{1,i}$;
- *i* is the number of the screw couple (labelling starts from the internal side);
- *T* is the horizontal component of the resultant pressure yielded by one couple of inclined screws;
- k_c is the distributed stiffness of fasteners;
- *a* is the distance between the centreline of the two elements;
- $\alpha = [(k_c EJ_\infty)/(EJ_0 EA_0)]^{0.5}$;
- EJ_0 is the flexural stiffness of the composite beam with no mechanical connections;
- EJ_∞ is the flexural stiffness of the ideal composite beam;
- $EA_0 = (\sum 1/EA_j)$-1;
- EA_j is the axial stiffness of the *j-th* element;
- *s* is the fastener spacing.

After determining $N_{1,i}$, the calculation of the *i-th* beam deflection can be attained as follows:

$$w_i''(x) = -\frac{N_{1,i}(x)\times a}{EJ_0}, \text{ with } w_i(0) = 0, w_i'(0) = 0 \qquad (3)$$

$$w_i(x) = \frac{Ta}{EJ_0 \alpha \sinh(\alpha si)} \times \left[x - \frac{\sinh(\alpha x)}{\alpha} \right] \qquad (4)$$

Hence it is easy to characterize the contribution of the *i-th* screw couple to the beam camber:

$$\Delta w_{i,L/2} = w_i(si) + w_i'(si) \times \left(\frac{L}{2} - si \right) \qquad (5)$$

Finally the evaluation of the beam camber is presented:

$$w_{L/2} = \sum_{i=1}^{n} \Delta w_{i,L/2} = \sum_{i=1}^{n} \left\{ \frac{1}{2} \times \frac{Ta\left[\cosh(\alpha si)\left(2si - L\right) + L\right]}{\sinh(\alpha si) EJ_0 \alpha} \right\} - \frac{nTa}{\alpha^2 EJ_0} \qquad (6)$$

where *n* is the total number (Fig. 7) of fastener couples.

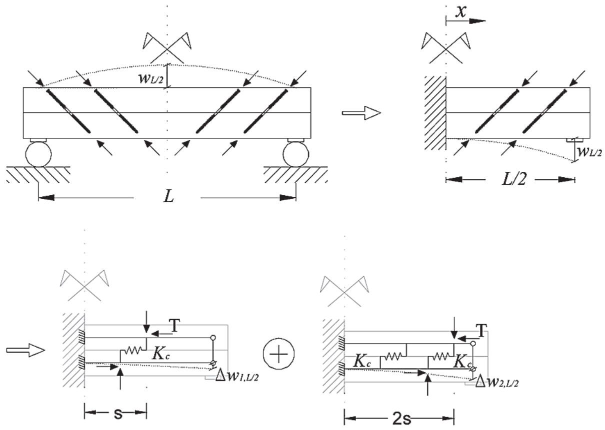

Fig. 6. Static scheme adopted for the analytical formulation

Table 4 provides a comparison between experimental data and analytical values obtained through eq. (6). The proposed formula seems able to reproduce the experimental camber of C1 specimen with quite good precision, while a certain error (13%) has been observed for C3 specimen. It should be noted that for composite beam C3 the numerical model gave a very similar prediction (19% err.).

Table 4 .Experimental data Vs. Analytical values [mm]

	Experimental	Analytical	Err. %
C1	13.39	13.28	0.82
C2	6.94	-	-
C3	14.92	12.88	13.68

As outlined in Fig. 7a, the effectiveness of an *i-th* screw couple depends on how many couples have already been inserted and on the fastener spacing. Although it has been

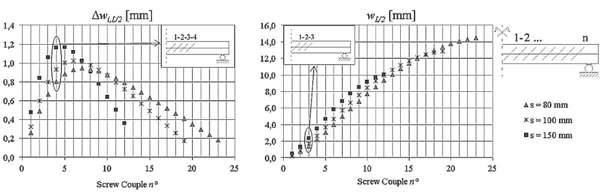

Fig. 7. a) Couple effectiveness to the upward camber; b) Camber evolution

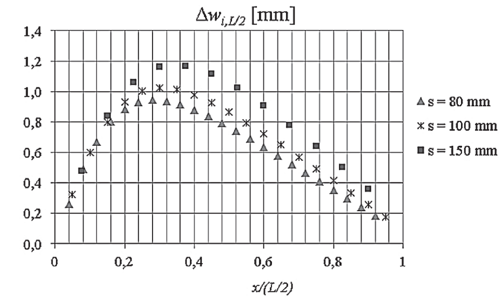

Fig. 8. Screw couple effectiveness Vs. Its position along the beam

observed that (Fig.8) the greater the spacing the greater the effectiveness, if one focuses on the global result it is clear that increasing the spacing reduces the amount of screws and consequently the final camber (Fig. 7b).

5. CONCLUSIONS

The exposed cambering procedure has proved to be effective and permits to obtain significant values of upward deflection. Obviously, the camber has to be consistent with what is connected to beam. In addition, it ought to be underlined that the experimental tests presented in the paper, have involved new timber beams with clearly defined boundary conditions. To assess the real effectiveness of this method (regarding the refurbishment of old floors), an experimental campaign on existing sagged beams, should therefore be undertaken. Particular attention will have to be paid to the internal forces that this procedure generates into an allegedly deteriorated beam.

Both the experimental tests and the numerical model have shown that the best way to obtain an upward deflection is to start the assembly from the centre and alternatively proceed towards the ends of the beam.

The proposed analytical formula seems to be able to reproduce the experimental behaviour and presents the benefit of being "easily manageable". This is mainly due to the choice of considering a constant fastener spacing along the beam axis. Otherwise, it would have been necessary to introduce Fourier transforms [4] that would have prevented the analytical model from being handled without a specific software for symbolic calculation.

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Abstract

The aim of this paper is to investigate the possibility of cambering a timber beam by simply putting another beam on the top of it and inserting screws inclined at *45*° relative to the beam axis. To this purpose, three experimental tests have been performed at the Laboratory of the Department of Mechanical and Structural Engineering (DIMS) of the University of Trento. After the calibration of a numerical model that helped in understanding the "cambering phenomenon", an analytical formulation has been proposed. The resulting formula for determining the upward camber (given the mechanical properties of the beams and of the fasteners) has shown the capability of reproducing the experimental behaviour with promising accuracy. However, further testing is recommended so as to validate the method feasibility to existing beams.

Streszczenie

Niniejsza praca ma na celu zbadanie możliwości wyginania drewnianej belki przez położenie na niej innej belki i zamocowanie śrubami pochylonymi pod kątem *45*° w stosunku do osi belki. W tym celu przeprowadzono trzy eksperymentalne testy w Laboratorium Wydziału Inżynierii Mechanicznej i Strukturalnej (DIMS) Uniwersytetu w Trento. Po skalibrowaniu modelu numerycznego, który pomógł lepiej zrozumieć "zjawiska wyginania", zaproponowano zapis analityczny. Otrzymana formuła na wyznaczanie wypukłości łuku (biorąca pod uwagę mechaniczne własności belek i elementów mocujących) wykazała zdolność powtórzenia zachowania eksperymentalnego z obiecującą dokładnością. Rekomendowane są dalsze testy aby sprawdzić możliwość zastosowania tej metody w odniesieniu do istniejących belek.