Single Step Joint Reinforced with Self-Tapping Screws: Design Models compared to Experimentation

Conference Paper · September 2017

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KEYWORDS

Timber, Single Step Joint, Reinforcement, Self-Tapping Screws, Design, Experimentation

ABSTRACT

In the field of Built Heritage Restoration, Architects and Engineers have to work with old timber carpentry connections including badly preserved Single Step Joints (SSJ). Over time, this traditional connection may be subject to structural damage such as the shear crack or the compressive crushing. These both SSJ failure modes cause high deformation as well as the destabilization of timber elements inside the carpentry. As the Self-Tapping Screws (STS) are widespread used in new timber constructions, this modern intervention technique has then been opted for the reinforcement of damaged Single Step Joints.

Featured by a good workability and reduced visual impact on-site, the STS strengthening is however very limited in Built Heritage Restoration because no European standard details how to design and to reinforce effectively old timber connections with STS. As the Single Step Joint is structurally damaged by both failure modes, several STS strengthening strategies as well as the related design equations have been defined for the SSJ reinforcement with STS, based on recent research and European standards about "Common connections with STS". In order to check the reliability of these design equations, the SSJ specimens damaged by shear crack and by compressive crushing have been reinforced with STS and then tested under monotonic compression.

For each STS strengthening strategy related to both SSJ failure modes, the design equations of Single Step Joint reinforced with STS have been defined and then compared with experimental results. It has been shown that the strengthening strategies R1 and R2 tested are efficient, providing to the reinforced Single Step Joints higher load-bearing capacities than those from initial Single Step Joints before being damaged. Being restrictive, the related design equations should be optimized by taking into account the geometrical recommendations from European standards in order to prevent the shear block in Single Step Joints reinforced with STS.

1 INTRODUCTION

At the foot (also called "step") of old traditional and contemporary timber carpentries, the Single Step Joint (SSJ) has been used so far to connect the rafter with the tie beam [1]. As shown in Figure 1, Architects and Engineers may be confronted with this joint structurally damaged by two failure modes due to either poor design of the connection, or normal overloading in the rafter $\mathrm{N_{rafter}}$ over time [2]. The former called "shear crack" occurs at the heel depth $\mathrm{t_v}$ along the shear length $\mathrm{l_v}$ in the tie beam, by causing the destabilization of the rafter along with the timber truss. The latter called "crushing" emerges at the front-notch surface inclined under an angle α_{front} to the normal of the tie beam grain, by generating high deformation inside the connection. From [3], traditional and modern intervention techniques exist in order to reinforce the old carpentry connections. For example, metal devices (i.e. stirrup, lateral bolts, binding strip, tension ties) are used to correct the structural disorders in the Single Step Joint [4].

In the last decades, the Self-Tapping Screws (STS) have stood out from other intervention techniques, for strengthening "Common connections" in timber engineering [5, 6]. Therefore, STS have been chosen to reinforce the Single Step Joints damaged by both failure modes, with respect to several strengthening strategies. The present paper then focuses on the determination of design models for the SSJ reinforcements with STS, through recommendations from European standards (Eurocode 5 [7]) or scientific reports [8, 9] about timber "Common connections" reinforced with STS. In order to check the reliability of design equations and the efficiency of strengthening strategies, the experimentation on SSJ reinforcements with STS has been performed in the lab. The SSJ specimens previously damaged by the shear crack or the crushing [2] have been reinforced with STS according to the strengthening strategies, and then tested under monotonic compression.

2 DESIGN MODELS

2.1 Self-Tapping Screws

Among the intervention techniques used for the joint strengthening, the Self-Tapping Screws (STS) stand out from the others in timber engineering, featuring many advantages: easy handling on-site, low cost, reduced visual impact, easy visual inspection, and high degree of reversibility. Because wood is an orthotropic material characterized by low tensile, compressive strength perpendicular to the grain as well as low shear strength parallel to the grain, the timber connections must be reinforced with STS in order to enhance their mechanical properties [6]. Thanks to their thread rod, these screws provide to the timber joint elements: lateral shear strength, high tensile strength, and withdrawal strength. Moreover, the reinforcement with STS may induce a ductile failure mode inside the timber connection [9], by preventing the emergence of brittle failures as the shear crack in the Single Step Joint for example. In addition to the load-bearing capacity, the stiffness of the joint reinforced with STS has also been changed. As it has a direct impact on the internal forces distribution and deformation inside timber connections, the modified stiffness must be taken into account when strengthening traditional joints. Indeed, differential deformation and eccentricity forces may then occur in reinforced carpentry connections due to the modified stiffness, reducing the structural efficiency of the timber truss.

Different STS geometries do exist, varying according to their tip, head, and thread as shown in Figure 2. As these screws are called “self-tapping”, the specific shape of the tip and the threaded rod ensure their easy implementation and maintenance time inside timber joint elements, by using only a screwdriver as work tool. Note that the pre-drilling in the connection is not required if the density of timber elements is not too high ($\rho_k \leq 500$ kg/m³) conform with Eurocode 5 [7]. However, the predrilled holes and proper spacing between screws ensure an accurate implementation of inclined STS, by decreasing the risk of timber splitting or shear bock inside timber joint elements at the headside screw [10].

2.2 Reinforcement strategies with STS

Because the shear crack splits the tie beam into two parts at the heel depth t_v along the shear length l_v, the upper side of the tie beam moves and causes the collapse of the rafter along with the timber truss [2]. As shown in Figure 3, the first strengthening strategy against the shear crack consists of positioning VGZ screws inclined under an angle α to the normal of the shear plane in the damaged tie beam. Because they are characterized by a whole threaded rod, these STS provide high withdrawal capacity so that the load-bearing capacity of the tie beam reinforced with VGZ screws increases with their inclination angle α. Because the heel depth t_v is very small in the Single Step Joint, the beneficial effect of the withdrawal capacity is however negligible on the load-bearing capacity from the reinforced tie beam, which depends only on the lateral shear strength of the screws. In order to conciliate the workability on-site with mechanical performances of optimal strengthening, the VGZ screws must be inclined under 45° angle to the normal of the shear plane. As illustrated in Figure 4, the second strengthening strategy against the shear crack deals with the perpendicular positioning of HBS screws to the shear plane in the tie beam. As the HBS screws have a smooth rod on the upper side of the tie beam, the related lateral shear strength is then higher than those from the VGZ screws. Moreover, the positioning of HBS screws in the tie beam is easier and faster because it does not require any guiding for the STS inclination on-site, unlike the VGZ screws. In addition to implement HBS screws perpendicularly to the shear plane in the tie beam, the third strengthening strategy also consists of positioning VGZ screws at the bottom-notch surface, perpendicularly to the grain in the rafter as shown in Figure 5. Thereby, the load-bearing capacity from this SSJ reinforcement with STS should be higher than those from other two strengthening strategies in the tie beam.

In contrast to the shear crack, the crushing at the front-notch surface inclined under an angle α_{front} to the normal of the tie beam grain is a ductile failure mode causing serious deformation inside the connection [2]. Therefore, the strengthening strategy against the crushing then consists of positioning VGZ screws at the bottom-notch surface, perpendicularly to the grain in the rafter as shown in Figure

6. Because the shear crack could occur in the tie beam as the finale failure mode of the Single Step Joint, the first two strengthening strategies with STS might also be considered. Because the rafter end is brittle due to the heel geometry, the workers must pay attention not to position the screws too close to the front-notch surface in order to prevent timber splitting and shear block inside the joint. Note that all the geometrical parameters dealing with the distance, spacing, and dimensions of screws (s_1, s_2, $l_{ef,1}$, $l_{ef,2}$, a_1, $a_{3,c}$, $a_{3,t}$) in timber "Common connections" can be given by Eurocode [7], the recommendations from [10], or the European Technical Approval ETA-11/0030 [11].

2.3 Design equations of SSJ reinforced with STS

2.3.1 Reinforcement against the shear crack

In order to optimize the strengthening of Single Step Joint (SSJ) with Self-Tapping Screws (STS) against the shear crack, the HBS screws must be positioned perpendicularly to the shear plane at the heel depth t_v in the tie beam while the VGZ screws are implemented perpendicularly to the rafter grain at the bottom-notch surface. Nevertheless, the internal forces resolutions related to both reinforced tie beam and rafter make complex the determination of the rafter load-bearing capacity in SSJ, noted $N_{rafterR}$, which is the sum of the load-bearing capacities from the reinforced joints in the tie beam ($N_{rafterR,tb}$) and in the rafter ($N_{rafterR,bott}$). In order to simplify the equations, each connection reinforced with STS can be related to its own internal forces resolution independently to each other, as shown in Figure 5.

Because the high tightening of the Single Step Joint is ensured by the STS positioned in the rafter, the friction coefficient μ or the friction angle φ_{bott} (such as $\mu = \tan(\varphi_{bott})$) at the bottom-notch surface between the rafter and the tie beam must be taken into account in the design equations. With respect to the internal forces resolutions in SSJ, the rafter load-bearing capacity related to the reinforcement of the bottom-notch connection with STS (noted $N_{rafterR,bott}$) and the rafter load-bearing capacity related to the reinforcement of the shear plane with STS in the tie beam (noted $N_{rafterR,tb}$) can be both detailed below by the equations (1) and (2) respectively. Note that both quoted load-bearing capacities mainly depend on the rafter skew angle β_{rafter}.

$$N_{rafterR,bott} = \frac{R_{V,bott,Rk}}{\cos(\beta_{rafter} - \gamma) - \tan\varphi_{bott} . \sin(\beta_{rafter} - \gamma)} \tag{1}$$

$$N_{rafterR,tb} = \frac{R_{V,tb,Rk}}{\cos\beta_{rafter}} \tag{2}$$

As illustrated in Figure 5, the load-bearing capacity of the bottom-notch connection in the rafter ($R_{V,bott,Rk}$) and the load-bearing capacity of the shear plane in the tie beam ($R_{V,tb,Rk}$) both reinforced with STS can be determined either by Johansen's equations from Eurocode 5 [7], or by the modified Johansen's equations [8]. By comparing both calculation methods with experimental results [9], it has been concluded that Eurocode 5 underestimates the load-bearing capacity of timber "Common connections" reinforced with inclined STS, subjected to shear-(tension or compression) stress.

Therefore, it is better to use the modified Johansen's equations [8] which are more reliable to design the SSJ reinforcement with inclined STS.

The tie beam and rafter reinforced with STS work together in order to counteract the rafter thrust inside the Single Step Joint. Besides, this SSJ strengthening with STS prevents the movement of the upper side element along the shear plane in the tie beam. Thereby, the design rafter load-bearing capacity for the SSJ reinforcement with STS against the shear crack, noted $\mathrm{N_{rafterR,Rd}}$, must be checked by the design equation (3), such as the sum of $\mathrm{N_{rafterR,tb}}$ and $\mathrm{N_{rafterR,bott}}$, given by the previous equations (1) and (2). Conform with Eurocode 5 [7], the modification factor for duration of loading and moisture content $\mathrm{k_{mod}}$, and the partial coefficient of the material γ_M are both included in the design equations to calculate the design value of timber mechanical properties.

$$N_{rafterR,Rd} \leq \frac{k_{mod}}{\gamma_M} \cdot \left(N_{rafterR,tb} + N_{rafterR,bott}\right) \tag{3}$$

2.3.2 Reinforcement against the crushing

The Self-Tapping Screws (STS) are positioned perpendicularly to the rafter edge at the bottom-notch surface, in order to reinforce the Single Step Joint (SSJ) against the crushing at the front-notch surface. As illustrated in Figure 6, the rafter load-bearing capacity related to the reinforcement of the bottom-notch connection ($\mathrm{N_{rafterR,bott}}$) can also be calculated by the equation (1). Although most of the internal forces go from the rafter to the tie beam through the STS at the bottom-notch surface, the front-notch surface transfers the remaining forces between both timber SSJ elements. Therefore, the maximal compressive strength against the crushing at the front-notch surface from unreinforced SSJ must be taken into account in the design equations. The design rafter load-bearing capacity against the crushing at the front-notch surface ($\mathrm{N_{rafter,CFN,Rd}}$) can be determined by the SSJ design equations from [2]. Hence, the design rafter load-bearing capacity for the SSJ reinforcement with STS against the compressive crushing at the front-notch surface, noted $\mathrm{N_{rafterR,Rd}}$, must be checked by the design equation (4) such as the sum of $\mathrm{N_{rafterR,bott}}$ and $\mathrm{N_{rafter,CFN,Rd}}$.

$$N_{rafterR,Rd} \leq \frac{k_{mod}}{\gamma_M} \cdot \ N_{rafterR,bott} + N_{rafter,CFN,Rd} \tag{4}$$

Because the shear crack may occur as the final failure mode of the Single Step Joint [2], the maximal shear strength along the shear length $\mathrm{l_v}$ at the heel depth $\mathrm{t_v}$ must then be considered in the unreinforced tie beam. The design rafter load-bearing capacity related to the shear crack in the tie beam ($\mathrm{N_{rafter,SC,Rd}}$) can be determined by the SSJ design equation from [2]. Hence, the design rafter load-bearing capacity for the SSJ reinforcement with STS against the crushing at the front-notch surface, noted $\mathrm{N_{rafterR,Rd}}$, must be checked by the design equation (5) such as the sum of $\mathrm{N_{rafterR,bott}}$ and $\mathrm{N_{rafter,SC,Rd}}$. Thereby, the design equation (5) can predict the emergence of the shear crack according to this strengthening strategy when the tie beam is not reinforced with STS beforehand.

$$N_{rafterR,Rd} \leq \frac{k_{mod}}{\gamma_M} \cdot \ N_{rafterR,bott} + N_{rafter,SC,Rd} \tag{5}$$

3 EXPERIMENTATION

3.1 Experimental process and specimens

The experimentation firstly consists of strengthening with STS all the SSJ specimens which had been damaged by the shear crack in the tie beam or the crushing at the front-notch surface [2]. As illustrated in Table 1, four strengthening strategies with STS have then been performed in the lab, under monotonic normal compression in the rafter, to obtain the mechanical behaviour of reinforced Single Step Joints. As shown in Figure 5, the first strengthening strategy labelled R1 consists of reinforcing SSJ specimens damaged by shear crack, with VGZ D9 200L (9 mm diameter and 200 mm length) screws positioned at the bottom-notch surface perpendicularly to the grain in the rafter, and with HBS D8 140L (8 mm diameter and 140 mm length) screws positioned perpendicularly to the grain in the tie beam. As illustrated in Figure 6, the second strengthening strategy labelled R2 deals with the reinforcement of SSJ specimens damaged by the crushing, only with VGZ D9 200L (9 mm diameter and 200 mm length) screws positioned at the bottom-notch surface perpendicularly to the grain in the rafter. To cause the possible emergence of the shear crack during the experimental tests, the tie beam has not been reinforced according to the second strengthening strategy with STS. For some SSJ specimens damaged by the shear crack, two other strengthening strategies with STS have been studied by focusing more in the tie beam. As shown in Figures 3 and 4, the third strengthening strategy labelled R3 consists of positioning VGZ D7 100L (7mm diameter and 100 mm length) screws under 45° angle to the grain in the tie beam while the fourth strengthening strategy labelled R4 is featured by HBS D8 140L (8 mm diameter and 140 mm length) screws positioned perpendicularly to the grain in the tie beam.

The labelling used for the SSJ specimens reinforced with STS can be described by illustrating the following example: GCTB_30o_tv25_240SL_1_R1. The first term deals with the three SSJ families (i.e. GCID, GCPR, and GCPTB) [2]. The second term is related to the rafter skew angle β_{rafter} [°]. The third term determines the size of the heel depth $\mathrm{t_v}$ [mm] while the fourth one defines the size of the shear length $\mathrm{l_v}$ [mm]. The fifth term indicates the number of specimens related to the same SSJ geometrical configuration (i.e. GCPTB_30o_tv25_240SL) while the sixth one refers to the labelling of the four reinforcement strategies with STS detailed above.

3.2 Interpretation of results

As illustrated in Figure 7, the maximal normal loads in the rafter from SSJ specimens reinforced with STS only in the tie beam against the shear crack (i.e. the third and fourth strengthening strategies, "R3" and "R4") are equivalent. Because the positioning of HBS screws makes the SSJ strengthening easier and faster on-site, it is then better to reinforce the tie beam with HBS screws, positioned perpendicularly to the grain, instead of the VGZ screws inclined under 45° to the tie beam grain which require some guiding. As shown in Figure 7, the maximal normal loads in the rafter related to these two strengthening strategies are much inferior to those from the unreinforced SSJ specimens before being damaged by the shear crack. Hence, the reinforcement of the tie beam with STS against the shear crack is not enough efficient to regain entirely the initial rafter load-bearing capacity of the joint. Therefore, the added STS positioning is required in the rafter to optimize the efficiency of the SSJ reinforcement with STS. As illustrated in Figure 7, the maximal normal loads in the rafter from the SSJ specimens reinforced with STS in both tie beam and rafter against the shear crack (i.e. the first strengthening strategy, “R1”) are indeed superior to those from the unreinforced SSJ specimens as well as those from the other two strengthening strategies (i.e. “R3” and “R4”).

As a reminder, the shear crack is a brittle failure mode occurring in the tie beam of unreinforced Single Step Joints [2]. As shown in Figures 7 and 8, the strengthening of both tie beam and rafter (i.e. first reinforcement strategy, “R1”) provides ductile failures to the Single Step Joint reinforced with STS, thanks to the emergence of plastic hinges in HBS and VGZ screws. Featured by high deformation of the joint according to maximal normal loads in the rafter, the ductile failures will always be appreciated for its safety in the strengthening of old timber trusses when the carpentry connections have already entailed some malfunctions. However, the shear block may occur like a timber splitting in the reinforced tie beam along STS rows, as illustrated in Figure 9 and in Table 1. As it causes irreversible damage in the tie beam and the drop of the normal load in the rafter, the shear block must then be prevented carefully by checking the geometrical recommendations about minimum spacing of STS with respect to the minimum thickness of timber joint elements [7, 10, 11]. If they are not checked, the SSJ reinforcement with STS against the shear crack becomes an irreversible intervention technique, by being in conflict with the principles of Built Heritage Restoration.

As shown in Figure 10 and in Table 1, the maximal normal loads in the rafter from the SSJ specimens reinforced with STS in the rafter against the crushing at the front-notch surface (i.e. the second strengthening strategy, “R2”) are much superior to those from the unreinforced SSJ specimens. As illustrated in Figure 10 for GCID_45°_tv30_240SL_1_R2, the mechanical behaviour of the reinforced SSJ specimens can ideally be characterized by a bi-linear curve divided into two steps, when the shear crack doesn’t occur as the final failure mode. The first step includes the linear compressive deformation until the maximum normal load in the rafter is reached. The second step is featured by a second linear compressive deformation along which the normal load in the rafter slightly increases according to high displacement of the front-notch surface due to the emergence of double plastic hinges in the VGZ screws (Figure 11). However, this ideal mechanical behaviour could not be encountered if the shear block occurs in the rafter, causing the slightly decrease of the normal load in the rafter according to high displacement of the front-notch surface. Moreover, the shear crack may emerge in the tie beam as the final failure mode in the Single Step Joint, causing the drop of the normal load in the rafter after reaching the maximal value as illustrated in Figure 10 and in Table 1. As shown in Figure 12, the shear crack may occur for the SSJ specimens damaged by the crushing if the tie beam has not been reinforced with STS beforehand.

3.3 Discussion about design equations

In order to check the reliability of design equations with respect to the strengthening strategies of damaged Single Step Joint (SSJ) with Self-Tapping Screws (STS), all the theoretical and experimental results have been compared to each other. As illustrated in Table 1, the maximum normal load in the rafter ($\mathrm{N_{rafterR,exp}}$) measured during the experimental campaign can be compared with the theoretical rafter load-bearing capacity ($\mathrm{N_{rafterR,theo}}$) calculated from the design equations. Concerning the theoretical calculations, the following parameters have been chosen for all the SSJ specimens tested: $\mathrm{k_{mod}}$=0.9, and γ_M=1.3. Besides, the relative variation $\Delta_\mathrm{rel,rafter}$ [%] of maximum normal loads in the rafter between the experimental result and the theoretical value is determined for each SSJ specimen reinforced with STS: $\Delta_\mathrm{rel,rafterR}=100.\,(\mathrm{N_{rafterR,exp}} - \mathrm{N_{rafterR,theo}})/\mathrm{N_{rafterR,theo}}$.

For the SSJ reinforcement with STS in the tie beam and in the rafter against the shear crack (i.e. first strengthening strategy, “R1”), the rafter load-bearing capacity predicted by the design equations (1)-(2)-(3) is too restrictive for all the SSJ specimens tested ($40.5\% \leq \Delta_\mathrm{rel,rafterR} \leq 112.5\%$). Because the thickness of the headside timber element $\mathrm{s_1}$ (i.e the heel depth $\mathrm{t_v}$) is small in the Single Step Joint as shown in Figures 3 and 4, the geometrical recommendations [7, 10, 11] about the minimum spacing of STS with respect to the minimum thickness of timber joint elements have not been checked when strengthening the tie beam. Therefore, the shear block always occurs by generating irreversible damage in the reinforced tie beam. Because it also causes the drop of the rafter load-bearing capacity, the shear block should then be taken into account in the design equations for the SSJ reinforcement with STS. Note that the same observations and discussion can be made for the SSJ specimens reinforced with STS only in the tie beam against the shear crack (i.e. third and fourth strengthening strategies, “R3” and “R4”).

Concerning the SSJ reinforcement with STS in the rafter against the crushing at the front-notch surface (i.e. second strengthening strategy, “R2”), the design equation (4) is high reliable for calculating the rafter load-bearing capacity ($3.5\% \leq \Delta_\mathrm{rel,rafterR} \leq 46\%$). Thereby, this reinforcement strategy is optimal for the Single Step Joint damaged by crushing. However, the shear crack may occur as the final failure mode at the heel depth in the tie beam due to high crushing of the grain at the front-notch surface [2]. The design equation (5) is suitable ($-4.5\% \leq \Delta_\mathrm{rel,rafterR} \leq 41\%$) to predict the emergence of the shear crack for the SSJ specimens featured by rafter skew angles $\beta_\mathrm{rafter} \leq 45°$. Hence, both equations (4) and (5) can be considered in determining the value range of rafter load-bearing capacity for the SSJ reinforcement with STS in the rafter against the crushing at the front-notch surface, by preventing the risk of shear crack appearance in the tie beam.

4 CONCLUSION

In the Built Heritage Restoration, the Single Step Joint (SSJ) may be subject to two failure modes (i.e. structural damage): the shear crack in the tie beam, and the crushing at the front-notch surface. Being a recent and attractive technique used in timber engineering, the Self-Tapping Screws (STS) have then been selected to reinforce the damaged Single Step Joint through four strengthening strategies proposed in the present paper. For each one, the geometrical configurations and the design equations of SSJ reinforcements with STS have been defined, based on the recommendations on timber "Common connections" strengthened with STS [7, 8]. The reliability of design equations, the emergence of failure modes as well as the efficiency of SSJ strengthening strategies with STS have then been checked by comparing the theoretical with experimental results.

Concerning the SSJ reinforcement with STS against the shear crack, the HBS screws positioning perpendicularly to the grain in the tie beam is more efficient than the VGZ screws inclined under 45° angle to the grain. Nevertheless, these two reinforcement strategies with STS in the tie beam are inadequate for regaining the initial strength of Single Step Joint. Therefore, the added STS positioning in the rafter is required because it ensures a higher load-bearing capacity than both reinforcement strategies only in the tie beam. The shear block may occur in the rafter and especially in the tie beam because the thickness of the upper part conditioned by the heel depth $\mathrm{t_v}$ is always small. As the shear block causes timber splitting inside the Single Step Joint, the reinforcement with STS becomes an irreversible intervention technique, in conflict with the principles of Built Heritage Restoration. To prevent the shear block, a compromise must then be found between the recommended minimum spacing of screws and the optimal load-bearing capacity of reinforced SSJ. The predrilled holes could also be a good alternative to restrain the emergence of shear block. Nevertheless, the design equations are too restrictive according to the experimental results and may be unsuitable to design the reinforcement with STS both in the rafter and tie beam against the shear crack. Further studies should focus on the optimization of these equations with Finite Element Models in order to determine the internal forces resolutions inside the reinforced SSJ.

For the SSJ reinforcement with STS against the crushing at the front-notch surface, the VGZ screws positioning perpendicularly to the rafter edge is very efficient because it provides higher load-bearing capacity than the maximal strength of the unreinforced SSJ specimens. Besides, the design equations are highly reliable to predict the maximal load-bearing capacity for the SSJ reinforcement with STS. Due to high crushing at the front-notch surface, the shear crack may occur as the final failure mode at the heel depth in the unreinforced tie beam. In order to prevent the shear crack, the related design equations are only suitable for SSJ specimens featured by low rafter skew angles $\beta_{\mathrm{rafter}} \leq 45°$. Nevertheless, the prediction of the shear crack could be improved by investigating the influence of crushing at the front-notch surface on the shear stress distribution at the heel depth along the grain in the tie beam. Another alternative to prevent the shear crack could be to reinforce the tie beam with HBS perpendicularly to the grain.

Although the strengthening strategies with STS seem very efficient for the SSJ reinforcement, they should be improved by considering better the intervention principles with respect to the Built Heritage Restoration. If future results lead to decisive conclusions, the STS can be used to reinforce the damaged Single Step Joint.

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