STRUCTURAL OPTIMISATION FOR MECHANICAL CONNECTION OF VERY HIGH STRENGTH (VHS) CIRCULAR STEEL TUBES

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ABSTRACT

The very high strength steel was developed in Australia in the 1990s. It has a yield stress of 1350 MPa and an ultimate tensile strength of 1500MPa. Studies showed that a reduction in strength was inevitable when the steel was connected using fusion welding methods. A reduction of nearly 50% in the connection strength was reported for butt-welded and fillet welded samples. In order to recover the strength loss due to welding, different strengthening techniques were attempted, including bonding CFRP sheets around a connection. Recently, a feasibility study was reported on using a mechanical jointing method. Results showed that full strength of the VHS steel tube was achieved with failure happened in the parent metal rather than in the joint. The mechanical joint consisted of a wedge-shape gripper, a sleeve and a plug. The aim of this study was to optimise this mechanical joint through finite element modelling so that the overall weight of the mechanical joint could be minimised while retaining its integrity and strength.

KEYWORDS

Very high strength (VHS) steel, mechanical joint, optimisation, connection strength.

INTRODUCTION

Due to issues surrounding cost, sustainability and climate change, high strength steel is often considered as one of the alternatives in structure design in order to reduce material usage. Very high strength (VHS) steel tubes were developed in the 1990s in Australia and have a yield stress of approximately 1350 MPa and ultimate strength of 1500 MPa (Zhao 2000). VHS steel tubes were manufactured from cold-formed steel circular hollow sections through quenching and tempering heat treatment processes. While VHS tubes have strength and ductility properties that conform to Australian Standards (Jiao & Zhao 2001; Jiao & Zhao 2002), it has been found that welding these sections severely reduces their strength. Tests on both butt-welded and transverse fillet welded VHS tubes showed a 50% reduction in the tensile strength in the heat-affected zone (HAZ) (Jiao & Zhao 2004b). Although an attempt was made to fully recover the connection strength using CFRP (Jiao & Zhao 2004a), this method seemed to be efficient in the strengthening of butt-welded VHS tubes only. There is a need to develop an alternative connection method for the connection of VHS tubes. Among the alternatives, mechanical connection methods have the advantages in that no heat is involved in the connection process.

A tensile test was conducted by Jiao et al. (2011) on a mechanical connection of VHS tubes. Full connection strength was achieved with failure happened in the parent metal. The configuration of the joint is illustrated in Figure 1. The major parameters include the flare angle (ϕ), the thickness of the sleeve (t_s) and the length of the plug (L).

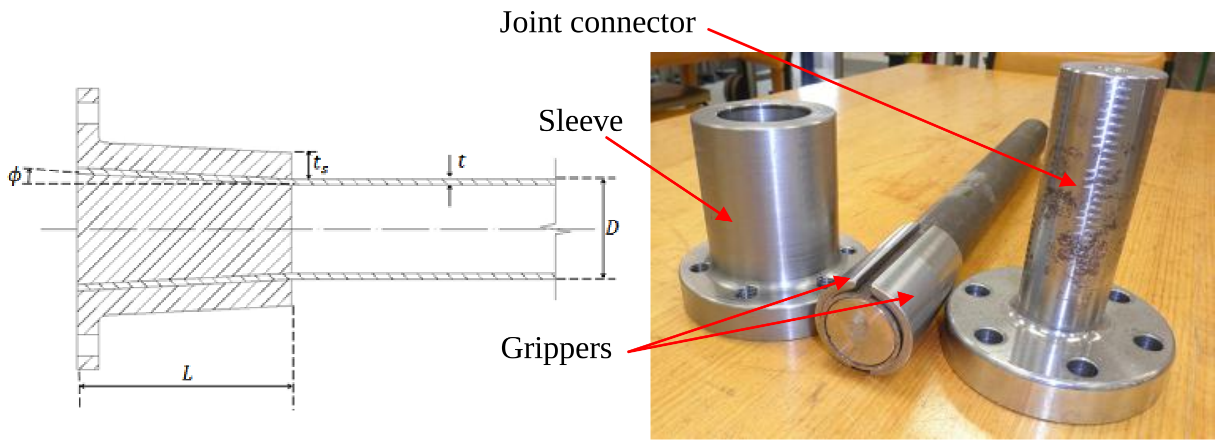

Figure 1. Mechanical joint configuration (Jiao et al. 2011)

The aim of this study was to optimise this mechanical joint by changing the parameters so that the weight of the joint could be minimised while retaining its integrity and strength. The mechanical joint was optimised through finite element modelling using the program ANSYS.

FINITE ELEMENT MODELLING

Material Properties

The material properties assigned to each component of the model were based on the material properties used in the experiment conducted by Jiao et al. (2011). Apart from the VHS tubes, the sleeve, grippers were made of high strength steel with a yield stress of 450MPa, whereas the plug was made of mild steel. The properties of these materials are listed in Table 1. The Young's modulus and the density of the steel components were taken as 200GPa and 7850 kg/m^3.

Table 1. Material properties (MPa)

Properties	Plug	Sleeve and Grippers	VHS tube
Yield stress	250	450	1350
Ultimate strength	460	500	1500

Model Geometry and Boundary Conditions

The initial dimensions of the mechanical joints were based on those used in the experiment by Jiao et al. (2011). A quarter model was selected for the analysis by taking into account the symmetry of the mechanical joint. The quarter model took into account the gap between the grippers by allowing one end of the gripper to be indented from the edge of the model. At the other edge of the model the gripper was flush with the other component as this was at the midpoint of the gripper. The total weight of the sample calculated from the model was approximately 3.2kg that was reduced after the optimisation.

A fixed support was applied to the end surface of the sleeve and the Compression Only Support was applied to the end surfaces of the plug, tube and gripper. The Compression Only Support had no influences on the model results if the model was pulled away from the support which reflected the senario when a tensile load was applied to the VHS tube. The symmetrical boundary conditions were applied to the side surfaces of the plug, tube, gripper and sleeve to restrain the displacemnet.

Contact Types

The mechanical joint had three contact regions between the plug and the VHS tube, between the VHS tube and the grippers, and between the grippers and the sleeve respectively.

A no separation contact was applied between the plug and the VHS tube as the fit between the plug and the VHS tube was very tight. This contact did not allow any gaps or separation between the two parts and only allowed minimal slippage as the coefficient of friction was high.

A bonded contact was assigned to the contact between the VHS tube and the gripper as Araldite 420, an epoxy resin, was used in the experiment to connect the VHS tube and the grippers (Jiao et al. 2011). The use of the epoxy created a strong bond between the VHS tube and the grippers. As the grippers were machined to fit around the VHS tube, no separation or gaps existed between the VHS tube and the grippers. The bonded contact did not allow for separation or gaps and it also did not allow any slippage between the two parts.

Initially a frictionless contact type was applied between the grippers and the sleeve since the contact region was slightly greased in the experiment (Jiao et al. 2011). This contact type had no resistance to slippage. However the model did not generate realistic results that could match the experimental performance of the joint. The greased surface decreased the coefficient of friction and ruled out the bonded contact, no separation contact and the rough contact. Therefore the frictional contact which the coefficient of friction was chosen by the user. Trial testing of the model was conducted while varying the coefficient of friction and the results showed that the changes in the coefficient of friction had minimal effect on the stresses in the plug, VHS tube and the grippers. A coefficient of 0.5 was adopted.

Model Verification

A 1500MPa pressure was applied to one end of the VHS tube which was farthest away from the joint to act as a tensile load on the VHS tube. After running the model, a maximum Von-Mises stress of 1555MPa occurred at a short distance away from the sleeve as shown in Figure 2(a). The location of the maximum stress was similar to the failed sample in the experiment (Jiao et al. 2011) as shown in Figure 2(b).

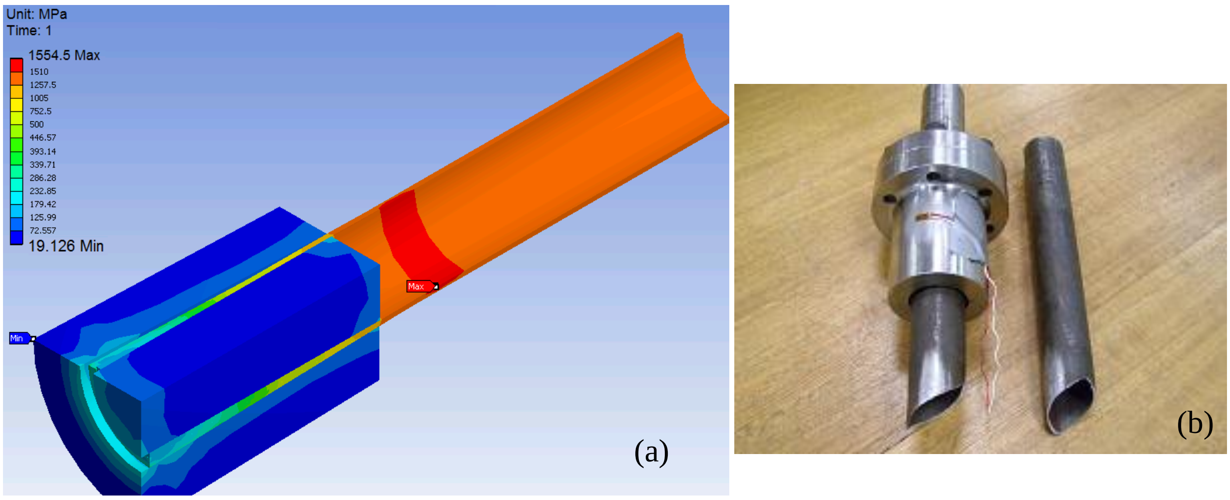

Figure 2. Comparison of the stress in the model (a) with the failure in the test sample (b) (Jiao et al. 2011)

The stresses in the sleeve and the plug were 230MPa and 160MPa respectively. These stresses are much less than the yield stress of the steel used for each component (450MPa for the sleeve and 250 for the Plug) which meant that there was a potential to reduce the dimensions of the components.

Optimisation of Parameters

The following input parameters were selected for the optimisation of the model: 1) Gripper/Wedge Length, which changed the length of the gripper as well as the length of the sleeve and the plug. This parameter changed the length of the three components because of the constraints that were applied to the model. 2) Gripper/Wedge Angle which changed the angle of the gripper and the angle of the sleeve as the sleeve was constrained to the gripper. 3) Sleeve Depth, which changed the wall thickness of the sleeve.

Two output parameters were selected to optimise the mechanical joint. The output parameters were: 1) the maximum equivalent stress, which gave the maximum stress in the mechanical joint. 2) Geometry Mass, which gave the mass of the model.

A range of values with evenly spaced intervals were selected for each parameter. Each interval point of a parameter was modelled with every interval combination of the other two parameters. A total of 540 design points were analysed. The range and interval spacing is listed in Table 2.

Table 2. Range and interval spacing for the input parameters

Parameter	Range	Interval Spacing	No of Intervals
Gripper Angle	1-3 degrees	0.25 degrees	9
Sleeve Depth	5-20 mm	1.36 mm	10
Gripper Length	50-100 mm	10 mm	6

After the optimised target parameters from the intervals in Table 2 were found, additional design points with smaller interval spacing for each parameter were selected for refinement. During the optimisation process, the stresses in all the components of the mechanical joint were checked using an application within ANSYS Static Structural called Safety Factor. The Safety Factor (*SF*) was defined as:

$$SF = \frac{f_y}{f} \tag{1}$$

where f_y is the tensile yield stress and f is the actual stress. Results showed that the safety factors for the VHS tube and the gripper stayed relatively constant which indicated that the maximum stress in these components did not fluctuate when changing the input parameters. A safety factor of 1.1 was selected for the sleeve and the plug to ensure that the failure of the mechanical joint did not occur in these two components.

As the tensile yield stress of the VHS steel was 1350MPa and the applied load was 1500MPa, it was expected that the *SF* for large portion of the VHS tube was less than one. The results from the model confirmed this. The minimum safety factor of VHS tube was 0.868 which implies that the tube had a maximum stress of 1555MPa.

It was expected that the minimum safety factor would be quite low in the angled tip of the grippers. This was because the tip of the grippers was very thin as the grippers were angled off to a point. The grippers might experience local failure at the tip but it was unlikely to cause the whole mechanical joint to fail as the majority of the gripper had a safety factor greater than one which would allow the gripper to distribute the load even through the tip of the gripper had reached the yield stress. The optimal sleeve depth was selected by graphing the results for each gripper angle and length.

The optimal sleeve depth and sleeve angle were selected by graphing the results for each gripper angle and length. Figure 3 shows the safety factors of each component and the weight of the model under different sleeve depths. It was found the optimal sleeve depth tended to decrease as the length of the gripper, sleeve and plug increased at a certain safety factor. Results showed that the optimal gripper length was around 70 mm and the sleeve depth was between 8.33mm and 10mm with the optimal gripper angle below 2 degrees.

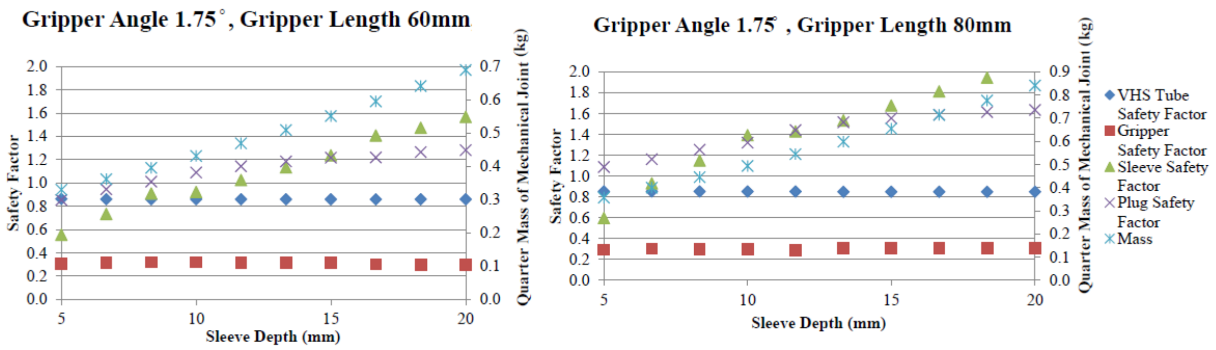

Figure 3. Safety factor versus the sleeve depth

Refinement of the parameters was conducted by specifying a small range at the values as shown in Table 3.

Table 3. Refinement of parameters

Parameter	Range	Interval Spacing	No of Intervals
Gripper Angle	1.625-2.125 degrees	0.125 degrees	5
Sleeve Depth	8-10 mm	1.36 mm	5
Gripper Length	60-75 mm	0.5 mm	7

The gripper and VHS tube safety factors stayed constant while the plug and sleeve's safety factors changed marginally. As the design points were made in the zone close to the optimal dimension combination the safety factor for the sleeve was relatively close to 1.1. As the intervals were quite small for the gripper angle values, there were multiple optimal gripper lengths and depths. There was a small range of values for the gripper angle with the optimal sleeve depth and gripper length that minimised the mass of the mechanical joint. The dimensions are summarised in Table 4.

Table 4. Optimised parameter options

Parameter	Option 1	Option 2	Option 3	Option 4
Gripper Angle (Deg)	1.75	1.75	1.875	1.875
Gripper Length (mm)	65	67.5	65	67.5
Sleeve Depth (mm)	9.5	9	9.5	9
Quarter Mass (kg)	0.397	0.398	0.398	0.399
Total Mass (kg)	1.588	1.592	1.592	1.596

It can be seen from Table 4 that the total weight of the model for the mechanical joint was about 1.6 kilograms. This weight did not include the extended plate and the bolts needed to connect the mechanical joint to other members in the structural frame. Therefore the actual mechanical joint would weigh slightly more. The optimal dimensions shown in Table 4 had minimise the weight of the mechanical joint from 3.2kg in the experiment to 1.6kg.

DISCUSSION

The finite element analysis optimised the mechanical joint of VHS tubes. Although the diameter and tube thickness used in the model were 38mm and 1.6mm respectively, this joining method should be suitable for joining different dimensioned VHS tube. This joining method served as an alternative to other mechanical connection methods, such as hydroforming and electromagnetic forming (Lennon et al. 1999; Homberg et al. 2006; Hammers et al. 2009) or nailing (Packer 1996). Further studies are anticipated to verify the suitability of this method on joining steel tubes with a yield stress of 460 MPa and 700 MPa which are commonly used high strength steel.

CONCLUSIONS

This paper conducted finite modelling of a mechanical joint connecting VHS tubes. The dimensions of the joints were optimised while maintaining the strength and integrity of the joint. Through the optimisation process, the weight of the mechanical joint was reduced from approximately 3.2kg to just less than 1.6kg, which was a significant saving in material costs and reduction of structural self-weight.

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REFERENCES

Hammers, T., Marre, M., Rautenberg, J., Barreiro, P., Schulze, V., Biermann, D., Brosius, A. and Tekkaya, A. E. (2009). “Influence of mandrel's surface and material on the mechanical properties of joints produced by electromagnetic compression”. *Steel Research International,* 80, 366-375.

Homberg, W., Marre, M., Beerwald, C. and Kleiner, M. (2006). “Joining by forming of light-weight frame structures”. In (Eds.), *Flexible Manufacture of Lightweight Frame Structures* (pp. 89-100), Dortmund, Germany, Trans Tech Publications.

Lennon, R., Pedreschi, R. and Sinha, B. P. (1999). “Comparative study of some mechanical connections in cold formed steel”. *Construction and Building Materials*, 13, 109-116.

Jiao, H., Mashiri, F. R., Xiao, Z. and Imms, D. (2011). "A feasibility study on mechanical connections of very high strength (VHS) circular steel tubes". *International Symposium on Steel Structures (ISSS),* 3-5 Nov 2011, Seoul Korea. pp. 804-809.

Jiao, H. and Zhao, X. L. (2001). "Material Ductility of Very High Strength (VHS) Circular Steel Tubes In Tension". Thin-Walled Structures, 39(11), 887-906.

Jiao, H. and Zhao, X. L. (2002). "Imperfection, Residual Stress and Yield Slenderness Limit of Very High Strength (VHS) Circular Steel Tubes". *Journal of Constructional Steel Research*, 59(2), 233-249.

Jiao, H. and Zhao, X. L. (2004a). "CFRP Strengthened Butt-welded Very High Strength (VHS) Circular Steel Tubes". *Thin-Walled Structures*, 42(7), 963-978.

Jiao, H. and Zhao, X. L. (2004b). "Tension Capacity of Very High Strength (VHS) Circular Steel Tubes After Welding". *Advances in Structural Engineering-An International Journal,* 7(4), 285-296.

Packer, J. A. (1996). "Nailed tubular connections under axial loading". *Journal of structural engineering*, 122(8), 867-872.

Zhao, X. L. (2000). "Section capacity of very high strength (VHS) circular tubes under compression". *Thin-Walled Structures*, 37(3), 223-240.