Canadian Journal of Civil Engineering

Behavior of bolted lap joints in above ground liquid-filled steel cylindrical tanks

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2020-0416.R2
Manuscript Type:	Article
Date Submitted by the Author:	12-Jun-2021
Complete List of Authors:	Moslemi, Mehdi; Ryerson University, Civil Engineering Kianoush, M. Reza; Ryerson University, Dept. of Civil Engineering
Keyword:	bolted lap joints, finite element, steel liquid tanks, leakage
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Behaviour of bolted lap joints in above ground liquid-filled steel cylindrical tanks

Mehdi Moslemi, M. Reza Kianoush

Draft

M. Moslemi. Department of Civil Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, M5B 2K3, Canada.

M.R. Kianoush. Department of Civil Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, M5B 2K3, Canada.

Corresponding author: M. R. Kianoush (e-mail: kianoush@ryerson.ca; Tel.: +1 416 979 5000 x 6455; Fax: +1 416 979 5122).

Abstract: Leakage is the main concern in steel bolted liquid tanks and some past experiences have shown serviceability problems due to leakage mainly from the joint locations even in situations where the tank has only been subjected to an internal hydrostatic pressure. In the present study, the performance of this type of construction is investigated using a detailed finite element (FE) analysis technique. Moreover, the validity of the AWWA design practice in terms of the safe design of this type of structures at a wide range of service loads is evaluated through a parametric study. The FE analysis is performed in two stages using shell and solid elements in a three-dimensional ANSYS environment including the effect of geometric nonlinearity. The proposed FE model is capable of estimating the ultimate behaviors such as capacity curve, yield/failure pattern, and the occurrence of ovaling and curling in bolted connections. In addition, the FE results are compared with experimental ones and a good agreement is found in general. The study shows that the bolt arrangement chosen in design can efficiently improve the joint performance. The study further recommends the use of a limited deformation criterion in the leak-resistant design of bolted lap joints in steel liquid containers.

Key words: leakage, bolted lap joints, finite element, steel liquid tanks.

Introduction

Tanks are considered as fundamental elements for the storage of different forms of materials including gas, solid, and liquid. Recently, the use of light designed modular steel storage tanks has gained attention as both temporary and permanent liquid storage containment facilities. Whether welded or bolted, in order to have steel storage tanks with low maintenance and long term performance, a robust tank design and state-of-the-art coating systems should be used in the construction of these structures.

To build the tanks, rectangular plates are first rolled to the correct curvature and then connected to each other using bolts to form a ring. The rings are then placed on top of each other to form the full tank. Where the storage of a large volume of solid or fluid is of concern, generally the most economical solution is a cylindrically shaped shell tank with a vertical axis of symmetry extending through its center. In this type of structures, due to reasons of functionality, leakage control is the main concern and uncontrolled leakage could lead to irreparable consequences. As a result, consistent knowledge of the deflection characteristics and deformation pattern of this type of connection and its relation to the liquid leakage is essential to ensure if the serviceability requirements are met. Even under hydrostatic loading condition, many steel tanks built by this technique have experienced slight to extreme levels of leakage mostly at joint locations (Doerich and Rotter 2008; Huang and Mannan 2013; Pircher and Bridge 2002; Tank Connection 2015).

Failure of liquid storage tanks could be caused by one of the following reasons: inadequate tank design, construction, inspection, and maintenance. Leaks can occur as the excessive liquid pressure or dynamic loads cause fittings, joints, and sometimes even the entire tank to shift. For the purpose of damage tolerance assessment of a bolted tank, it is necessary to evaluate the

fracture critical load of bolted connection interfaces (Galambos et al. 1982). Given recent progresses in computer technology, researchers now have the opportunity to explore this issue rigorously both experimentally and numerically using advanced simulation techniques such as Finite Element (FE) modeling (Kulak et al. 2001; Može and Beg 2016; Wallace et al. 2001).

Pawar et al. (2015) conducted a series of FE analysis on single-lap bolted joints using ANSYS workbench package. They investigated the effect of preload on the joint behavior and observed that a direct relationship between the amount of prestressing force and that of deformation/stress response could be defined. In a more recent work, Raghunathan et al. (2017) investigated the net-tension strength and corresponding failure modes of single-lap, single-bolted connections both analytically and experimentally using thirty five specimens consisting of a GFRP structural angle member connected to a gusset plate using steel bolts and nuts. As per the results of their study, the optimum plate width and edge distance to achieve maximum connection efficiency were reported as three and five times diameter of the bolt, respectively.

Detailed information and applicable provisions regarding the design of bolted joints can be found in the following codes and standards: AWWA. D103-09 (2009); Eurocode, CEN. (2010); AISI (2016); AISI S100 (2007).

The objective of this study is to propose a FE model as a means of providing insight into the deformation behavior of the flat-plate connections in order to evaluate the effect on the potential for leakage and damage to coatings. To this end, a variety of tank configurations are arranged to enable various combinations of flexural, tensile and shear stresses across the joints. The main aim is to investigate if the proper choice of design (e.g. bolt spacing and number of rows) could lead to superior performance in the context of leakage control. The issue will be

addressed analytically, using a detailed finite element (FE) technique. This study could be of particular significance to industry, as leakage is a major concern in such structures. The amount of research conducted in this area is very limited. Even then, most of these rare studies are generally focused on tanks made of normal concrete. It is expected that the results of this study can provide some practical guidelines for design of safe leak resistant bolted steel tanks to be used by engineering community for future applications of these structures.

Shell analysis of the entire tank

Tank design

At this stage of study, three cylindrical tanks covering a wide range of aspect ratios and liquid depths found in today's practice namely "Shallow", "Intermediate", and "Tall" are designed and their response under hydrostatic loading condition is analyzed numerically. The tanks have similar capacities of 1MG (3785 m³) and their dimensions are provided in Table 1. The tanks and their flat-plate bolted lap joints are designed as per AWWA D103 (2009) that is based on AISI S100 (2007) and AISC 360 (2005). The results of this step will provide a reference on the practical range of different stress components variations at critical joint locations which will be used in the next step of study for the detailed investigation of an individual joint response.

Steel plates of grades 55 and 60 ksi are used in the design. The lower strength material is used for the upper portion, while the higher strength material is used for the lower portion of the tank. The sheets have standard dimensions of 2.68m long and 1.40m high except for the starter ring (S.R.) which is 0.51m high.

As per AWWA D103, the minimum and maximum specified thicknesses for flat panel shell plates are limited to 2.4 mm (0.094 in.) and 12.7mm (0.5 in.), respectively. The standard further sets the minimum thickness as not less than 2.4 mm (0.094 in.) for the bottom sheets of steel water storage tanks. Bolts having 1/2" (12.7mm) diameter (d) with 14.29mm hole diameter (d_h) are considered for design. To investigate the effect of bolt pattern on the leakage performance of joints, each tank is designed for different number of bolt rows varying from 1 to 4 (corresponding to "Design 1" to "Design 4") and bolts center-to-center spacing (S) varying from $2d$ to $5d$, respectively. Bolt arrangements considered are given in Figure 1. The design summary together with the stress analysis of the Shallow tank assuming a bolt spacing of $2d$ (25.4mm) and an upper freeboard of 0.15m is provided in Table 2 as a sample. The tank was designed as part of an actual project, built in USA. Given in the table, t_p is shell plate design thickness, T_h is applied unit hoop tension force, P_{h1} and P_{h2} are ASD (Allowable Stress Design) shell plate tension strengths for single/aligned multi-rows and staggered multi-rows, respectively. P_b and P_v are ASD bolt bearing and shear strengths, respectively. The designed geometry of Tank 1 is indicated in Figure 2. Shown on the figure is also the location of web truss stiffeners installed at two different heights of 6.1 and 8.9 m from the base around the tank's circumference. The function of a web truss stiffener is to resist wind load effects around the tank. These intermediate horizontal wind stiffeners are designed in the form of a web truss with extended tail to create multiple layers of stiffener, permitting wind load to transfer around the tank. It should be noted that these intermediate stiffeners are not allowed to be designed as rolled angle stiffeners.

FE modeling

Analysis is carried out using ANSYS®, v.18 finite element package. The entire tank structure is modeled using four-node quadrilateral shell elements (SHELL63). The element has six degrees of freedom (DOFs); translations and rotations at each node and both bending and membrane behaviors are permitted. Both normal and in-plane loads are allowed. The fluid is not modeled discretely however its effect is considered by applying an equivalent hydrostatic pressure triangularly distributed over the internal face of shell elements.

Stiffeners are modeled and assembled around the tank's circumference at different heights according to the design using 3D finite beam elements (BEAM4); a uniaxial element with tension, compression, torsion, and bending capabilities with six degrees of freedom at each node.

To account for the restraining effect of fasteners, at every bolt location two coincident nodes; one for the inner and one for the outer skin are defined and their translational DOFs are coupled to each other through coupling equations defining the load-deflection properties of the bolts as per design. Due to the bolts being closely spaced and also their distribution both vertically and horizontally throughout the tank's body, this results in quite a large number of elements.

Coupling is a robust feature letting the modeller establish relationships among the different DOFs of the model by defining a specific coupling condition. This enables the analyzer to model distinctive features of a geometry, such as bolting of separate bodies as well as various joint/hinge effects which otherwise cannot be adequately described with typical modeling techniques. In this instance, one can create a set of vertices which have a coupled DOF (nodal direction in which these nodes are to be coupled) by using the coupling boundary condition. Coupling the DOFs of a set of geometric entity constrains the results calculated for one member of the set to be the same for all members of the set implying that these nodes are forced to take

the same displacement in the specified nodal coordinate direction. In this study, all three translational DOFs (UX, UY, or UZ displacements) of coincident nodes defined at the location of bolts are coupled. The first DOF of the coupled set is the "prime" DOF. All other DOFs in the coupled sets are eliminated from the solution matrices by their relationship to the prime DOF. On this basis, the use of coupled nodes reduces the set of coupled DOFs to only one DOF.

The tank wall is considered to be rigidly anchored to the rigid foundation assuming hinged boundary condition at the base. For the sake of simplicity, the roof is excluded from modeling. However, the effect of roof rigidity is included by applying an adjusted high level of rigidity at the wall/roof interface using elastic ring beam elements. The top stiffener (ring beam) is made of a 5" x 5" x 3/8" angle bolted to the tank wall around the circumference. Usually in these structures, when the roof is present the magnitude of relative radial displacement at the roof/wall interface is quite negligible implying an almost a full rigidity constraint. The appropriate level of stiffness for the beam is achieved through a trial and error process by increasing the modulus of elasticity of the angle in increments to a level that the relative radial displacement at the top interface becomes negligible. This was reached at the modulus of elasticity of 10 times that of regular structural steel for the angle size given above.

A typical FE idealization of a portion of the tank's wall indicating the horizontal and vertical lap joints is shown in Figure 2(b). As shown in the figure, the neighboring sheets overlap with each other along their respectively commonly adjoining edges both horizontally and vertically, providing an overlapping joint of the two separate sheets connected to each other through the bolts.

Results of FE analysis

Based on the calculated results, the magnitude of average hoop stress corresponding to the location of maximum response along the height of the tank varies between $0.28F_y$ to $0.52F_y$ for different tank models considered in this study. This can be introduced as the practical range of hoop stress. As mentioned before, only three cylindrical tanks with a similar capacity of 1MG (3785 m³) but with different aspect ratios ranging from shallow to tall are studied (geometric details are given in Table 1). The liquid depth ranges from 9.8m in Tank 1 (Shallow), to 13.85m in Tank 2 (Intermediate), to 23.3m in Tank 3 (Tall). Furthermore, the resulting hoop stress in the tank's wall is calculated assuming an un-factored (nominal) internal hydrostatic pressure.

The hoop tension (T_g) in the tank's wall over length S as indicated in Figure 3(a), generated due to the internal pressure of q for a tank with a radius of R is calculated as:

$$(1) \quad T_g = qRS$$

Using the above equation, the pressure value corresponding to a stress of $0.6F_y$ in the base metal allowing for no reduction for the holes, is determined as given below.

$$(2) \quad T_g = 0.6 F_y A_g = 0.6 F_y S t_p = qRS \rightarrow q = \frac{0.6 F_y t_p}{R}$$

Where, $A_g = S t_p$ is the gross tension area, S is bolt spacing, and t_p is plate thickness. To induce the practical range of hoop stress presented above, it is suggested to increase the pressure (kq) incrementally using $k = 0.50, 0.60, 0.70, 0.80$, and 0.85 , which will in turn increase the resulting hoop tension proportionally, $T = kT_g$. These load increments used with 350W steel plate represent the range of plate materials ($F_y = 30$ to 60 ksi) at service loads as per AWWA D103 (2009).

For brevity, the von Mises stress contour of only one of the models (Shallow tank) is provided here (Figure 4). It can be clearly noticed from the figure that the stress distribution pattern and

deformed shape of the bolted tank with discontinuity between the sheets are considerably different from the one with continuous sheets and no end laps (e.g. sheets welded together along the common edge). The stress concentration can be clearly observed at the locations of vertical lap joints especially toward the bottom of the tank where stiffener ring assemblies are not present. Due to the presence of ring stiffeners, the stress level remains insignificant at the top sections of the tank shell. In each sheet, the magnitude of hoop stress starts from a maximum along the vertical end laps and reaches a minimum near the middle of the sheet length. It can be further noticed that the direction of curvature is reversed from outward to inward, moving toward the middle of the sheets.

In an effort to find an optimum design with respect to leakage control, the effect of bolt pattern on the leakage performance of the joints is investigated by looking into between one to four rows of aligned bolts corresponding to bolt spacings of $2d$ to $5d$, respectively. Tank 3 is considered for this purpose. The fifth ring from the base of the tank (including the starter ring) is designed for four different bolt arrangement case scenarios mentioned above. As per AWWA D103 (2009), the minimum bolt spacing permitted for design of flat plate lap joints with standard holes is twice the nominal bolt diameter ($2d$), while maximum spacing is unlikely to exceed $5d$. It is also a recommended practice that maximum number of rows in multi-row connections do not exceed 4 or 5. Following the AWWA D103 design procedure will result in a Gr.60 plate of 8mm thickness with Gr.5 bolts of $1/2''$ (12.7mm) diameter. Horizontal spacing between the rows and bolt edge distance (center of leading-edge bolt to plate edge) are assumed to be fixed at $2''$ (50.8mm) and $1.25''$ (31.75mm), respectively.

Under the applied internal pressure and due to dissimilar deflection of plates, most importantly in the radial direction (x), the two layers of overlapping plates at the location of joints tend to separate from each other creating a gap between their faying surfaces. The gap is of significantly smaller order along the bolt row lines than that along the free edges of the plates. Obtained results suggest that the size of the gap may be controlled effectively by the bolt pattern chosen in design. In addition, the gap size should be considered as one of the key factors in determining the joint susceptibility to leakage. To avoid leakage, the order of strain at the joint should be kept below a certain limit under service loads such that no excessive gap may be formed between any two adjacent surfaces in direct contact with the contained liquid.

According to the FE results, the size of the gap at the free edge of the plate at the mid-height of the ring is reduced from 4.4 mm in a single row connection (Design 1) to 0.45 mm in a double row connection (Design 2). This is mainly due to the bending stiffness introduced to the system as a result of the coupling action developed between the axial components of the bolts resisting force in multi-row connections. Increasing the number of rows above two (up to four as is the case here) has only a negligible effect on the size of the formed gap. This is also evident from the values calculated for the radial displacement of the tank at the mid-height of the ring for different bolt patterns, indicating a sharp reduction in response by shifting from a single to a double-row joint. However, no considerable improvement (less than 2%) is observed afterward by moving from a two to a three or four-row connection. In connections with three and four rows of bolts (Design 3 and 4, respectively) the gap size is found to be 0.43 and 0.42mm, respectively. A partial view of the lap joint deformed shape for the single row connection is also indicated in Figure 4.

Another issue of interest to be investigated here is the effect of bolt spacing on the deformational behavior of the joint. The acquired FE results propose that for the range of bolt spacings used in today's practice (between $2d$ to $5d$) which is also the range presumed in this study, increasing the bolt spacing has little or no distortional effect on the deformation state of the part of the plate located between the two consecutive bolts. As per the FE analysis, by increasing the bolt vertical spacing along the bolt row line from $2d$ to $5d$, the gap between the overlapping plates for the portion fastened between the two neighboring vertical bolts only increases negligibly by 0.1 mm.

In conclusion, it seems that for the purpose of design of bolted lap joints in liquid tanks, deflection-wise, there is no tangible advantage in increasing the number of bolt rows above two as no considerable change in the joint's deformation state is observed among two to four-row connections. On the other hand, the deflection improvement of the joint achieved by replacing a single-row with a multi-row design pattern is quite apparent.

However, apart from analysis perspective, it should be noted that in order to achieve better leakage control performance, it is preferable to employ joints with higher number of bolt lines. This is partly due to the fact that placing the bolts in more rows of far-spaced bolts rather than less rows of closely-spaced bolts provides a larger effective overlapping area to apply the sealant material and also results in a more number of leakage-blocking lines. This in turn helps maintain a leak tight seal along the joint's overlapping area.

Solid analysis of the joint

In this section, the practical stress range determined in the previous section corresponding to the k factor of 0.50 to 0.85 is applied incrementally on an individual joint and the stress-strain state of the assembly with elastomeric sealant positioned between the faying surfaces is investigated at different load increments using nonlinear 3D solid elements.

This detailed solid model makes possible the study and identification of some important aspects of the behavior of the joint under the range of service hoop stress estimated in the previous part, which was otherwise impossible to realize with the simplified, linear, elastic shell model of the previous step. The magnitude of edge traction tensile load (T) applied to the solid model in this step, as shown in Figure 3(a) is decided based on the outputs of the parametric study performed in the previous step using the simplified shell model.

The proposed solid model is capable of incorporating material nonlinearity/plasticity, and geometric nonlinearity effects in an effort to study issues such as bolt tilting, elongation of the bolt hole, distortion of the plates around the bolt, and large-strain response of gaskets. The model can also effectively account for important unique aspects of fasteners response such as surface-to-surface bearing contact detection and treatment between bodies involved in the assembly, friction/slip, and most importantly pre-tension condition in bolts caused by torque. Of particular interest in this study is also to define the threshold load at which the deformation in the plate becomes inelastic, as well as the magnitude of ovaling of the bolt hole.

The considered joint is a typical single-lap with two columns of bolts as depicted in Figure 3(b) and discussed below. The joint is representative of a vertical seam located near the bottom of a 11m diameter tank made of a 8mm thick 350W steel plate with the yield (F_y) and tensile (F_u) strengths of 50 ksi (345 MPa) and 70 ksi (483 MPa), respectively. J429 GR8 bolts of 1/2"

(12.7mm) diameter with yield and tensile strengths of 130 ksi (896 MPa) and 150 ksi (1034 MPa), respectively connect the two overlaying plates. Other geometrical properties of the model are taken as follows:

$$\begin{aligned} d_h = 14.3 \text{ mm, Hole diameter} \quad S = 3.5d = 44.5 \text{ mm, Bolt spacing} \quad \rho = S = 44.5 \text{ mm, Pitch} \\ g = \frac{S}{2} = 22.2 \text{ mm, Gage} \quad S_e = 1.5d = 19 \text{ mm, Edge distance} \quad t = 1.6 \text{ mm, Gasket thickness} \end{aligned}$$

The specified torque to compress the seal/gasket is assumed to be on the order of 47.5 N.m.

Torque results in the stretch or elongation of the bolt that provides the clamping force of a joint and is related to the pretension in the bolt using the following equation:

$$(3) \quad T = \frac{KdP}{1000}$$

Where, T is torque (N.m), d is nominal diameter (mm), P is desired clamp load tension (N), and K is torque coefficient (dimensionless). K coefficient mainly accounts for the friction level in the joint assembly and is assumed as 0.2 for this study representing a plain/slightly oily assembly condition. Substituting the above numbers in eq. 3, a pretension force of 18.7 kN is estimated.

Material properties

Steel components

The “classical bilinear kinematic hardening” plasticity algorithm using the von Mises yield criterion together with the kinematic hardening rule is adopted to capture the nonlinear behavior of mild steel material for both the plates and the bolts. The ratio of tangent modulus (2.05 GPa) to elastic modulus (205 GPa) is taken as 1%. This is the number typically used in numerical modeling works for the purpose of bilinear idealization of the inelastic behavior of mild steel material and is well supported in the literature by many researchers (dos Santos et al. 2020; Han et al. 2008; Kaeding and Lindemann 2015; Salmon et al. 2009).

Gasket layer

Gaskets act as sealing components between structural components and are usually very thin and are typically made of elastomeric materials such as neoprene, nitrile, silicone, or other similar material. When aimed for application in bolted steel liquid tanks, aside from their sealing capability, they should be able to resist expansion and contraction and fully transfer the load between mating components.

- *Under compression*

Elastomeric gaskets usually exhibit high nonlinearity with rather complicated behavior under compression especially during unloading. Here, gasket is modeled as compression-only elements and its primary deformation is confined to through-thickness direction only.

AASHTO (2002) has published some stress-strain curves for accurately predicting a strain for a bearing of a given shape factor and hardness at a range of compressive stresses. Several studies including Muscarella and Yura (1995) revealed a reasonable correlation between the stress-strain data collected experimentally and the one proposed by AASHTO. Consequently, the same curves are used for the purpose of the current study which is reproduced here for a Shore 'A' durometer hardness of 50 and a shape factor of 16 representing the current problem as shown in Figure 5(a). The shape factor basically describes the tendency of elastomer to bulge under compressive load which is defined as the loaded plan area, divided by the area free to bulge. The unloading data is adopted from Muscarella and Yura (1995) in which the performance of elastomeric pads was analyzed on the basis of elastomer hardness, shape factor, degree of taper and compressive stress level through a comprehensive experimentation. As can be observed in the figure, the greater the unloading level, the greater the initial unloading slope. The two unloading curves

provided appear to be sufficient to characterize the through-thickness behavior of the layer for this specific problem.

- *Under shear*

The inclusion of transverse shear stiffness is generally required when the interfaces between the gasket and the mating parts are modeled as sliding contact, which is the case here. Gasket's shear stiffness is typically much smaller than the compression stiffness. As per the available literature (Ardizoglou 1994; Muscarella and Yura 1995), the shape factor has no considerable influence on the shear modulus of elastomers; not more than the overall average of 7%. As a result, for the purpose of this study and as a relatively accurate estimation, the shear modulus is readily adopted from AASHTO (2002) assuming a Shore 'A' hardness of 50 which leads to a shear modulus of 95 psi (0.68 MPa).

FE modeling

The isotropic SOLID-185, an 8-Node brick element with three degrees of freedom per node is used for modeling of the plates and bolts. The element is capable of modeling the plasticity behavior and is particularly designed for simulating material with elastoplastic behavior experiencing large plastic deformations. This model is advantageous over the shell model used in the previous section. 3D continuum elements are capable of modelling the nonlinear behaviour through the thickness of the parts compared to conventional shell modelling.

The INTER-195, a 3D 8-Node linear interface element is used to simulate the gasket. To simulate contact and sliding between mating components, the surface-to-surface contact element CONTA-174 is used. The element is located on the surfaces of solid elements and has the same geometric properties as the target element face with which it is connected. In a typical

contact problem, CONTA-174 elements are associated with the 3D target segment elements (TARGE-170) through a shared real constant set. The model also allows separation of bonded contact to simulate interface delamination.

Assuming a reasonable value for friction coefficient is especially important in this problem due to the convergence difficulties in the FE simulation. Models involving contact conditions as is typically the case in bolted connection models are highly non-linear and modellers usually experience high computational expense and converging difficulties. As a result it is necessary to introduce a reasonable friction level to the models involving contact between parts that can move relative to each other during the load incrementation. It should be noted that the type of coating together with the treatment of the faying surfaces and coating are the two main factors affecting the slip coefficient of the joint. As recommended by several research works (Kulak et al. 2001; Bickford 2008), in the current study the coefficient of friction is assumed as 0.2 for all contacting surfaces representing a hot-dip galvanized coating.

To perform a typical pretension analysis in ANSYS, one needs to mesh the bolt, then cut the mesh and insert the pretension elements into volume to form the pretension section. In this work, the PSMESH operation in ANSYS is used to separate the elements of the bolt into two unconnected groups across the bolt's mid-height, the separated sides are then tied together with PRETS179 pretension elements. The element has only one translational DOF, representing the defined pretension direction. It is important that there are coincident nodes on the two sides of the pretension section. The pretension load is then applied across the pretension section in the axial direction and the job is submitted for running. The obtained results from the pretension

analysis (first step) suggest that as expected the axial stress is tensile in the bolt, and compressive in the portion of the plates compressed by the bolt heads.

Verification study

To verify the proposed solid model, the bolted connection specimen D1-55 with 208×470 mm connected pieces tested under single shear by Talja and Torkar (2014) was modelled in the FE environment ANSYS using 3D continuum elements and the comparison of numerical and experimental failure responses under tension is indicated in Figure 5(b). The material was a ferritic stainless steel of grade EN 1.4509 (ASTM 441) with a thickness of 4.5 mm and M12 bolts of grade A2 with property class 70. Total of 6 aligned bolts in two rows were used. The direct load vs. joint displacement was recorded until the complete failure of the connection. It may be noticed that the numerical results from the current study are in good agreement with the experimental ones confirming the validity of the proposed numerical model. Furthermore, the failure mode identified by experiment as block shear failure coincides well with the FE observations. The mode of failure for specimen D1-55 is shown in Figure 5(c). This failure mode is triggered by an initial tensile rupture along the leading-edge row of bolts, and then shear yielding around the bolts block's perimeter with each of the individual failures occurring separately. To better explain the observed behaviour, the failure path is also shown on the figure.

The von Mises stress distribution of the joint obtained from FE analysis is shown in Figure 5(d). As can be observed, a failure mode similar to that from the experimental study is suggested by the FE analysis. The red dotted lines represent the planes of failure perfectly matching those observed in the experiment. It is clear from the figure that the bolted portion of the connection has failed as a block around the bolt holes in the periphery. The bolted block has torn out due to

combination of fracture along the tensile section and yielding in shear at the gross section of the perpendicular plane.

After the successful verification of the model, the next step was to perform a similar FE analysis on the lap joint under study shown in Figure 3(b), for which a similar failure mode was obtained. The deformed shape at the time of joint failure obtained from FE simulation is given in Figure 6(c), which clearly suggests the failure mode to be a block shear failure. The corresponding planes of failure are shown on the figure by red dotted lines.

Results of FE analysis

A two-step FE analysis is performed using the full Newton-Raphson method. First, a static analysis is conducted to apply the pretensioning in bolts by adding an initial stress to the bolt elements. This produces frictional resistance between the contacting surfaces such that by the end of this step the maximum attainable friction is developed. Second, the tension force (T) is applied at both edges of the plates as an edge traction uniform stress increasing incrementally to the target value in hoop direction. The capacity curve of the connection obtained from FE analysis is shown in Figure 7. The deformed shape and stress distribution of the joint at the end of first load step is shown in Figure 3. At this stage the gasket experiences a maximum compressive closure of 0.09 mm at a contact pressure level of 13.8 MPa which is in perfect correlation with the gasket material curve defined in Figure 5(a).

According to the figure there is high stress concentration at the points of contact between the bolts heads and the plates. At this stage of analysis, there is no contact between the bolts shanks and the inner faces of the holes. The stress level in the whole assembly is lower than the yield stress of materials. Maximum stress of 303 MPa (44 ksi) occurs locally in the bottom plate

along the edge of the hole. Aside from these local points of high stress concentration, stress in other regions of plates is well below the yield strength. Along Plane “A”, passing vertically at the mid-distance between the two bolt lines, the maximum stress hardly reaches 145 MPa (21 ksi).

With regards to the bolts, the maximum stress of 331 MPa (48 ksi) (shown in red) is recorded locally at the top and bottom of the shank at its interface with the bolt head. Away from these local points, across the plane passing through the mid-height of the bolts, the stress has an average magnitude of 144 MPa (20.9 ksi), which can be simply verified by dividing the initial pretension force by bolt area resulting in an average tensile stress of 147 MPa (21.4 ksi). Furthermore, an average bearing stress (contact pressure) of 166 MPa (24.1 ksi) is obtained at the locations of contact between the bolts heads and the mating surfaces of the plates.

In the second load step, the joint is subjected to a uniformly distributed and incrementally increasing (from $k = 0$ to 0.85) hoop force, T along the side edges of the plates. The analysis shows that the body remains at rest during the first few sub-steps due to the friction between the contacting surfaces. The friction is a self-adjusting force equal to the applied force which acts in a direction opposite to the direction of the load. This is true until the applied load reaches or exceeds the limiting frictional force (at $T = 290 \frac{kN}{m} (1657 \frac{lb}{in})$) at which time the plates start moving and accelerating in the loading direction. The plates come to rest again once the inner walls of the holes are in full contact with the bolts shanks walls, i.e. there is no gap left between the two.

Once the bolts and the plates are in full contact, any further increase in the load will be directly transferred to the contacting elements resulting in a continuous change of stress-strain state of the entire model.

As per the FE observations, four characteristic loading stages can be recognized clearly under shear loading in a typical bolted flat panel lap joint connection: 1. There is no slip in the joint due to the action of static friction, 2. the joint slips into bearing once the load surpasses the frictional resistance, 3. The assembly deforms in a linear elastic fashion, 4. Plate fracture/yielding and/or complete shearing of the fasteners following the yielding in plates, bolts, or both.

It is noticed that the plates first start yielding along the bolt lines on their contacting faces, that is the bottom face of the upper plate and the top face of the lower plate. At earlier stages of loading ($k = 0.6$ and less) the observed yielding is trivial and limited to the surface and there is not yet that much of through-thickness yielding involved. As the applied load and consequently deformation increases, the yield status is reached in more elements along the bolt lines both over the surface and through the thickness.

As stated above, except superficially along some contact surfaces, no sign of considerable yielding is observed in general until $k = 0.7$. At this time in both plates the yielded regions around the holes progressively grow in size and intersect each other along their center line and reach all the way to the exterior edges (Figure 8). The yielding does not stop at the edges, once reaching the edge it moves its way downward and upward along the thicknesses of the bottom and top plates, respectively. Given in the figure is the yielding contours of the plates, that is the areas of the plates undergoing stress levels greater than the material yield strength, 345 MPa (50 ksi). Maximum stress in the plates first reaches the tensile strength 483 MPa (70 ksi) during this load step. When the stress level at the extreme fibres reaches this ultimate value, the stress-strain response becomes perfectly plastic with no increase in stress as strain increases. Once reaching this state, the exterior fibres are, in a sense, supported by elastic interior fibers. Consequently,

the elastic resistance of the remainder of the section masks the effect of yielding of the surface fibers during their early stage of yielding. Figure 8(b) indicates the yielding progress on the faces of the plates contacting the surface of the gasket. In parallel to the yielding progress across the surface fibres, yielding also advances deep inside the elements along the thickness. Comparing the elastic-plastic transition contours at $k = 0.60$ and 0.70 , it becomes evident that yielding has progressed rapidly both horizontally and vertically through the elements. As can be seen in Figure 8(c), at this stage of loading the yielding state started earlier from the bottom face of the top plate reaches the top surface leading to the formation of yielding over a major part of the cross section in the distance between the adjacent holes.

The calculated results show that at higher levels of loading ($k = 0.80$ and 0.85), the remaining two bolt lines with reserve load capacity; the two and three-hole bolt lines in the bottom and top plates, respectively come into play effectively as key parts of the load-carrying system. This shows the redundancy of the joint in the sense that after suffering damage along the leading-edge bolt lines, the assembly has the ability to redirect loads effectively from damaged areas into areas with reserve capacity.

All in all, the general assessment of the obtained yielding progress pattern reveals that yielding is more concentrated along the bolt lines and the contact surfaces of the holes. Few elements around the edges of the holes on the faces of the plates contacting the gasket reach the yield stress first. As the load increases the region of yielding grows outward from the holes edges toward the bolts center lines and finally reaches the exterior edges of the plates. Simultaneously, the yielding finds its way across the hole circumference and through the height such that at $k = 0.85$ holes are almost fully yielded across their contact surfaces. The estimated

numerical results further indicate that as yielding progresses through the stressed contact areas along bearing surfaces, the plate material flows plastically, increasing the circumference and thickness of the bearing area, and redistributing the contact force exerted by the bolt.

With respect to the bolts, at all stages of loading the calculated stress is lower than the yield strength almost in all parts except locally at some points. Observed yielding in the bolts is of a local nature and occurs only at the points of high stress concentration on the exterior edges of the bolts heads along their contact interfaces with the mating surfaces of the plates (Figure 6(a)). Since the damage is local and is not globally distributed over the entire bolt, the yielding of the bolts does not seem to be a significant concern at least under the range of applied load considered in this study. The FE stress contours of the bolts given in Figure 6(a) clearly show the shearing in the direction of load transfer as a result of bolts bearing against the surfaces of the holes in opposite directions.

As another important design parameter, the magnitude of ovalling of the hole at the final load step, $k = 0.85$ for the most critical hole is shown in Figure 6(b). The bearing between the bolt shank and the hole results in an elongation of the hole. As a result of this effect, the hole with the original diameter of 14.29mm is ovalled to 14.55mm in the loading direction. The deformed shape shows the connecting bolt pulling away from the plate at the right, while bearing toward the plate at the left. According to the obtained FE results, the ovalling effect has resulted in an estimated hole elongation of about 2% along the loading direction, which is not considerable. This is also true about the curling of the sheets which was found to be negligible at the range of service loads considered in this work. However, at higher loads the effect could be significant.

Usually, it is not until considerable yielding has taken place at the contact between the bolt and the hole that any noticeable ovaling effect is apparent.

The deformed shape of the joint at failure is indicated in Figure 6(c). It is clear from the figure that the failure is characterized by large hole elongation. The joint has shown sufficient bearing deformation capacity which has in turn resulted in bearing forces fully distributed on all bolts with no sign of significant reduction in the strength.

The failure mode can be identified as block shear failure coupled with curling (out of plane deformation) of the plates. The failure state is associated with tearing of sheet in net section between the two leading-edge bolts and development of deformations in the shear plane. The failure path is also shown in the figure, on which the combination of tensile rupture and shear yielding is evident.

The obtained FE results suggest that after yielding of the block around its perimeter, the rate of increase in tensile strain in the net section between the two bolt holes is much faster than that of shear straining so that finally the block fails by tensile rupture and shear yielding, suggesting that in such systems the tensile strains are more critical than the shear strains.

From the figure, one can also identify shear-out deformations. However, it should be noted that according to the obtained results, these deformations were over-run by the tensile rupture and shear yielding mechanism. Analyzing the FE results reveals that the start of tensile yielding in the net section between the two holes has resulted in the change-over in the failure mode. The derived failure sequence is thus as follows: 1. Shear strain hardening along the shear-out paths, 2. Rupture of the tensile net section, 3. Yielding in the shear plane around the block's perimeter.

In general, the results show that large deformations could happen before reaching the maximum load capacity such that the initial pretension force present in the bolts is completely released by the time of joint failure due to large shear deformations and plate yielding. As a result, one can suggest a limited deformation criterion (rather than merely maximum load criterion without limited deformation) to be used as the basis for the design of these joints especially when the design of a leak tight seal is of concern. The study recommends setting a design limit on the elongation of the hole in serviceability limit state (SLS), exact magnitude of which remains to be identified in the future and through further research. This will also remove the need for additional checks/equations at SLS. Although the study confirms the adequacy of AWWA in the safe design of this type of structures at a wide range of service loads, it does not change the fact that excessive deformations could unfavourably affect the performance of the joint in both serviceability and ultimate limit states particularly when dealing with liquid contents and where cyclic loadings such as earthquake is present.

Limitation

It is important to note that the conclusions made in this study are based on, and restricted to results from analyses conducted on a limited number of case studies. As a result, studying a greater number of tank models with varying capacity, liquid depth, and aspect ratio as well as investigating the variables beyond the scope of this work is necessary to assess the generalisability of these findings and to provide a more accurate estimation of the behavior of this type of structures. Furthermore, the observed response is only limited to lap joints with the maximum of four bolt rows and 5d spacing. Complementary research needs to be carried out in

order to further verify the findings for configurations which is outside of the scope of this study. In addition, the sufficiency of the design procedure adopted in this study was only verified for three case studies and thus its validity for a wider spectrum of conditions is still under question.

It is also to be emphasized that the observations here apply only to the response under a static loading condition. To assess the effect of earthquake on the performance of bolted lap joints in liquid-filled steel tanks, further research needs to be conducted.

Summary and conclusions

Supplementing the previous literature on the subject, the main purpose of this research is to investigate the performance of thin-walled steel bolted lap connections at different limit states as well as to assess the adequacy of current design practice in bolted steel water tanks through a rigorous numerical analysis. The study was conducted in two phases: shell analysis of the entire tank and solid analysis of the individual joint. Ultimate behaviors such as failure mode, ultimate strength, and the occurrence of ovaling and curling were also addressed.

In this paper, a robust FE model is developed capable of capturing nonlinearity effects important in this context such as geometry, material, and boundary condition (contact, friction/slip) as well as pre-tension condition in bolts and introduced the appropriate procedures of FE analysis including element type, analysis technique, and material constitutive model. In particular, The FE model was found to be in a good agreement with laboratory-based experimental data over the entire force-displacement path. Using the proposed FE model, the deformed shape, stress/strain distribution, and yield/failure pattern in bolted joints were examined in detail at specified load levels.

The practical range of maximum average hoop stress in bolted steel liquid tanks under service loading covering a wide range of tanks' aspect ratios in current practice was determined numerically. Under this loading range, the magnitude of ovaling in holes and curling in plates was measured as trivial.

The parametric study on a number of lap joints with single and multiple row bolt arrangements (varying from 1 to 4 rows) revealed that the size of the gap at the free edge of the plate could be controlled effectively by the bolt pattern chosen, implying a significant reduction in gap size in a double-row as compared to a single-row connection. However, increasing the number of rows above two had no considerable influence. The effect of bolt spacing on the deformational behavior of the joint was also studied and was found to have little effect for the range considered in this research (2d to 5d).

The threshold load corresponding to the development of considerable inelastic deformation in the plates was determined as $k = 0.7$. An acceptable level of redundancy was observed in the joint behavior. Yielding was found to be more concentrated along the bolt lines and the contact surfaces of the holes. With respect to the bolts, yielding pattern was of a local nature having no significance.

The AWWA design procedure proved satisfactory in terms of the safe design of this type of structures at a wide range of service loads. However, the obtained results also confirmed the formation of large deflections in the joint before reaching its maximum capacity, suggesting the need for introducing a limited deformation criterion to be used as the basis for the leak tight design of these joints.

Acknowledgements

This research was partially supported by Landmark Structures. Insight and expertise provided by Mr. Pawski, P.E. from Landmark Structures who greatly assisted the research is highly acknowledged. Financial support received by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Discovery grant program to the second author is also gratefully acknowledged.

References

- AASHTO, LRFD. 2002. Standard specifications for highway bridges. Officials, 17th Edition, American Association of State Highway and Transportation Washington, DC.
- AISC Committee. 2005. Specification for structural steel buildings (ANSI/AISC 360-05). American Institute of Steel Construction, Chicago-Illinois.
- American Iron and Steel Institute (AISI). Committee on specifications, Mexico. Camara nacional de la industria del hierro y del acero, & Canadian standards association. Technical committee on cold formed steel structural members. 2016. North American specification for the design of cold-formed steel structural members. American Iron and Steel Institute.
- American Iron and Steel Institute (AISI) S100. 2007. Supplement no. 2 to the North American specification for the design of cold-formed steel structural members, 2007 edition. AISI S100.
- ANSYS software (Version 18). Penn.: ANSYS Inc., 2017.

- Ardizoglou, Y. 1994. Tests on rubber, Master's Thesis, University of Texas at Austin, 84 pp.
- A.W.W.A. Standard. 2009. D103-09. Factory-coated bolted steel tanks for water storage.
- Bickford, J. H. 2008. Introduction to the design and behavior of bolted joints. In: Non-Gasketed joints. CRC Press, Taylor & Francis Group.
- Doerich, C., and Rotter, J. M. 2008. Behavior of cylindrical steel shells supported on local brackets. *Journal of Structural Engineering*, **134**(8): 1269-1277. doi:10.1061/(ASCE)0733-9445(2008)134:8(1269).
- dos Santos, L. R., de Sousa Cardoso, H., Caldas, R. B., & Grilo, L. F. (2020). Finite element model for bolted shear connectors in concrete-filled steel tubular columns. *Engineering Structures*, 203, 109863.
- European Committee for Standardization (CEN). 2010. Design of steel structures, part 1-8: Design of joints. Eurocode 3.
- Galambos, T. V., Reinhold, T. A., and Ellingwood, B. 1982. Serviceability limit states: connection slip. *Journal of the Structural Division*, **108**(12): 2668-2680.
- Han, L. H., Wang, W. D., & Zhao, X. L. (2008). Behaviour of steel beam to concrete-filled SHS column frames: Finite element model and verifications. *Engineering Structures*, 30(6), 1647-1658.
- Huang, S., and Mannan, M. S. 2013. Technical aspects of storage tank loss prevention. *Process Safety Progress*, **32**(1): 28-36. doi:10.1002/prs.11550.
- Kaeding, P., & Lindemann, T. (2015). Load Carrying Capacity of a Hot Rolled Wing. In Proc. of the 3rd Intl. Conf. on Advances in Mechanical and Robotics Engineering, Zurich, Switzerland, AMRE 2015 (pp. 1-5).
- Kulak, G. L., Fisher, J. W., and Struik, J. H. 2001. Guide to design criteria for bolted and riveted joints second edition, American Institute of Steel Construction.
- Može, P., and Beg, D. 2016. On the bearing resistance of bolted connections. In Eighth International Workshop on Connections in Steel Structures.

- Muscarella, J. V., and Yura, J. A. 1995. An experimental study of elastomeric bridge bearings with design recommendations (No. FHWA/TX-98/1304-3). University of Texas at Austin. Center for Transportation Research.
- Pawar, J. S., Chouksey, M., and Tripathi, K. 2015. Modeling and stress analysis of single lap bolted joint. *Universal Journal of Mechanical Engineering*, **3**(1): 21-26. doi: 10.13189/ujme.2015.030104.
- Pircher, M., and Bridge, R. Q. 2002. A model for the post-buckling of thin-walled silos and tanks under axial load. *Advances in Structural Engineering*, **5**(1): 23-36. doi:10.1260/1369433021502515.
- Raghunathan, M. D., Senthil, R., and Palani, G. S. 2017. On the tensile capacity of single-bolted connections between GFRP angles and gusset plates-testing and modelling. *KSCE Journal of Civil Engineering*, **21**(6): 2259-2272.
- Salmon, C.G., Johnson, J.E., Malhas, F.A. 2009. *Steel Structures Design and Behaviour - Emphasizing Load and Resistance Factor Design*. 5th Edition New Jersey, U.S.A: Pearson Prentice Hall
- Tank Connection, LLC. 2015. Bolted tank design review, light designs vs. premier designs. Parsons, KS, USA: Tank Connection Affiliate Group. Retrieved from Tank Connection Website: <https://www.tankconnection.com/resources/literature/bolted-tank-design-review.pdf>
- Talja, A., and Torkar, M. 2014. Lap shear tests of bolted and screwed ferritic stainless steel connections. *Thin-Walled Structures*, **83**, 157-168.
- Wallace, J. A., Schuster, R. M., and LaBoube, R. A. 2001. Testing of bolted cold-formed steel connections in bearing (with and without washers).

Fig. 1. Different bolt arrangements studied; (a) Design 1, (b) Design 2, (c) Design 3, (d) Design 4

Fig. 2. Tank 1 (Shallow); (a) Final geometry; (b) FE model consisting of shell and bolt elements.

Fig. 3. (a) Typical lap joint geometry, (b) Von Mises stress (whole assembly), (c) Von Mises stress (only bolts), (d) Gasket contact pressure. Units: psi (MPa).

Fig. 4. Von Mises stress contour for Tank1 and deformed shape of joint (single row) (Units N, m).

Fig. 5. (a) Bearing stress-strain data adapted from AASHTO (2002) and Muscarella and Yura (1995), (b) Results of verification study, (c) Mode of failure of Specimen D1-55 (experimental) adapted from Talja and Torkar (2014), (d) Mode of failure of Specimen D1-55 (Finite Element)

Fig. 6. Shearing of bolts, (a) Full stress and yielding contours at $k = 0.70$; Units: psi (MPa), (b) Hole ovaling at final load step ($k = 0.85$); Units: mm., (c) Deformed shape at failure.

Fig. 7. Capacity curve of the connection assembly from FE analysis

Fig. 8. Yielding contour of plates at $k = 0.70$, (a) Assembled, (b) Disassembled (showing contacting faces of plates), (c) Section cut through the bolt line of top plate. Units: psi (MPa).

List of symbols

A_g	gross area of the plate over length S
d	bolt diameter
d_h	hole diameter
D	tank diameter
F_y	shell plate yield strength
F_u	shell plate ultimate tensile strength
g	bolt gage
H	tank height
k	pressure coefficient
K	torque coefficient
P	bolt pretension clamping force
P_{h1}	shell plate tension strength for single/aligned multi-rows

P_{h2}	shell plate tension strength for staggered multi-rows
P_b	bolt bearing strength
P_v	bolt shear strength
q	internal hydrostatic pressure
R	tank radius
ρ	bolt pitch
S	bolts center-to-center spacing
S_e	edge distance
t	gasket thickness
t_p	shell plate thickness
T_h	applied unit hoop tension force
T	hoop tension in the wall over length S
T_g	hoop tension in the wall over length S corresponding to a stress of $0.6F_y$

Draft

Table 1. Tanks dimensions.

Dimension (m)	Tank1 (Shallow)	Tank 2 (Intermediate)	Tank 3 (Tall)
Diameter (D)	22.19	18.10	14.50
Height (H)	9.95	14.00	23.45
Aspect Ratio (H/D)	0.45	0.8	1.6

Draft

Table 2. Stress analysis and design summary of Tank 1.

Ring	Head (m)	Total pressure (kPa)	T_h (N/mm)	P_{h1} (N/bolt)	P_{h2} (N/bolt)	P_b (N/bolt)	P_v (N/bolt)	t_p (mm)/ grade	Total # of bolts/grade
1	0.9	8.8	97	9654	18105	29257	25678	4.5 (Gr.55)	1144 (Gr.5)
2	2.3	22.5	249	9654	18105	29257	25678	4.5 (Gr.55)	1144 (Gr.5)
3	3.7	36.2	401	9654	18105	29257	25678	4.5 (Gr.55)	1144 (Gr.5)
4	5.1	49.9	554	9654	18105	29257	25678	4.5 (Gr.55)	1144 (Gr.5)
5	6.5	63.6	706	11799	22128	35759	25678	5.5 (Gr.55)	1144 (Gr.5)
6	7.9	77.4	858	13792	25865	42556	32098	6.0 (Gr.60)	1144 (Gr.8)
7	9.3	91.1	1010	16090	30176	49648	32098	7.0 (Gr.60)	1768 (Gr.8)
8	9.8	96.1	1065	18389	34487	56741	32098	8.0 (Gr.60)	520 (Gr.8)

Draft

Fig. 1. Different bolt arrangements studied; (a) Design 1, (b) Design 2, (c) Design 3, (d) Design 4

Fig. 2. Tank 1 (Shallow); (a) Final geometry; (b) FE model consisting of shell and bolt elements.

Fig. 3. (a) Typical lap joint geometry, (b) Von Mises stress (whole assembly), (c) Von Mises stress (only bolts), (d) Gasket contact pressure. Units: psi (MPa).

Fig. 4. Von Mises stress contour for Tank1 and deformed shape of joint (single row) (Units N, m).

Draft

(a)

(b)

(c)

(d)

Fig. 5. (a) Bearing stress-strain data adapted from AASHTO (2002) and Muscarella and Yura (1995), (b) Results of verification study, (c) Mode of failure of Specimen D1-55 (experimental) adapted from Talja and Torkar (2014), (d) Mode of failure of Specimen D1-55 (Finite Element)

Fig. 6. Shearing of bolts, (a) Full stress and yielding contours at $k = 0.70$; Units: psi (MPa), (b) Hole ovaling at final load step ($k = 0.85$); Units: mm., (c) Deformed shape at failure.

Fig. 7. Capacity curve of the connection assembly from FE analysis

Fig. 8. Yielding contour of plates at $k = 0.70$, (a) Assembled, (b) Disassembled (showing contacting faces of plates), (c) Section cut through the bolt line of top plate. Units: psi (MPa).