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Stiffened Hollow Structural Section Joints in Fire

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Abstract – This research examines the ability of stiffened Hollow Structural joints to withstand elevated temperatures when subjected to axial compressive loads on the brace. Extensive numerical simulations were conducted to assess the impact of geometrical factors in the main members and reinforcing plate on the fire resistance of SHS T-joints. The accuracy of the numerical models was verified by comparing them to existing test results. The findings demonstrate that the use of stiffener significantly enhances the ability of SHS T-joints to withstand elevated temperatures. The fire resistance of the reinforced joints primarily relied on the brace-to-chord width ratio and the reinforcing plate thickness to chord wall thickness ratio. However, increasing the reinforcing plate thickness beyond 1.5 times the chord wall thickness did not yield any beneficial effects on fire resistance. Additionally, factors such as half-width to thickness ratio of the chord, reinforcing length, and reinforcing type had negligible effects as long as they adhered to the required limit values based on Eurocode 3 EN 1993-1-8.

Keywords – Stiffened Hollow, Joints, Wall Thickness

I. Introduction

Tubular structures are widely employed in both onshore and offshore applications due to their notable benefits from both structural and architectural perspectives. Square Hollow Section (SHS) is among the commonly used section types in these structures. Joints play a critical role in tubular structures, and typically, failure occurs in the chord member. This is attributed to the smaller transverse stiffness of the chord member compared to the axial stiffness of the brace members. Moreover, the mechanical properties of steel undergo significant degradation at high temperatures, necessitating the consideration of reinforced joint behavior in fire conditions.

There have been a couple of studies on the behaviour of the stiffened SHS T-joints at ambient temperature until now. Feng et al. [1] and Ozyurt and Das [2] experimentally and numerically examined the joint resistance of collar and doubler plate reinforced SHS T-joints with compressive load in the brace member. They noted that using either a collar plate or doubler plate considerably increased the joint capacity. Ozyurt and Das [2] noted that the current method in the Eurocode 3 EN 1993-1-8 [3] may not be safe for all configuration of reinforced SHS T-joints and introduced a simple design method to predict their capacity, considering geometrical parameters of the main members and reinforcement plates.

Extensive research studies have examined the joint resistance of Circular Hollow Section (CHS) T-joints reinforced at ambient temperatures. Choo et al. [4] and van der Vegte et al. [5] conducted experimental and numerical investigations on both unreinforced and reinforced CHS T-joints. They observed a significant increase in joint capacity when an appropriately sized reinforcing plate was used. Shao et al. [6] focused on the effect of local reinforcement in the chord member on the capacity of CHS T-joints under axial compression in the brace member. Their numerical study revealed that increasing the chord thickness at the intersection beyond its original thickness altered the joint's failure mode. Nassiraei et al. [7-10] conducted parametric studies on collar plate and doubler plate reinforced CHS T-joints with brace members experiencing tensile or compressive loads. Their aim was to understand the influence of geometrical parameters on ultimate load, initial stiffness, and failure modes. They proposed design methods for different loading conditions and types of reinforcement. Fung et al. [11] performed experimental and numerical investigations on reinforced CHS T-joints and found that the brace angle and the ratio of brace to chord thickness had an insignificant effect on joint capacity.

Currently, there is a lack of research addressing the behavior of reinforced Square Hollow Section (SHS) T-joints under axial compressive loads in the brace member at elevated temperatures. Additionally, there is a notable absence of a fire design method specifically tailored for these joints operating at elevated temperatures. Consequently, the purpose of this study is to investigate the joint resistance of collar plate and doubler plate reinforced SHS T-joints subjected to axial compressive loads in the brace member at high temperatures. To accomplish this, a non-linear finite element method was employed.

II. Materials and Method

Numerous finite element analyses were conducted to investigate collar plate and doubler plate reinforced Square Hollow Section (SHS) T-joints at different temperature levels ranging from 20°C to 700°C. The study focused on examining the impact of geometrical parameters in the main members and reinforcement plates on the fire resistance of the reinforced joints. To serve as reference points, the corresponding unreinforced joints were also analyzed. The reinforced joint resistance ratio, defined as $N_{r,\theta}/N_{r,20}$, was utilized to compare the resistance of the reinforced joint at elevated temperature ($N_{r,\theta}$) to that at ambient temperature ($N_{r,20}$). Similarly, the unreinforced joint resistance at ambient and elevated temperatures was represented by $N_{u,20}$ and $N_{u,\theta}$, respectively. Fig. 1 depicts the typical configuration of a reinforced T-joint.

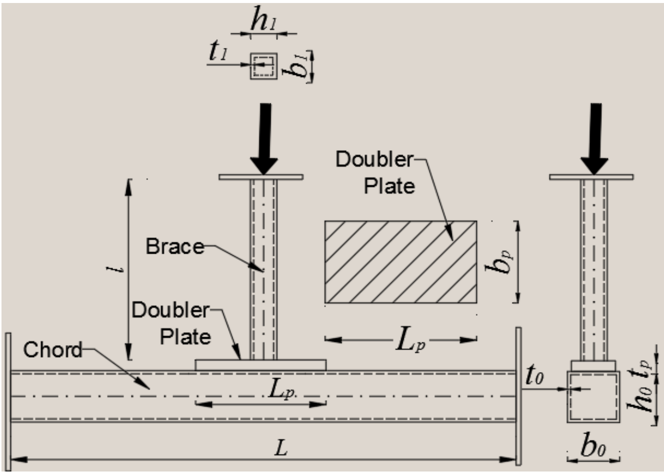

Fig. 1 Stiffened SHS T-joint

In each of the numerical models, the chord width was set at 200 mm, while the brace wall thickness matched the chord wall thickness for every case study. The ends of the chord member were restrained as a simply supported beam, ensuring consistent boundary conditions. To mitigate the influence of boundary effects and the chord's short length, the chord length was extended to 12 times its width. Rigid plates were affixed to the ends of the chord and brace members to facilitate the application of loading and maintain boundary conditions. Fig. 2 presents the typical mesh size employed for the chord member, brace member, in a reinforced SHS T-joint. At ambient temperatures, the yield stress was 355 MPa, and the Young's modulus was 210 GPa. The stress-strain curves and Young's modulus for elevated temperatures were derived in accordance with Eurocode EN 1993-1-2 [20]. To account for significant deformations, the true stress-strain curve was converted into a logarithmic stress-strain curve, as recommended by Boresi et al. [12].

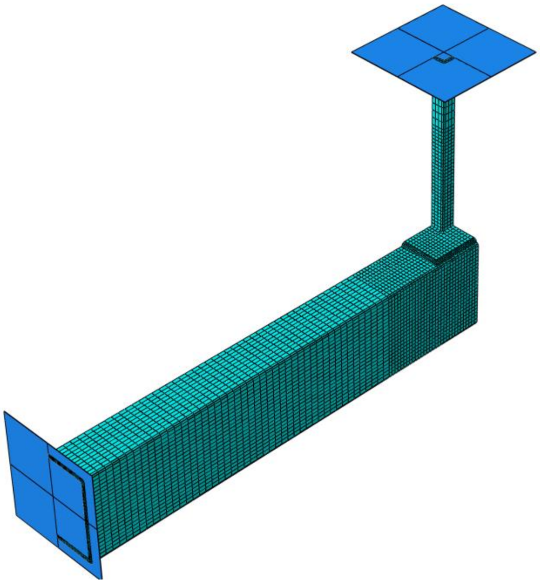

Fig. 2 Typical mesh layout of a quarter joint

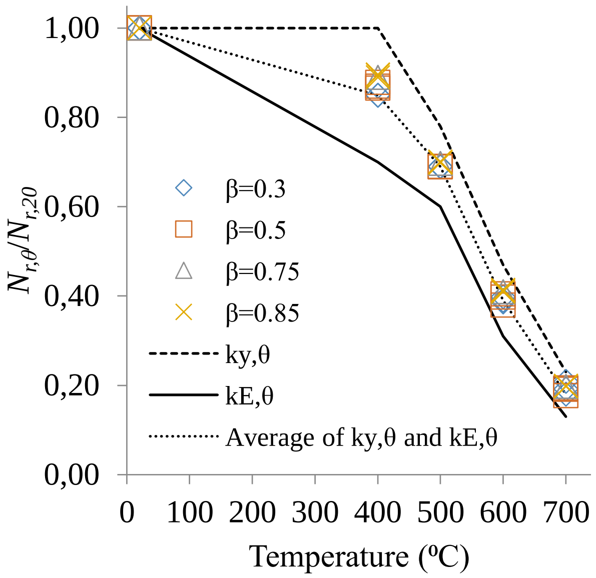

Fig. 3 The joint resistance ratios compared at elevated temperatures for different β values

III. RESULTS

A. The impact of β on the fire resistance of joints

Fig. 3 illustrate the reductions observed in joint resistance based on the numerical analyses, as well as the reduction factors for steel yield strength ($k_{y,\theta}$) and Young's modulus ($k_{E,\theta}$) as specified in Eurocode EN 1993-1-2 [13]. Additionally, the average values of $k_{y,\theta}$ and $k_{E,\theta}$ are presented. Comparing these values, it becomes apparent that the joint resistance ratios obtained from the numerical results exhibit a gradual increase as the β ratio rises, for reinforced joints. However, it is noteworthy that the numerical joint resistance ratios remain lower than the reduction factor for steel yield strength at elevated temperatures. This suggests that it may not be safe to solely modify the steel yield strength in the ambient temperature design method when calculating the capacity of unreinforced or reinforced SHS T-joints subjected to axial compressive loads in the brace member at elevated temperatures.

B. The impact of γ on the fire resistance of joints

In the case of reinforced joints, failure was attributed to plastification occurring on the reinforcement plate surrounding the brace member and the chord surface near the weld toe. Fig. 4 presents a comparison of the joint resistance ratio between reinforced and unreinforced joints at different γ values, considering both ambient and elevated temperatures. The findings revealed that the γ value had a negligible effect on the increase in the reinforced joint resistance ratio across various temperatures. The higher resistance ratio observed at elevated temperatures was primarily due to plasticity predominantly occurring at the intersection of the brace and chord in unreinforced joints, where significant deformations governed the joint resistance. However, in reinforced joints, the yielded area was more extensive, and local deformations around the intersection were relatively smaller compared to unreinforced joints.

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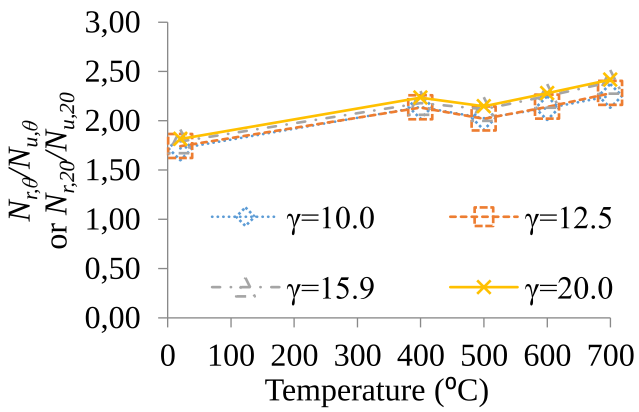

Fig. 4 The impact of γ on the fire resistance of joints

C. *The impact of the temperature distribution on the joint resistance*

Fig. 5 depicts the temperature distributions of the selected joint. It is noteworthy that the welding element region exhibited the lowest temperature among the areas exposed to fire due to its thicker region compared to other parts of the joint. Conversely, the lowest temperatures were observed at the center of the top surface of the chord member. Specifically, the temperatures were recorded as 547.8°C, 567.6°C, and 610.5°C, respectively, when the reinforcing plate thickness equaled the chord wall thickness. Among these joints, the doubler plate reinforced joints with a τ_p=2.00 exhibited the maximum difference of 200°C between the target temperature of 700°C and the lowest temperature.

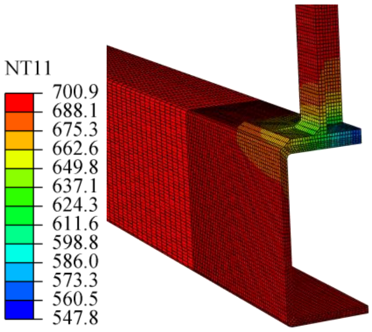

Fig. 5 Non-uniform temperature distributions of a reinforced joint

IV. CONCLUSION

The utilization of stiffener plate significantly enhanced the capacity of the SHS T-joints at elevated temperatures. Also, the capacity of reinforced SHS T-joints at elevated temperatures can reach up to 3.75 times that of the corresponding unreinforced joints at the same temperature level. Moreover, at elevated temperatures, the joint with the minimum β value exhibited the lowest joint resistance ratio. Nevertheless, the influence of β on the joint resistance ratio was found to be insignificant across the different elevated temperature levels. Overall, the reinforced joints demonstrated superior resistance to high temperatures in comparison to their corresponding unreinforced joints. This can be attributed to the fact that reinforced joints had a larger area where yielding occurred and experienced smaller localized deformations when compared to the unreinforced joints. Despite the occurrence of temperature differences as high as 200°C in non-uniformly heated reinforced joints, it was observed that the temperature distribution did not influence the behavior of the reinforced joints.

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