A Simplified Model of a Reinforced Square Hollow Section (SHS) T-Joint for Stress Evaluation in Bus Superstructures

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Abstract. This study aims to create a simplified model of a reinforced square hollow section (SHS) T-joint found in bus superstructures. The approach is to use a combination of one- and two-dimensional finite element models to represent a reference three-dimensional finite element (solid) model of the joint and determine stress concentration factors (SCFs) as functions of the geometrical variables of the joint. This approach requires the stiffness of the simplified model to be equivalent to the stiffness of the reference solid model. Trial models, therefore, must be proposed and their stiffnesses must be evaluated against the stiffness of the reference solid model. The best trial model is then selected based on the stiffness error function defined to represent the deviation of the simplified model’s stiffness from the reference model’s stiffness. After a trial model with minimum stiffness error is selected, its SCFs, relating the maximum stress in the simplified model to the maximum stress in the reference solid model, are determined. Since the maximum stress is assumed to be at the weld toe where structural discontinuity exists, the maximum stresses on both simplified model and reference solid model are evaluated based on a hot spot stress (HSS) method. In this study, three trial models, namely Model A, Model B, and Model C, were investigated. Model B, consisting of beam and shell elements with particular constraints on the joint-reinforcement geometry, was found to provide the minimum stiffness errors of 8.09\%, 6.87\%, and 6.44\% for three different joint dimensions. The SCFs were then determined as a function of the thickness-to-width ratio of the joint under static in-plane bending load. The resulting simplified model allows the stress evaluation on the bus superstructures to be done more quickly compared to a solid model while maintaining the accuracy of the solutions. Consequently, the designs of bus superstructures can be explored more thoroughly, leading to a better design.

1. Introduction
Buses are one of the vehicle types that people use as a means for transportation in many countries. In Thailand, the size of buses, which is signified by the bus length, can be 8m, 10m or 12m. A number of

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bus makers are located in different provinces in Thailand such as Chonburi, Ratchaburi, and Nakornrachasima. In the bus production, the design of the bus superstructure is one of processes that are vital for the safety of passengers. The strength of the superstructure has to be sufficient in order to ensure the safety of passengers while the weight of the superstructure has to be minimal in order for the bus makers to stay competitive in terms of product cost and fuel consumption. Various forms of structural steels, such as hollow square beam, I-beam, C-beam, and plates, are normally used in the bus superstructure. Different types of joints are used to assemble those structural steels. Welding is the jointing technique widely used in the fabrication of the bus superstructure. Although the welding process is perfectly controlled but the strength of the structure at welded joint areas are decreased because of peculiarities such as inhomogeneous material, welding residual stress, and weld geometry [1]. Those peculiarities cause difficulty in stress evaluation at welded joints. Moreover, most bus superstructures are designed by experiences of experts in a company. Those experiences, if without engineering knowledge, limit the continuous improvement of the design. Engineering knowledge, therefore, needs to be applied in order to increase the effectiveness of the bus superstructure design process. Computer Aided Design (CAD) and Computer Aided Engineering (CAE) are ones of the tools that can be used to evaluate stresses on the bus superstructure under several loading conditions.

Figure 1. Bus superstructure wireframe

Figure 2. Reinforced Square Hollow Section T-joint

Manokruang S. [2] presented the bus structure design using finite element analysis (FEA) under static loading condition. It was found that a wireframe, which consists of one-dimensional finite elements as shown in figure 1, could be used to identify structural members that might initiate structural failure in bus superstructures. However, according to the results, the maximum stress normally occurred at welded joints where structural discontinuity existed. The absence of the details in joint geometry, therefore, limits the applications of the wireframe model. Stress calculation approaches for welded structure have been developed for many years. Local stress approaches namely Nominal Stress method, Hot Spot Stress method, and Notch Stress method were presented by Radaj D., Sonsino C.M., and Fricke W. [3] to evaluate stresses of welded structures. Advantages and disadvantages were also presented for each method. Useful recommendations of welded structures are also given as guidelines, e.g. International Institute of Welding (IIW) [4], Eurocode [5]. However, they are only applicable to thick structures having a thickness greater than 5 mm. In bus superstructures, weight has to be reduced as much as possible to lower the material cost and fuel consumption. Thin-walled hollow square beams are usually used in the bus superstructure design. Hot spot stress (HSS) method can be applied to various applications, particularly to an automotive field. Savaidis G. and Fokilidis G. [6],[7] studied various welded joints of bus structures by HSS method. There were good agreements between experiments based on strain gage measurement and FEA using shell elements. In addition, Brennan F.P. [8] studied stress concentration factor (SCFs) of welded T-joint and skewed T-joint under tension and pure bending by two-dimensional plane stress analysis. The closed-form solutions of weld geometry parameters were represented to evaluate the SCF model.
The strength of joints can be increased by reinforcements. Those reinforcements are applied to a number of joints in bus superstructures but they are usually ignored in a stress analysis. Joints in bus superstructures may be reinforced by various means. Some joints may be reinforced by steel plates. One of interesting means to reinforce the joints is to use a hollow square beam to reinforce square hollow section (SHS) T-joint as shown in figure 2. A hollow square beam is cut to a right angle and then assembled to the SHS T-joint as shown in figure 3 by welding process. The purpose of this study is to create a simplified finite element model of this reinforced SHS T-joint using beam and shell elements. The stiffness of the simplified model has to be equivalent to the stiffness of the reference model. In addition, the SCFs are calculated by determining the relationship between the maximum stress in the simplified model and the maximum stress in the reference solid model based on HSS method. The SCFs are presented as a function of joint geometries. The scope of this study is to focus on a reinforced SHS T-joint having thickness less than 5 mm under static in-plane bending.

![Figure 3. Reinforced tubular T-joint assemble](image)

![Figure 4. Work process](image)
2. Methodology

Work process of this study is shown as a diagram in figure 4. After various joints in the bus superstructure had been reviewed, the reinforced square hollow section (SHS) T-joint was found to be an interesting geometry for the study. Geometry and dimension of the joint are shown in figure 5, where \( W \) is the width of hollow square beam and \( t \) is its thickness. The same cross-sectional dimensions of hollow square beams are used for both T-joint and the reinforcement. Width of 38-60 mm and thicknesses of 2.3-5.0 mm are dimensions of hollow square beams commonly sold in the market. Those dimensions are used to construct CAD models to be used for the analyses in this study.

![Figure 5. Geometry dimension](image)

2.1. Computer Aided Design

Computer aided design (CAD) is the use of computer program to design the geometry for many applications, mostly for engineering. It makes engineers more convenient to design. The reference solid model and three trial models namely Model A, Model B, and Model C are analyzed in this study. The trial models are allowed to consist of beam and shell elements. For Model A, only beam elements are used to represent SHS T-joint. As shown in figure 6, the reinforcement is not modelled, which is a case usually found in the bus superstructure analysis. Model B and Model C consist of beam and shell elements with the same dimensional geometry. However, the difference between Model B and Model C is shell thickness, which is represented by parameter “\( T \)”, specified to complete the definition of shell elements. As shown in figure 7 and figure 8, shell thickness of Model B equals to the width of the hollow square beam while shell thickness of Model C equals to two times of the hollow square beam thickness.

![Figure 6. Trial Model A](image)

![Figure 7. Trial Model B](image)
2.2. Finite Element Analysis

Finite element analysis (FEA) is a numerical technique used to evaluate approximate solutions. FEA is used for structural analysis in various applications, particularly in automotive field.

The joint in bus superstructure has been analyzed using finite element analysis solver. CAD of reference solid model and trial models are transferred to CAE analysis. Loads and boundary conditions of the reference solid model and trial models are set up to determine the in-plane stiffness matrices. Furthermore, the reference solid model and simplified models, which is selected from trial models, are also analyzed to determine the stress concentration factors (SCFs) as a function of joint geometries to relate the maximum stresses in two models based on hot spot stress (HSS). Material properties are significant data for FEA. Table 1 shows the material properties of structural steel used in the FEA. Figure 9 shows bending load and boundary conditions of reinforced square hollow section (SHS) T-joint.

Reference solid model and trial models from CAD have been transferred to CAE model by meshing. 10-node tetrahedral elements with 3 DOFs at each node are used to mesh reference solid model. Trial models consist of 2 types of element in this study. The first type is 2-node beam element with 6 DOFs at each node. Cross-sectional properties of a hollow square beam have to be specified for the beam elements. The other type of element is 4-node shell element with 6 DOFs at each node. For this element, shell thickness has to be specified.

Table 1. Structural steel properties.

| Property            | Value       |
|---------------------|-------------|
| Elastic of modulus  | $2 \times 10^5$ MPa |
| Poisson’s Ratio     | 0.3         |

Figure 8. Trial Model C

Figure 9. Bending in-plane loading
2.3. Stiffness

The structural behaviour of the simplified model must be equivalent to that of the reference model. This behaviour is represented as a stiffness matrix shown in equation (1). The stiffness matrices are calculated using equation (2) which is a basic equation of finite element method theory. The stiffness of each trial model calculated by using FEA is compared to the stiffness of reference model.

\[
[K] = \begin{bmatrix}
K_{11} & K_{12} & K_{13} & \cdots & K_{19} \\
K_{21} & \ddots & \vdots & & \vdots \\
\vdots & & \ddots & & \vdots \\
K_{91} & \cdots & & K_{99}
\end{bmatrix}
\]  

(1)

\[
[F] = [K][U]
\]  

(2)

Where \([K]\) = Stiffness matrix, \([F]\) = Load apply and \([U]\) = Displacement

The stiffness error function in equation (4) is defined to represent the deviation of each trial model’s stiffness from reference model’s stiffness. The stiffness errors between reference solid model and trial models were calculated using equation (2), equation (3) and equation (4). The trial model which provides the minimum stiffness error is selected as the most suitable simplified model.

\[
ERR_{ij} = \frac{K_{s,ij} - K_{ij}}{K_{s,ij}} \times 100\%
\]  

(3)

\[
ERR = \left(\frac{\sum \left(ER_{ij}\right)^2}{n}\right)^{1/2}
\]  

(4)

Where: \(K_{s,ij}\) = Stiffness matrix of reference model, \(K_{ij}\) = Stiffness matrix of trial model, \(ERR_{ij}\) = Stiffness error matrix of trial model, \(ERR\) = Stiffness error function and \(n\) = number of member of stiffness matrix

2.4. Hot Spot Stress Method

Hot spot stress, sometimes called Geometric stress, has been discussed in a former paper [9]. Hot spot is described as a point that high stress occurs. In welded joint, this point corresponds to the weld toe. Thus, HSS method is limited to the failure location occurring at weld toe in complicated structures. HSS method includes all stress raising effects of a structural detail excluding all stress concentrations due to the local weld profiles itself. HSS can be determined using reference points away from weld toe by extrapolation on surfaces in order to avoid stress singularity. A set of reference points in HSS method depends on thickness of weld components. Both linear extrapolation and quadratic extrapolation shown in figure 10 and figure 11 can be applied to evaluate the HSS. Surface stresses can be measured experimentally by strain gauges.
For a thin-walled structure, surface stresses are difficult to be determined by experiment because the distance between reference points are too small to place strain gauges. Instead of using experiment, FEA can be used to determine surface stresses without any difficulty. Based on a finite element model, it is possible to place nodes on lines where stress must be measured to evaluate HSS. Because local weld profiles are excluded in stress raising effects, weld geometry may be modeled or not modeled in FEA. In this study, weld geometry is not modeled. Reference points can be determined by distances away from structural discontinuity points. HSS of both reference solid model and simplified model are determined by extrapolating surface stresses located at distances from the edge of the reinforcement where the structural discontinuity exists as shown in figure 12 and figure 13. A quadratic extrapolation is recommended to be used for hollow square beams. According to IIW recommendations, fine mesh is required for FEA. The stress values at the reference points 0.4t, 0.9t and 1.4t away from structural discontinuity has been collected to calculate the quadratic HSS by equation (5).

\[
\sigma_{HSS,\text{quadratic}} = 2.52\sigma_{0.4t} - 2.24\sigma_{0.9t} + 0.72\sigma_{1.4t}
\]  

(5)
2.5. Stress concentration factor
The maximum stress of reference solid model and simplified model were determined using HSS method on reinforced structures. SCFs are calculated based on maximum stresses of the two models. Each value of SCF is determined using equation (6) as a HSS of reference solid model to HSS of simplified model ratio.

\[
SCF = \frac{\sigma_{HS,\text{solid}}}{\sigma_{HS,\text{simplified}}}
\]  

(6)

3. Result
The results of stiffness errors for Model A, Model B, and Model C are summarized as shown in table 2. Model B provides the minimum stiffness error, which represents the deviation of trial model’s stiffness from the reference solid model’s stiffness. This model is, therefore, the most suitable to be a simplified model whose stress concentration factors (SCFs) will be determined. This simplified model consists of beam elements and shell elements without weld geometry. Beam elements are positioned along neutral axes of hollow square beams. The thickness of shell elements is specified to be equal to the beam width.

Table 2. Stiffness error function

| W × W × t | 50 × 50 × 3.2 | 50 × 50 × 4.0 | 50 × 50 × 5.0 |
|-----------|-------------|-------------|-------------|
| Model A   | 10.7424%    | 8.2063%    | 8.2013%    |
| Model B   | 8.0852%     | 6.8732%    | 6.4382%    |
| Model C   | 9.4627%     | 7.0188%    | 6.7590%    |

Maximum stress occurs at the discontinuity points of reference solid model and simplified model. Figure 14 presents the SCF of square hollow section (SHS) T-joint having thickness t of 3.2 mm with different beam width. The best fit equation of the beam width is equation (7). Figure 15 presents SCF of SHS T-joint having width W of 50 mm with different beam thickness. The best fit equation of beam thickness is a linear equation of (8).

\[
SCF_{t=3.2\text{mm.}} = -0.0002W^2 + 0.031W + 0.3404
\]  

(7)

\[
SCF_{W=50\text{mm.}} = -0.2195t + 2.1324
\]  

(8)

Figure 14. SCF static in-plane bending load for t=3.2mm.

Figure 15. SCF static in-plane bending load for W=50mm.
Thicknesses to width Ratio of hollow square beam is presented as geometrical variable of SCF in figure 16. The best fit equation is equation (9)

\[
SCF_{/W} = -62.188 \left( \frac{t}{W} \right)^2 - 1.1101 \left( \frac{t}{W} \right) + 0.7572
\]  

(9)

Figure 9. Bending in-plane loading

4. Conclusion

The reinforcement of square hollow section (SHS) T-joints, usually ignored in bus superstructure analysis, is considered carefully in this study. Trial models namely Model A, Model B, and Model C were investigated to evaluate the stiffness errors, which represent the deviations of trial model’s stiffnesses from the reference solid model’s stiffness. It was found that Model B, providing the minimum stiffness error, is most suitable to be used as a simplified model. Finite element analysis (FEA) was then used to evaluate hot spot stress (HSS) of both reference solid model and simplified model in order to determine the stress concentration factor (SCFs). The SCFs of reinforced SHS T-joint in bus superstructure without weld geometry were presented as a function of thickness to width ratio of hollow section beam. This simplified model allows the stress evaluation on the bus superstructure to be done more quickly compared to reference solid model while the accuracy of the solution is maintained. The SCFs are valid for SHS T-joints having thickness less than 5 mm. However, the simplified model, as well as its SCFs, determined in this study is limited to some values of geometric variables. The simplified model should be studied further for a more complete range in the values of geometric variables. Moreover, the simplified model can be improved by optimizing the geometrical parameters of the finite element model in order to represent more accurate stiffness of the joint. Nonetheless, only bending load is applied in this study. Other load types may occur in reality. Reinforced SHS T-joint has to be studied further on various load types to evaluate the accuracy of the stress results.

5. References

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