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New system of self-tensioning for long-span wooden structural floors

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ABSTRACT: A self-tensioning system that improves the behavior of elements under bending is described, from a resistant point of view such as deformations. The system is based in a force multiplying device tied in the opposite ends of the piece. Such device is activated with the loads which are transmitted to the supports, generating an eccentric tensioning force whose value varies with the magnitude of the applied loads. That tensioning force achieves an efficient redistribution of bending stresses. Different design parameters that determine the structural behavior of π-type section floors subjected to symmetrical and asymmetrical loads have been analyzed. The effectiveness shown by the system makes it especially interesting for its use in long-span structural floors with reduced depths.

KEYWORDS: Pre-stressing; Self-tensioning; Post-tensioning; Wooden floors; Long-span flooring; Timber construction.

1. Introduction

The use of the pre-tensioning technique is thoroughly known and it has acquired an enormous development in the concrete structures field. The possibility of introducing in a structural element an effect which is contrary to the one that is provoked by the gravitatory actions, improves both the resistant behavior and the one in a service situation (deflections, cracks), allowing the use of less dimension sections. In the case of concrete, the pre-tensioning is especially efficient due to the low resistance to tensile internal forces of the material and its cracking problems, what justifies the success of this technique.

In the case of wood, for internal forces which are parallel to the fiber, the material presents a high resistance both to compression and tension and, consequently, to bending too. This makes that, in terms of stress distribution in the section, the pre-tensioning does not mean a significant improvement. On the other hand, in wood there are not the concrete cracking problems and, from the deformations point of view, the possibility of easily obtaining a manufacturing precamber allows to compensate, to a certain extent, the deformability of the material. All the above explains why the use of the pre-tensioning technique is much less widespread in wood and, because of analogous circumstances, in steel than in the case of concrete.

There is however an approach in which the use of pre-tensioning in wooden structures might represent a clear improvement. The difficulty to obtain rigid joints with this material makes that frequently the affected pieces are arranged simply supported. The rotation of the ends leads to a highly inefficient bending moments and deformation behavior, what considerably damages the sizing. In these conditions, the pre-tensioning allows to achieve a redistribution of the bending moments along the directrix of the piece, reducing the stress state and improving, in a very significant way, its deformation behavior. Pre-tensioning, in this case, becomes an indirect way of obtaining a behavior of the deflected piece which is closer to the one corresponding to an element that has its ends rigidly connected.

Up to now, the tensioning of deflected wooden pieces has been made by using fundamentally two types of techniques: adherent tendons and unadherent tendons.

Pre-tensioning with adherent tendons consists on gluing a previously tensioned tendon on a wooden piece. The tendon is eccentrically disposed with the aim of generating a flexion which is contrary to the one produced by external actions. This tendon can be made of steel in the shape of a bar or a sheet [1,2] or using fiber reinforced polymers (FRPs) [3-6]. The types of adhesives which are used are varied, although frequently the most widespread are polyurethane and the ones based on epoxy formulations. One of the most characteristic problems of this kind of solutions is the concentration of stresses in the anchoring of the ends of the tendon, which might lead to delamination phenomena [7,8].

The use of unadherent tendons has also been the object of a number of studies, both with pre-tensioning and post-tensioning solutions. One field that has been especially developed is the one of the use of post-tensioning as a technique to improve the stiffness of beam-pillar joints in framed structures, facing traditional joints using ironwork [9-13].

The present article describes the efficiency of a new self-tensioning system that allows to reduce deflections of bending pieces. It is especially suitable for its use in wooden structural floors of long-spans.

2. SELF-TENSIONING SYSTEM

The sizing of bending wooden pieces that are simply supported is usually determined by the observance of deformation conditions. In such circumstances, reaching the necessary stiffness to satisfy deflection limitations leads to oversized sections in a resistant level. One way to try to reduce this problem is by applying a manufacturing precamber, easily enforceable in laminated timber pieces but not so much in other type of products. It is also possible to get a precamber through pre-tensioning. These solutions are efficient for the limitation of deformations on appearance and for low service imposed loads; a classic situation in roofing structures.

In structural floors with public service imposed loads (3.0 to 5.0 kN/m²) the serviceability criteria that determines the sizing is the one of the integrity of constructive elements. It is about delimiting the value of relative deflection produced from the placing of a harmful element (usually partition walls and coating).

As wooden structures are very light, the self-weight of the floor intended for public use, represents a reduced percentage of the whole load. This means that when the harmful element is implemented, the applied load is still low and, besides, it has not been produced any creep deformation. Henceforth, the profit of an initial precamber is going to be necessarily reduced, because the sizing is going to be determined by the deflection (instantaneous + creep) produced from the implementation of the harmful element by all the loads that are still to apply. These loads represent an important percentage of the total load on the piece.

The previous difficulties can be efficiently solved by arranging a post-tensioning of the piece with a value variable with the magnitude of the applied loads. Self-tensioned system SsS® consists on supporting the piece on a force multiplying device to which the end of the tensioning tendons are connected. The load which is transmitted to the supports (R) originates an axial force on the tendon (N) that leads to the piece post-tensioning effect.

Self-tensioning system can be materialized with different types of devices, both mechanical and hydraulic. An efficient solution consists on a system of connecting rods to which the end of the tendon is connected (Figs. 1,2). When that device receives load the connecting rods lengthen the tendon generating a tensioning force, which is proportional to the outer applied action. This significantly improves its flexural behavior.

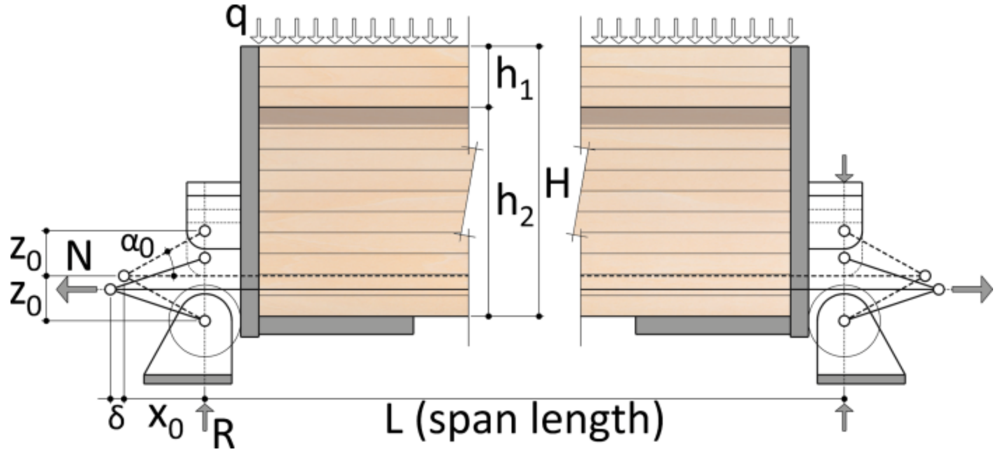

Figure 1: Force-multiplying device

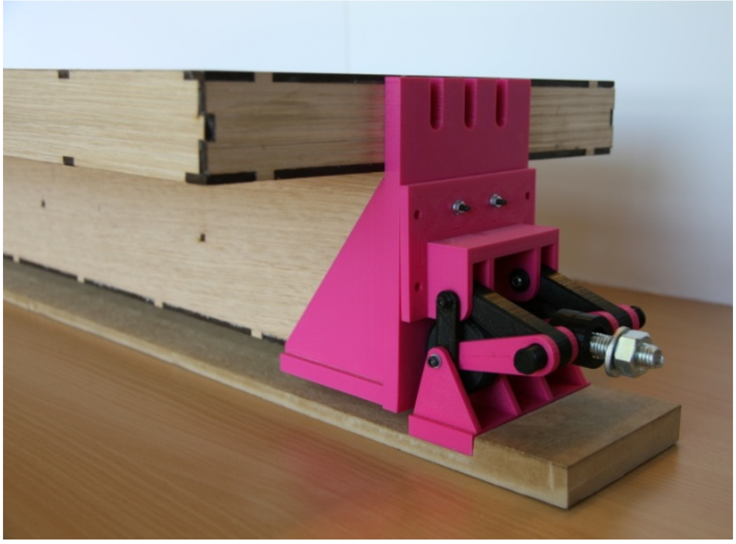

Figure 2: Force-multiplying device. 3D-priter prototype

The axial force value in the tendon (*N*) is related to the reactions in the supports (*R*) through a multiplying factor (Ӿ) whose value varies with the geometry of the device in each position *i* (Fig. 1) according to the following equation (1):

$$Ӿ_i = \frac{N_i}{R_i} = \frac{2.R_i/tan\alpha_i}{R_i} = \frac{2}{tan\alpha_i} \quad (1)$$

By increasing the load on the element, the reactions of the supports and, consequently, the magnitude of the post-tensioning increase too. On the other hand, the multiplying effect increase with the reduction of the angle α between the connecting rods. This way we get a tensioning effect whose intensity depends on the geometry of the system and on the magnitude of the acting loads.

Therefore, the main advantages of the system are, on the one hand, the tensioning force adjusts to the magnitude of the acting loads, increasing or decreasing its effect according to the changes in the actions. On the other hand, the tensioning is made automatically, without hydraulic jacks or other devices for its tensioning. It is, ultimately, and from a conceptual point of view, a device that makes the most of the loads that the structural element has to bear to generate a favorable effect on its behavior (the contrary flexion to the one which is produced by the outer actions).

3. EFFICCIENCY OF THE SYSTEM FOR LONG-SPAN STRUCTURAL FLOORS

With the aim of illustrating the efficiency of the system in timber structural floors with long span and high imposed loads (public uses), the behavior of a building structural floor has been analyzed with the following characteristics:

- π-type transversal section shaped by two laminated timber ribs GL28h, according to the established classification in EN 14080:2013 [14], and a cross-laminated timber top board (CLT-cross laminated timber) [15] (Fig. 3).
- *B*=1200 mm; *b*=180 mm; *H*=420 mm;
- h_1=90 mm; h_2=330 mm.

- Two types of section:
  S1. Section without pre-tensioning and initial manufacturing precamber.
  S2. Section with a precamber of L/500 and self-tensioning system.
- Span of 14 m.
- Self-tensioning system with the following geometrical features (Fig. 01):
  x_0=100 mm; z_0= 50 mm; α_0=26,6º
  Area of the self-tensioning tendon Ω=1.000 mm².
- Acting loads according to Eurocode 1 [16]:
  Permanent load: G_k=2.0 kN/m² (it includes the self-weight of the structure).
  Imposed load: Q_k= 3.0 kN/m² corresponding to the administrative or public use with furniture.
  Coefficient for obtaining the quasi-permanent fraction of variable loads: ψ_2=0.3.
- Load hypothesis considered:
  H0: No load. Initial position.
  H1: Permanent load, G_k=2.0 kN/m².
  H2: Quasi-permanent load, $G_k + \psi_2.Q_k$=2.9 kN/m²
  H3: Total load, $G_k + Q_k$=5.0 kN/m²

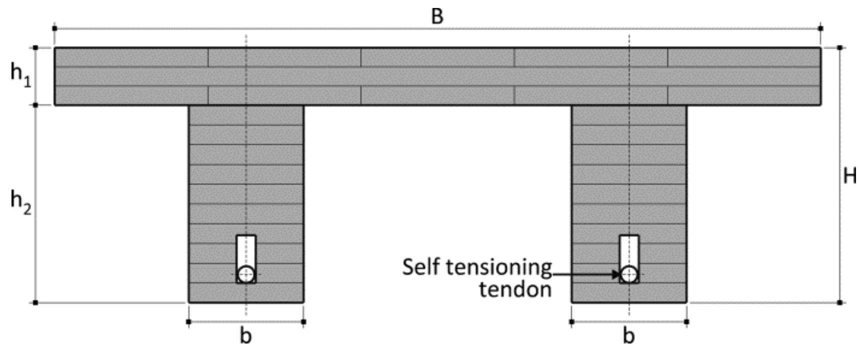

Figure 3: π-type cross section

The loading of the device leads to a seat of the supports (s). The relative deformation or deflection (w) of the element is obtained as the difference of the maximum vertical displacement (u) of the midpoint of the span and the seat (s) of the supports. In the calculation of the vertical displacement (u) it has been considered both the instant deformation (u_{inst}) and the creep one (u_{creep}) produced on wood by the action of permanent loads due to the combined effect of humidity and creep. To this end, a creep factor has been taken (k_{def}) with a value of 0.60 according to what is established by Eurocode 5 [17] for a service class 1 corresponding to inner environment structures.

$$u_{creep} = u_{ini} \psi_2 k_{def} \tag{2}$$

The seating of the supports leads to a significant change in the geometry of the multiplying device, which originates that the value of the seat and the tensioning force grow with the applied load in a nonlinear way [18, 19]. This has made it necessary to deal with the analysis through an increasing load process, in which the multiplying effect corresponding to the deformed state in every step has been taken into account.

3.1. SIMMETRICAL LOADS

The final deformations (instant and creep) have been represented in Fig. 4. They correspond to the two types of section (S1 and S2) for the 4 load hypotheses that have been considered. (H0 to H3).

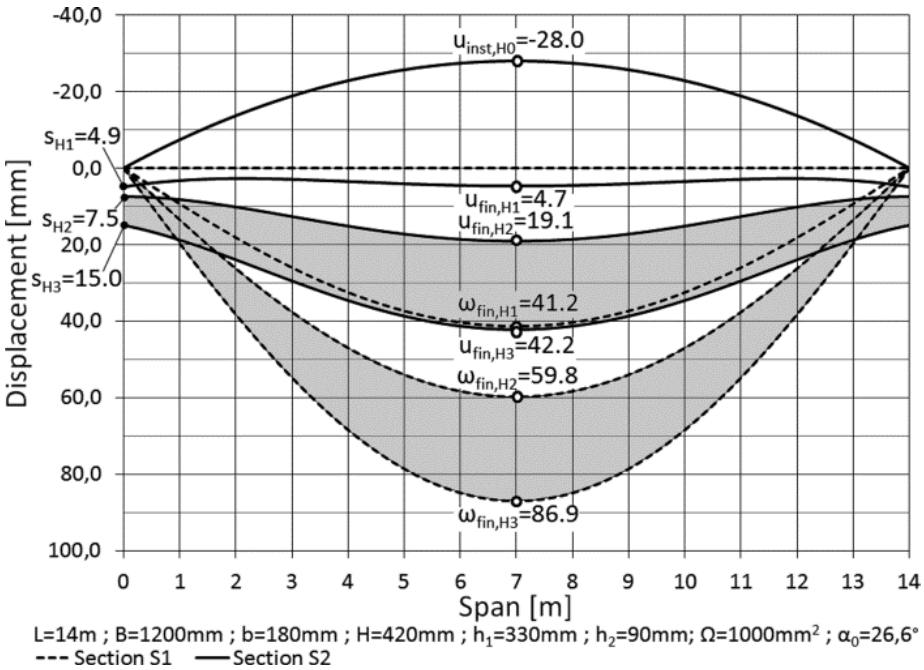

Figure 4: Deformation comparation for non-prestressed sections (S1) and sections with the self-tensioned system (S2)

The efficiency of the system is verified by comparing the deformations corresponding to hypotheses H2 and H3, because those hypotheses correspond to the situations that delimit the service position in which the structure is going to stay for its service life (indicated by a shading in the figure). In the case of the timber section without pre-tensioning nor precamber (S1), the final deflection ($u_{fin}=u_{inst}+u_{def}$) for hypothesis H2 gets the value of 59.8 mm, what represents a relative deflection of L/234. In the case of section S2 (precamber + self-tensioning) the descent of the midpoint of the span for the same hypothesis is H2 $u_{fin,H2}$=19.1 mm. But, at the same time, the supports assume a value s_{H2}=7.5 mm. Consequently, the relative deformation is $w_{H2}=u_{fin,H2}-s_{H2}$=11.6 mm, what represents a relative deflection L/1207. In the case of the total load hypothesis H3, the final deflection for section S1 is 86.9 mm (L/161), as long as for the self-tensioning solution with initial pre-tensioning, the value of the relative deflection is $w_{H3}= u_{fin,H3}-s_{H3}$=27.2 mm (L/515).

The previous results lay bare the great efficiency of the self-tensioning system, because it allows to execute long-span structure floors (14 m in the example) with a considerably reduced depth, achieving that, when the structure is in service (applied load of 2.90 kN/m^2 to 5.00 kN/m^2, hypotheses H2 and H3, respectively) deflection varies among values from L/1207 to L/515.

3.2. ASYMMETRICAL LOADS

The support of the piece in both ends over multiplying devices only works correctly if the applied load transmits identical actions on the supports. In that case, compression forces on the device connecting rods balance themselves with the tension of the tendon.

In a situation with asymmetrical loads, such balance is not possible because the acting forces on each one of the multiplying devices require a tension in the tendon of a different magnitude on each of its ends. This situation is easily solved by arranging a central anchoring of the tendon. Therefore, the tendon can reach different tension values that achieve a balance in the central section of the piece. The force values that need to be transferred to the wood in the anchoring area have a reduced magnitude, as a short and simple adhesive can be used through a resin injection.

To analyze the behavior of the system under the action of asymmetrical loads, we accompany the obtained result for a structural floor with the same features and subjected to the loading hypotheses of figure 5. The efficiency of the system is evident, as we can see in Figs. 6 and 7, that compile deformations and bending moments. The asymmetrical disposal of the load leads to reactions on the supports of different magnitude and, consequently, the multiplying devices generate tensioning forces which are different in each end, leading to a higher post-tensioning, precisely on the most demanded zones in the piece. As a result, we can state that the action produced by self-tensioning system “adapts” itself not only to the magnitude of the acting loads, but also to its display along the directrix of the piece.

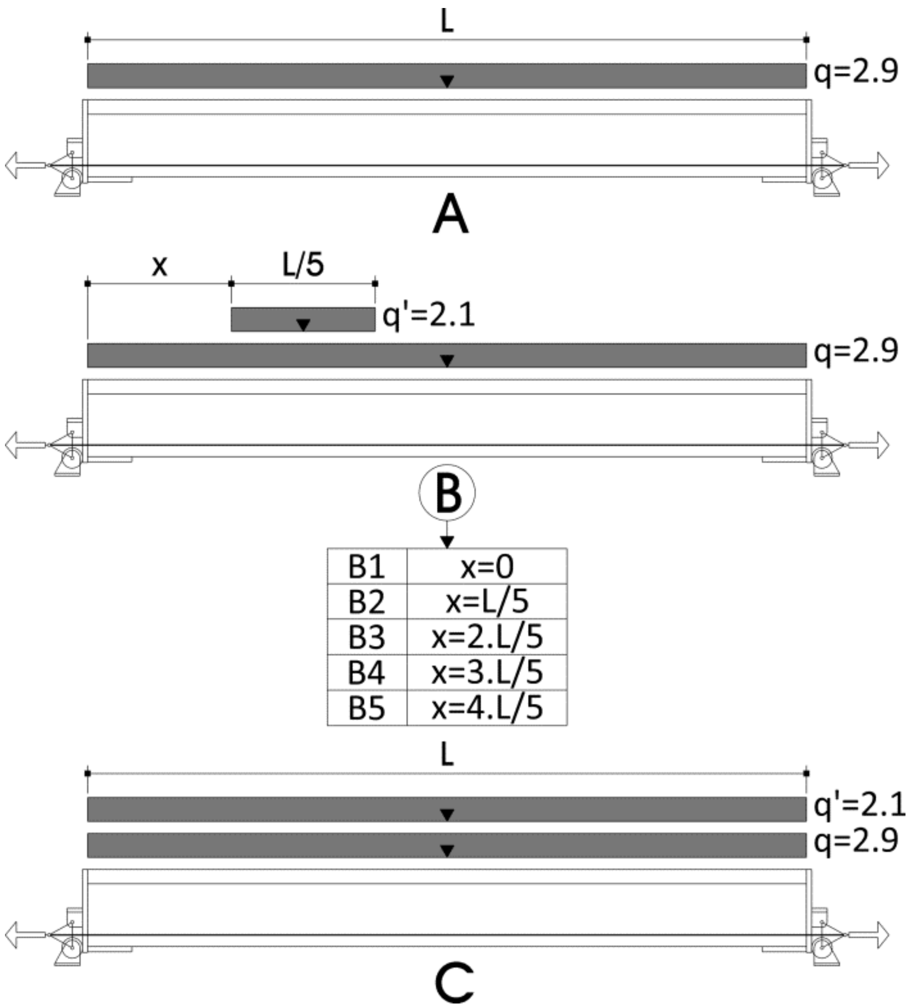

Figure 5: Load hypotheses for an asymmetrical analysis

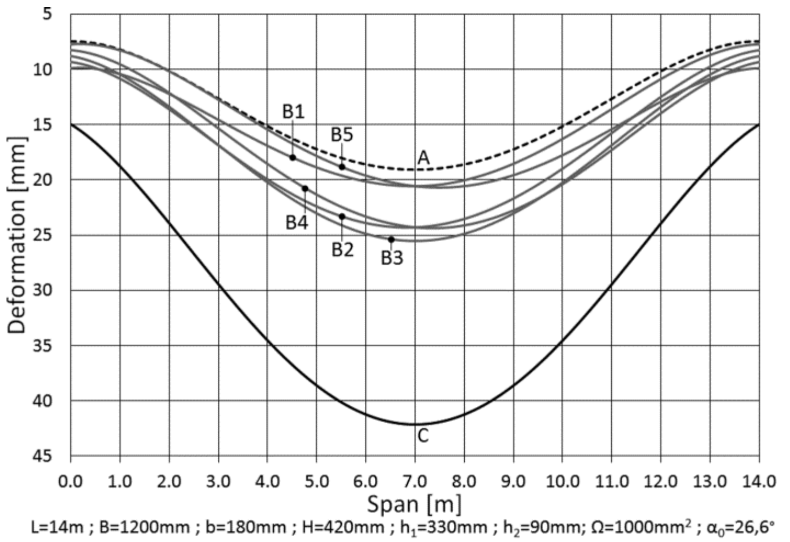

Figure 6: Deformation. Load hypotheses A, B1 a B5, C

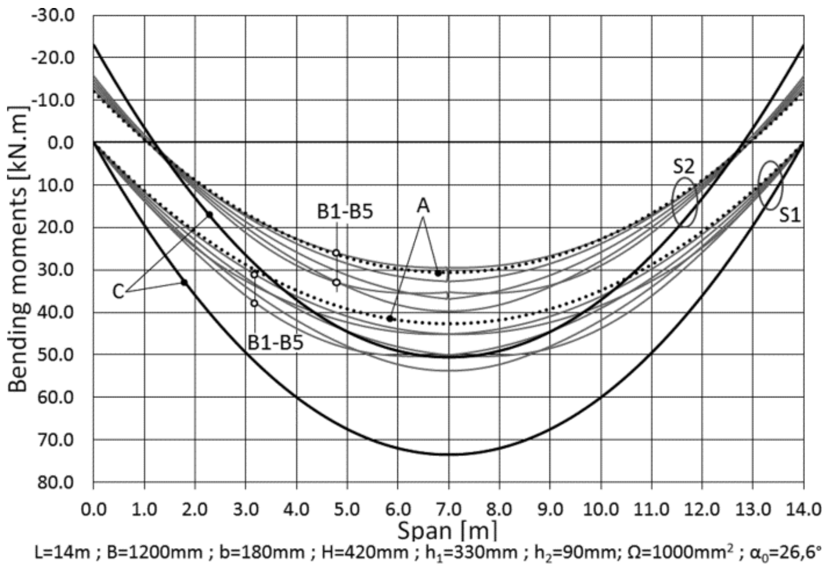

Figure 7: Bending moments. Load hypotheses A, B1 a B5, C

4. DESIGN PARAMETERS

The efficiency of the self-tensioning system in the behavior of the deflected piece fundamentally depends on the geometry of the multiplying device (connecting rod angle), the axial stiffness of the tendon (tendon area) and the stiffness to flexion of the piece (principally, the depth of the element) [19].

4.1. CONNECTING RODS ANGLE

The angle α that is shaped by the connecting rods of the self-tensioning device has a fundamental impact in two aspects: the magnitude of the multiplying effect $\mathcal{X}$ and the value of the seat s of the supports.

The smaller is the angle α greater is the multiplying effect and, consequently, the tensioning force. This leads to a better behavior of the piece from the deformation point of view, due to the positive effect produced by the moment applied on the ends of the piece.

However, the positive effect of an angle α reduced in the magnitude of the tensioning force is compensated by an increasing of the seats. On the other hand, a reduced angle limits the total load that can be applied to the multiplying device, because it reaches an asymptotic growth of the seats very quickly. Figure 8 shows the variation of both the multiplying effect and the seat according to the total load applied on the element. The curves have been obtained for a piece with the same span and geometrical features previously defined.

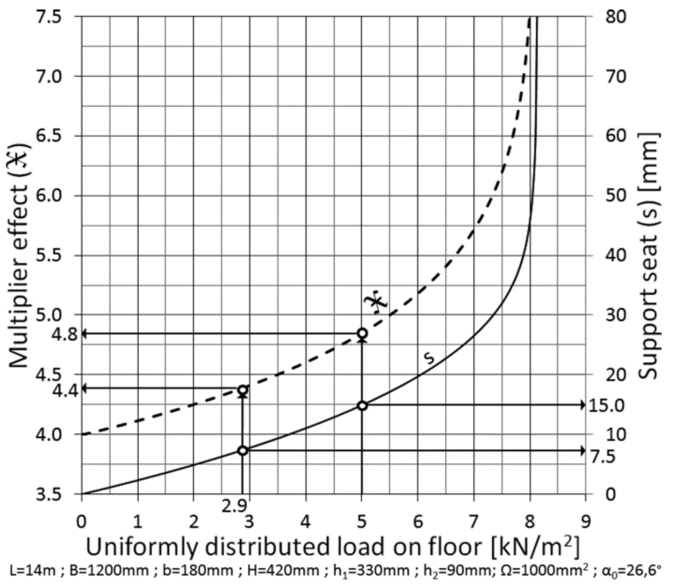

Figure 8: Multiplier effect and support seat variation as a function of loads

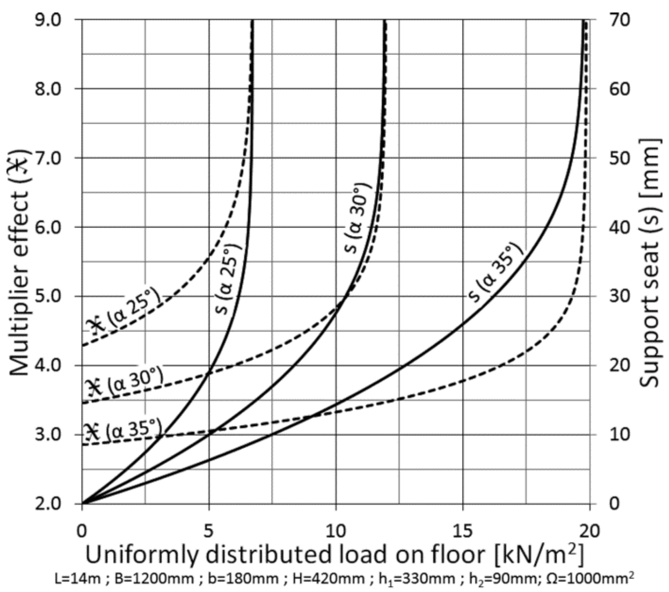

Figure 9: Multiplier effect and support seat variation as a function of loads for different angle between rods

Figure 9 shows the variation of the seat s and the multiplier Ӿ for three angles between connecting rods (25°, 30° and 35°). With the aim of visualizing the effect of the angle between the connecting rods on the behavior of the deformation of a piece, it has been represented in Fig. 10 the final deformations (instant + creep) corresponding to hypotheses H0 and H3 for three connecting rods angles (25º, 30º y 35º). These deformations show the effect of the connecting rods angle. By reducing the angle there is an increasing of the value of the seat of the supports, while there is very little difference in the total displacement produced in the midpoint of span. As a result, the piece deflection, understood to mean the difference in displacement between the midpoint of the span and the supports, is smaller. That is, with reduced angles we can obtain smaller relative deflections, at the expense of seats with a greater magnitude, what, undoubtedly, constitutes a favorable effect, because the damages on constructive elements (specifically partition walls) are directly related to the deflection of the element on which they support themselves.

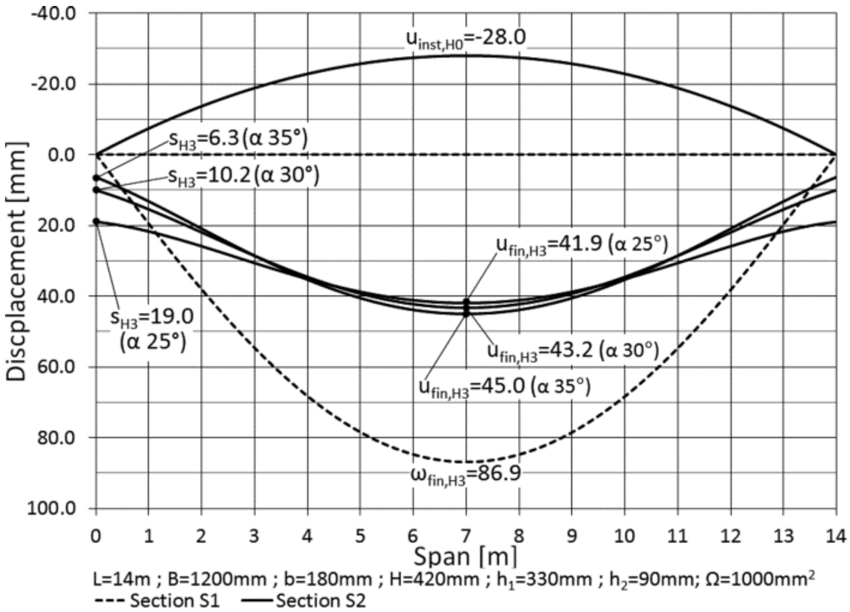

Figure 10: Deformation comparation for non-prestressed sections (S1) and sections with the self-tensioned system (S2) for different angle between rods

4.2. SELF-TENSIONING TENDON AREA

The deformation experimented by the multiplying device when it is loaded is also related to the axial stiffness of the self-tensioning tendon, and, therefore, to its area (*Ω*). The influence that the area of the tendon has on the behavior of the piece through deformation, is very similar to the effect which is produced by the angle between the rods. A tendon of reduced area experiments a bigger lengthening, which means a greater deformation of the multiplying load device, and therefore, a bigger seat. But, on the other hand, due to the non-geometrical linearity, the bigger deformation of the device leads to a higher tensioning force and a smaller final deflection of the piece. Ultimately, while the area of the tendon is reduced, the relative deformation of the piece is reduced too, but at the expense of important seats on the supports. The described effect can be clearly seen in Fig. 11 corresponding to a piece with features previously indicated and where it is represented the deformations corresponding to the load hypotheses H0, H2 and H3 for the two types of section (S1 and S2) using three different tendon areas (750, 1000 and 1250 mm²).

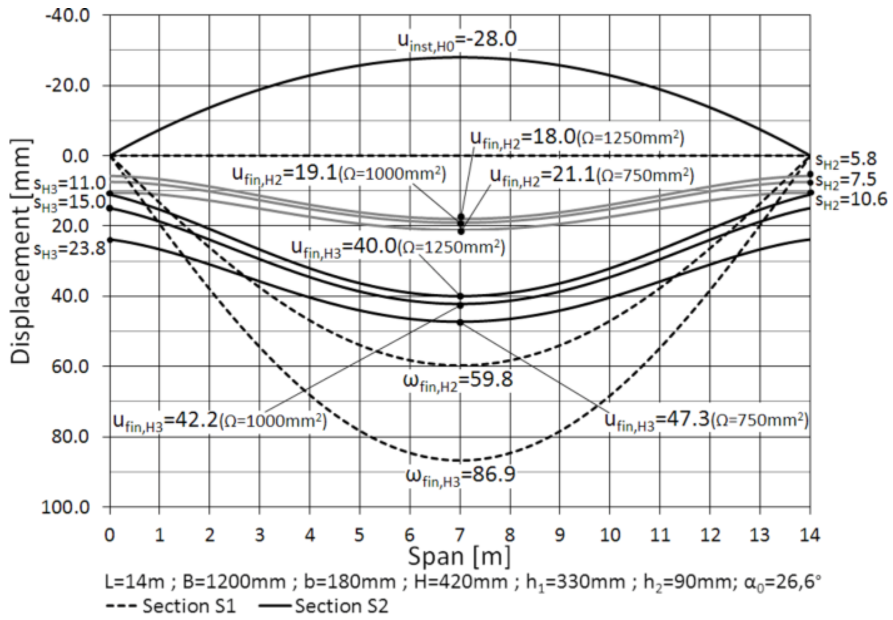

Figure 11: Deformation comparation for non-prestressed sections (S1) and sections with the self-tensioned system (S2) for different tendon areas

4.3. STRUCTURAL FLOORS DEPTH

The efficiency of the self-tensioning system allows to obtain long-span structural floors with great slenderness. The depth of structural floors influences on the behavior of deformation from two points of view: on the one hand, obviously, an increasing of the depth increases the flexion stiffness, reducing its deformability; on the other hand, by increasing the depth, the distance between the tendon and the centre of gravity increases, so on equal tensioning force, it generates a bigger moment and, consequently, a reduction of the deformation.

With the aim of viewing the influence of the depth used on the behavior of the element, it has been represented on Fig. 12 the corresponding deformations to hypotheses H0, H2 and H3 of the piece S2 previously described, using three different depth values (0.025L, 0.030L and 0.035L). Given that the depth does not affect the geometry of the multiplying device or the tensioning force, the obtained seat is the same on the three cases, only varying the deflection which, however, obeys the normative requirements in every case.

Finally, we need to indicate that a design with an appropriate choice of the previous parameters (rod angles, tendon area and structural floor depth) combined with the initial precamber value, allows us to obtain a structural floor solution whose deflection on the quasi-permanent load hypothesis is practically nonexistent. As a kind of example, it has been represented in Fig. 13 the deformations corresponding to the piece type S2 with features already indicated in which there is a variation on the floor depth, tendon area and the initial manufacturing precamber. It can be seen how in the service situation (hypothesis H2 corresponding to quasi-permanent combination) we can achieve a practically nonexistent relative deflection with an appropriate choice of the three quoted parameters, which guarantees the efficiency of the patented system.

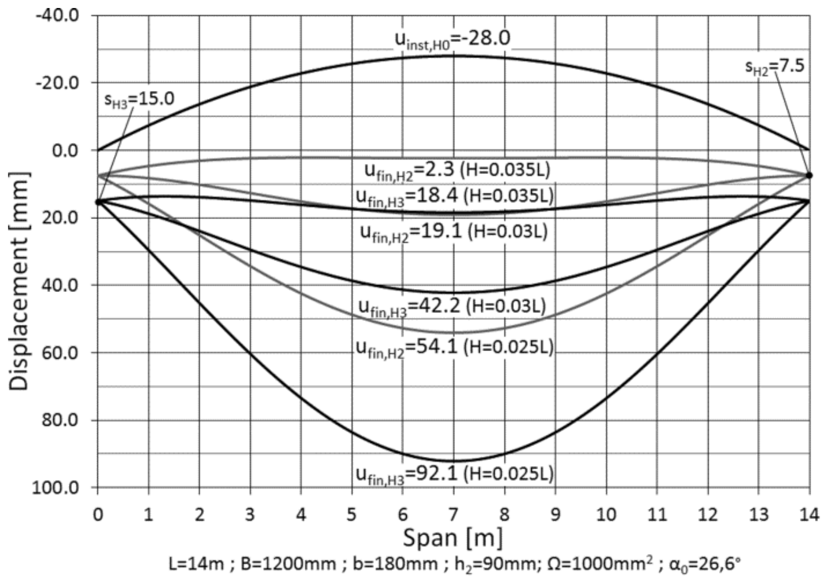

Figure 12: Deformation of section with the self-tensioned system (S2) for different structural floors depths

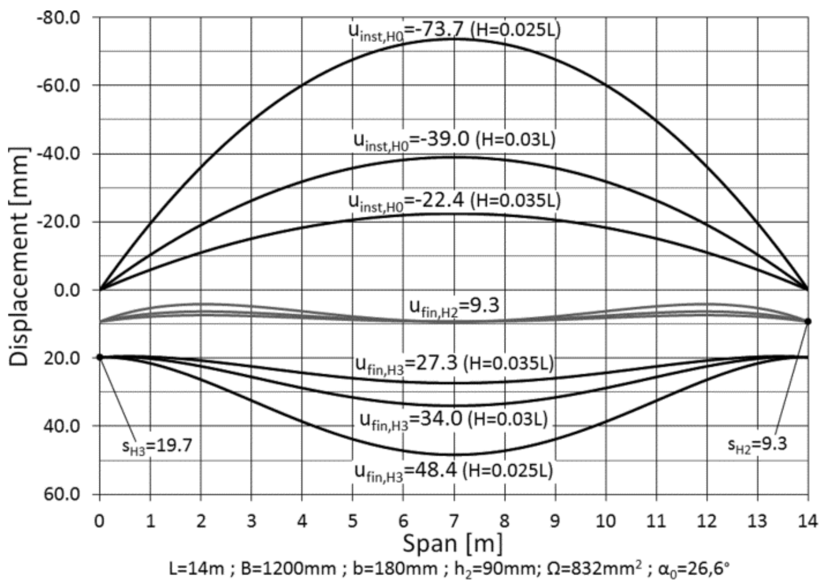

Figure 13: Deformation of section with the self-tensioned system (S2) with different design parameters

5. CONCLUSIONS

Self-tensioning system SsS® provides a much more favorable distribution of the bending moments, so that a high efficiency of the deflected sections in terms of both resistance and deformation is achieved. This makes the system especially suitable for use in long-span wooden structural floors.

An appropriate use of the different design parameters which determine the structural behaviour of the self-tensioning system allows us to design long-span structural floors with reduced depths with a relative deflection during service of very low magnitude.

ACKNOWLEDGEMENT

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