Cold formed hollow section joints are increasingly popular in structural applications, such as buildings, bridges and off-shore platforms because of their high strength-to-weight ratio, great flexibility, and attractive aesthetic appearance. Cold formed hollow sections have some advantage compared to the hot-finished hollow sections.The manufacturing method needs less energy and manufacturing lines are more compact and less expensive resulting in a positive effect on the CO_2 equivalent emission. Cold formed hollow section can be produced with tighter tolerances and they have better surface quality. The structural behaviour of hollow sections of steel grades up to S355 has been studied over the past decades. The research findings of those studies have been published and developed into design standards for hollow sections. Most of these results, however, are based on tests of hot-formed structural sections (HFSHS) at room temperatures. Relatively few test results are available for cold-formed structural hollow sections.
Owing to the advancements in steelmaking, higher strength steels (HSS) hollow sections with steel grades from S460 up to and including S700 are becoming increasingly competitive in long span structures. Reduction of self weight is accomplished with the smaller wall thickness of the hollow section, leading to fabrication, transport and execution benefits. The use of HSS has a positive effect on the CO2 equivalent emission, which is aligned with the European Green Deal for the future development of the construction sector. Lack of experimental evidence is identified as one of the main reasons to propose rather pessimistic material factors in the revised version of EN1993-1-8 for design in tubular joints. The revised version, published in 2020, recommends material reduction factors for the design of joints made of steel with yield strength larger than 460 and up to 700 MPa, in the range from 0.9 to 0.8. It should be noted that the existing design guidelines are developed based on a limited number of experiments, since there were insufficient experimental data at that time. In recent years, experimental and numerical studies have been conducted on various types of circular and rectangular hollow section joints with different geometrical parameters to facilitate the application of HSS hollow section joints in practice. The experimental results have revealed that the reduction factor prescribed EN-1993-1-8 for steels up to 700 might be too conservative. In other words, the introduction of these factors provides a simple and safe design at the expense of structural efficiency. Previous research investigations on the behaviour of RHS hollow section joints have primarily focused on joints under bending and compression. There is lack of research study on the tensile behaviour of RHS X-joints under tension. Therefore, in this research work, a comprehensive experimental and numerical investigation on the structural behaviour of mild steel and HSS RHS X-joint subjected to axial tension in the braces will be conducted. Finally, the need for the reduction factors will be justified.
Five full-scale welded X-joints in tension with rectangular hollow section were tested Stevin Lab II, TUD. Additionally, base material and butt-welded coupon specimens are tested to obtain the engineering stress-strain relationship of the base material, weld and heat affected zone (HAZ).
Based on the results of coupon tests, finite element software ABAQUS is used to model X-joint and to supplement the limited number of experiments. Furthermore, result of a parametric study is presented in which effects of three parameters: the yield strength, the parameter β (ratio of the width of the brace member to that of the chord member) and the thickness of the chord are investigated to analyse their influence on the structural performance of X-joints. Following properties are thoroughly examined: static strength, stiffness, ductility and failure mode. Finally, conclusions are drawn on the validity of the material reduction factors.

Description of methods and results

Material test:

The experimental study consisted of tensile tests, microstructures observations and microhardness tests. Tensile tests are conducted on coupon specimens with a transverse butt-weld in the middle of steel grades S355, S500 and S700. The test showed that all the joints fractured within the HAZ. The results revealed that the post-welding properties, namely the strength and ductility of the joints, were deteriorated due to the existence of the softening zone. In addition, it is found that the mechanical properties of the welded coupon are inferior to that of the base material for the S700 butt welded specimens. t is found that the strength reduction of the butt-welded coupon specimens in steel grade S700 was more significant than that of the butt-welded coupon specimens in steel grade S355 and S500, because of the more pronounced material strength reduction in HAZ of S700 specimens. Compared to the yield strength of the base material, the yield strength in HAZ is reduced by 20% in the S700 sample, while for the S355 and S500 the strength reduction equals 5%, as shown in Figure 1.

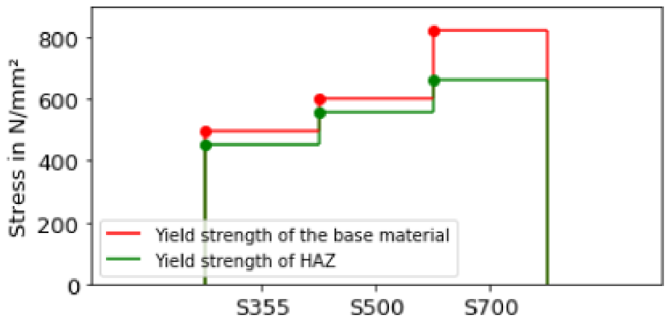

Figure 1 The yield strength of the base material versus the yield strength of HAZ

Microhardness examination and low-force Vickers hardness test were employed to identify the width of the different region corresponding to the weld and HAZ. The results revealed that a softening zone is generated from welding and is characterized by inhomogeneous microstructure and low hardness value compared to the base material. It should be noted that the digital image correlation (DIC) technique was used in the tensile test to measure the deformation and strain on the butt-welded coupon specimens. Using DIC makes it possible to change the position of the initial set range after the tests. In addition, it is very useful when studying the strain localization which would be rather difficult to study with a simple strain gauge or extensometer. Therefore, DIC was employed to determine the local material properties across the weld zone. Based on the measured strain distribution along the length of the specimens, different regions corresponding to the base material, weld, HAZ are identified. The deformation of the weld and the HAZ are derived from DIC by placing 'virtual' extensometers over each individual zone. The length of the extensometer is taken to be equal to the width of each zone obtained from the hardness test. Based on these measured deformations and the recorded applied force, the engineering stress strain curves of the weld and HAZ is derived.

The tensile tests on the butt-welded coupon specimens showed a significant the influence of the observed failure mode on the resistance of the butt-welds. The current design resistance of the full presentation butt-weld according to prEN 1993-1-8:202 are carried out in the base material and not in the weld seam or the heat affected zone. The strength of welds or the heat-affected zone is often lower than the strength of the base metal. As found from the tensile tests results, all the coupon specimens failed in HAZ. Therefore, the current rules for the full penetration butt welds are insufficient and unsafe. The research project HighButtWeld carried out experimental investigations on butt-welds made of high-strength steels. They proposed a design resistance function which takes the exitance of the softening zone as well as the possible failure modes of a butt welded joint in high-strength steel into account. The load-carrying capacities of the butt welds obtained in this thesis are compared with the proposed design resistance. The results have shown that the introduction of the softening coefficient x in the design resistance provides a reasonable prediction for the strength of the HAZ. It can be concluded that the proposed design model for the butt welds, where the existence of a soft zone is taken into account, provide a safe and sufficient design for the butt-welded high strength steel connection.

Full-scale joint test:

Five X-joint composed of cold-formed steel tubes made of steel grade S355, S500, and S700, are tested under axial tension in the braces. The tests are conducted on tubular joints of square and rectangular hollow sections using different values of the ratio of brace width to chord width (β) ranging from 0.25 to 1, the ratio of brace thickness to chord thickness (τ) from 0.5 to 1, and the ratio of chord width to chord thickness (2γ) from 15 to 25. The full-penetration butt weld is designed according to EN1993-1-8 and laid using MAG welding. For the S355 joints, the weld is matched for the S355 joints. For the high strength steel joints, the filler metal produced an overmatched weld for the S500 joints and undermatched for the S700 joints. For the test, two different measuring methods are used. The first measuring method is 3D digital image correlation (DIC)which is used to measure the displacement field on one side of the joint. The second measuring method is the linear variable displacement transducers (LVDTs) which are employed to measure the deformations between two cross sections in the brace. The curves of the applied load versus the deformation, in terms of the chord face indentation, of the joints are shown in Figure 3. The deformation of the X-joint is determined based on the vertical displacement of the two black points shown in Figure 4.

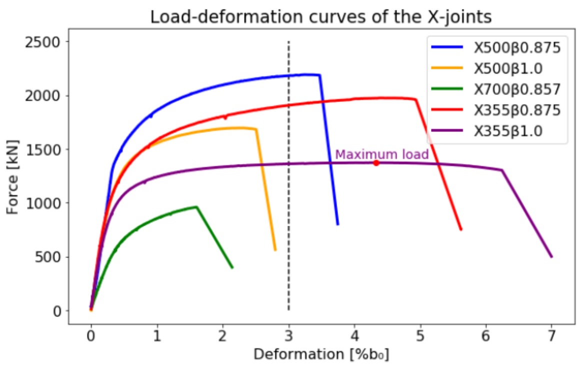

Figure 3 Load-deformation curve of the X-joints

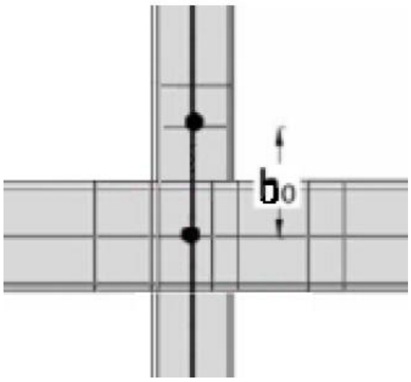

Figure 4 Measuring points to determine the 3% deformation limit

The experiments are supported by a preliminary numerical simulation to validate the finite element (FE) model of the X-joint against the test results. To provide an accurate and consistent prediction of the structural performance of X-joints, a distinction is made between the base material, heat affected zone (HAZ) and the weld region in the X-joint modelling. Each region is assigned with an appropriate material property which is obtained from the tensile coupon tests. The validated FE models are used to conduct a parametric study on the geometry of the joints is performed to investigate the structural performance of RHS X-joints and evaluate the applicability of the reduction factors introduced in EC3 part 1-8 [5] for steel grades of S355, S500 and S700. Three varying parameters are considered in this study: steel grade, the brace width to chord width ratio (β) and the brace to chord thickness ratio (τ). A range of common values used in practice were assumed for the parameters: β = 0.5, 0.7, 0.85, 1 and τ = 0.8, 1.0.

Based on the test results the following conclusions are drawn: Increasing the steel grade from S355 to S500 has a higher influence of the ductility reduction of the joints than the joint strength increase. The ductility reduction is more pronounced in the joints with β=1.0 where the joint failed before the 3% deformation limit. Considering the S355 and S500 joints with β=0.875, it is observed that the joint strength increases by 14% as the steel grade increases from S355 to S500, while deformation at the ultimate load decreased by 40%. Similar observations are found for S355 and S500 joints with β=1.0, the joint strength increases by 24% as the steel grade increases from S355 to S500, while the deformation at the ultimate load decreased by 60%. In addition, almost all the joints failed in the HAZ, except for joint X355β1.0, the observed failure mode is chord sidewall failure. These observations reveal that the HAZ has a certain effect on the structural performance in terms of strength and ductility of the X-joints. The material reduction in HAZ has a significant influence of the capacity and ductility of the S700 joints. The joint failed in the brace in the HAZ before reaching the 3% deformation limit. This observation is inline with what is observed from the tensile tests on the butt-welded coupon specimens it is found that the strength reduction in the S700 joint are more pronounced because of the significant material reduction in HAZ compared with the base material.

The joint capacity of RHS X-joints of steel grade S355, S500 and S700 with β = 0.5, 0.7 are sensitive to the increase of the chord thickness by 80%. As the steel grade increases, the influence becomes more pronounced. The increase of the chord thickness by 80%, result in an increase of the joint strength by 61% for the S355 and S500 joints and an increase of 70% in the S700 joints. All the joints failed by chord plasticisation. Regarding, the initial stiffness, the same increase for the three steel grade of 75% is found, when the chord thickness increased by 80%. The joint strength increase is explained by the increase of the bending resistance of the chord face, and subsequently the bending stiffness of the chord face which mainly resist the applied load when the chord thickness increased. The joint capacity of RHS X-joints of steel grade S355, S500 with β = 0.85 are sensitive to the increase of the chord thickness by 80%, while the effect is less in the S700 joints. The increase of the chord thickness by 80% in RHS X-joints with β equals 0.85, results in an increase in the joint strength of 36% in the S355 and S500 joints, while in the S700 joints, the joint increased by 32%. Both S355 and S500 joints failed by punching shear, while the S700 joint failed in the brace in HAZ for both values of τ. The more pronounced increase in the joint strength of S355 and S500 joints is, because of the increase of punching shear resistance as the chord thickness increased, while the capacity of the S700 joint is governed by load bearing capacity of the brace in HAZ. Regarding, the initial stiffness, the same increase of 50% for the three steel grade is found, when the chord thickness increased by 80%.

The material reduction in HAZ is more pronounced in the S700 joints with β=1 than that in the S355 and S500 joints when the chord thickness increases by 80%. The increase of the chord thickness by 80% in RHS X-joints with β equals 1.0, results in an increase in the joint strength of 28% in the S355 and S500 joints, while in the S700 joints, the joint increased by 24%. All the joints regardless of the steel grade failed in HAZ when the chord thickness increased by 80%. The less increase in the joint strength is explained by the more significant reduction of HAZ in the S700 joints compared to the S355 and S500 joints. The effect of the material reduction in HAZ on the strength and ductility is more significant in the RHS X-joints made of steel grade S700 with β ˃ 0.85, regardless the value of τ. These joints failed in the brace in HAZ before reaching the 3% deformation limit. In other words, the joints exhibit a limited deformation capacity and the failure was sudden and brittle in nature.

The applicability of the reduction factors introduced in EC3 part 1-8 [5] for steel grades of S500 and S700 are evaluated. The joint strength obtained from experimental tests and the numerical simulation are compared to the design resistance predicted according to EN-1993-1-8 [5] without applying the material reduction factors. It is found that the design resistance becomes increasingly conservative for RHS X-joints with small brace to chord width ratio (β <1). Therefore it is suggested that reduction factor can be relaxed i.e. 1.0 for steel grade S500 and S700. For the joints with β =1, the design resistance without applying the reduction factor are unconservative and becomes conservative when the reduction factor are applied for S500. For S700, it is observed that the material reduction in HAZ has a significant influence on the joint strength and ductility. It is therefore necessary to account for the material reduction in HAZ in order to provide safe design. It is concluded that the material reduction factors are necessary for HSS RHS X-joints with (β =1). It should be noted that the conclusion regarding the material reduction factor are based on the experimental tests and the numerical simulation of RHS butt-welded X-joints within a specific range of geometric parameters.