APPLICATION OF THE HOT SPOT STRESS METHOD TO THE FATIGUE ASSESSMENT OF HOLLOW SECTION SHIPLOADER BOOM CONNECTIONS

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Abstract: In the design of shiploader box truss booms, Connell Wagner has often used CHS sections for both chord and web members. To achieve satisfactory static and fatigue performance, the connection between these members has used a relatively complex detail including both annular and fin plate stiffeners. This design was initially developed relatively empirically over 30 years ago using the “Detailing Category” method based on nominal stresses to assess fatigue performance. The connection has performed well on the numerous shiploaders where it has been applied. Since the development of this connection system there have been considerable advances in the understanding and modelling of the static and fatigue performance of hollow section connections.

This paper explores the feasibility of achieving adequate performance for hollow section connections typical of those in a shiploader boom using a detail that does not involve the use of stiffeners. Ongoing investigations for proposed new shiploaders have identified this as potentially providing a significant reduction in fabrication costs particularly with a change from CHS to RHS and SHS sections. This paper applies the Hot Spot Stress (HSS) method to assess and compare the fatigue performance of typical shiploader boom connections comprising CHS members both with and without stiffeners.

Keywords: Fatigue, Hollow section joints, Hot spot stress, Shiploader, Stress concentration, Welded Structure.

Nomenclature:

- \(L, D & T\) Chord length, diameter & wall thickness
- \(l, d & t\) Brace length, diameter & wall thickness
- \(\theta\) Brace to chord inclination
- \(\phi\) Angle measured around intersection from crown toe
- SCF Stress Concentration Factor = Ratio of maximum stress in connection to nominal brace stress assessed simply as Axial load / Area or Moment / Section modulus.
- \(\alpha\) Chord slenderness ratio, \(\alpha = \frac{2L}{D}\)
- \(\beta\) Joint diameter ratio, \(\beta = \frac{d}{D}\)
- \(\gamma\) Chord diameter number, \(\gamma = \frac{D}{2T}\)
- \(\tau\) Thickness ratio, \(\tau = \frac{t}{T}\)

1 Introduction

Space frame trusses fabricated from steel hollow sections are commonly used in both shiploader and crane structures. Typically, the hollow section members are connected by welding the profiled ends of the web or brace members to the face of the chords. The connection region is defined as a joint. Corresponding to the sectional shapes, joints can be classified as circular or rectangular. Attributes such as high strength-to-weight ratio and low wind drag have made hollow sections particularly useful for industrial structures. New cutting, preparation and fabrication techniques are making their use, more feasible and competitive. A typical example of the use of hollow section members is the shiploader shown in Figure 1.
Shiploader booms are subject to high stresses during rare extreme events. The movement of the “shuttle” within the boom gives rise to events with both stress ranges and frequencies of moderate magnitude. Generally such shuttle related loading, affects only localised areas and typical connections are only marginally affected by fatigue considerations. Despite this the fatigue performance of all joints must be adequately investigated.

There are several methods that may be used for fatigue assessment of hollow section joints. AS4100 [1] in Clause 11.3.1 provides a “Detailing category” method that makes use of amplified nominal stresses. This method is only applicable to unreinforced joints. This paper makes use of the more general Hot Spot Stress method. This method of fatigue assessment involves the following steps:

- Calculate, for each design load case, the nominal stress ranges in the braces and chords using a simple beam element model.
- For standard non stiffened joints, use accepted parametric equations to determine the Stress Concentration Factors (SCF) and hence the Hot Spot Stress ranges.
- To confirm the SCF value or for non standard and stiffened joints develop an FE model using proven meshing techniques to directly predict the maximum hot spot stress and thus the SCF as the ratio of this maximum stress to the nominal stress.
- Determine the Miner’s summation of the (Hot Spot) stress range over the design life of the structure and assess whether this is acceptable on the basis of an S-N curve for the CHS material such as that published by the American Welding Society [2]. Note that this is a single S-N curve that is independent of the “detail category”.

2 Basic terminology and parameters reinforced joints

The shiploader boom considered in this paper is made of two circular hollow section trusses together with top and bottom horizontal trusses forming a rectangular box truss. This section introduces the tubular joint arrangements for K joints typical of the boom and defines the joint geometric parameters. The joint geometries and the joint parameter lists will be defined by following conventional formats, e.g. [3].

Referring to Figure 2, the main member that supports the other components is referred to as the chord. The chord is necessarily a through member, i.e. a member that extends with no holes or other intrusions over the length of that structural segment. Other tubes are welded to the surface of the chord without piercing it. These tubes are referred to as braces. The braces may be as large as the chord, but never larger. A brace physically terminates on the chord skin. The “stub” is the extremity of
the brace, sometimes locally reinforced with an increased wall thickness. The “can” is the section of the chord that may be reinforced with an increased wall thickness, or stiffeners.

![Diagram of a tubular joint with labeled parts: Chord, Can, Crown, Saddle, Brace.]

**Figure 2.** Definition of common terms for non-stiffened connections

The brace is welded onto the chord surface without piercing the surface of the chord. Depending on the joint angle, the welding path could be a circle or an ellipse. The two extreme positions on the welding path have special names. The “crown” is the intersection of the welding path with the plane of the brace and chord (the plane of Figure 2); and the “saddle” is the intersection of the welding path with the plane that is normal to the brace-chord plane and contains the brace axis. The angle between the brace and chord (θ) of K joint model is based on 45 degree which is typical of normal practice.

Reinforced joints are commonly used in tubular structure joints. Use of steel rings, diaphragms, gussets and doubler plates may internally or externally stiffen joints. This technique is often used to increase the strength of the main chord region of the joint [4]. In most cases, the introduction of the reinforcement leads to relatively complex geometries and invalidates the use of simple parametric Stress Concentration Factor (SCF) equations as described later. An example of a complex reinforced joint with gusset slotted through the truss chord as often used in shiploader booms is shown in Figure 3.

![Diagram of a typical stiffened joint with labeled parts: Chord, Can, Brace, Gusset, Weld.]

**Figure 4.** A typical stiffened joint

### 3 Hot Spot Stress ranges and stress concentration factor

The maximum hot spot stress range is considered to control the complete fatigue life of a tubular welded joint. It is the maximum stress at the weld toe calculated either by means of a linear extrapolation to the weld toe of the geometric stress or directly from the FE model provided the mesh is of adequate fineness and form. Hot spot stress ranges may also be evaluated for potentially critical
joint locations by applying Stress Concentration Factors (SCF) that are calculated using parametric
formulæ [5]. The hot-spot stress is the peak stress, and it can be expressed as follow:

\[ \sigma_{HSS} = SCF \sigma_{Nominal} \]  (1)

From Equation 1, \( \sigma_{Nominal} \) for the chord and brace members is simply either N/A or M/Z where the axial load \( N \) and the moment \( M \) are determined from a beam element analysis of the truss. Various researchers have proposed equations for the SCF’s of a tubular K-joint subjected to the primary load cases of axial load, in plane bending and out of plane bending. Typical equations can be found in International Institute of Welding [6, 7], Ethymiou & Durkin [8], Smedley & Fisher [9], Herion et al. [10], Morgan & Lee [11] and Van Wingerde et al. [12]. Reasonable agreement has been found between different sets as reported by Nazari et al [13, 14, 15]. The following set of equations is taken from American Petroleum Institution (API) for K-joints [16].

For axial load: \( SCF = 1 + 0.375(1 + (\frac{\tau}{\beta})^{0.5}(1.8\tau^{0.5}0.7071)) \)  (2)

For in plane bending: \( SCF = 1 + 0.375(1 + (\frac{\tau}{\beta})^{0.5}(1.8\tau^{0.5}0.7071)(\frac{2}{3})) \)  (3)

For out of plane bending: \( SCF = 1 + 0.375(1 + (\frac{\tau}{\beta})^{0.5}(1.8\tau^{0.5}0.7071)(\frac{3}{2})) \)  (4)

In these equations \( \beta, \gamma \) and \( \tau \) are as defined earlier.

4 Finite element analysis

Figure 4 shows a view of a detailed finite-element model used to directly assess the hot spot stress distribution around the joint and thus the maximum hot spot stress. The FE analyses were carried out using the software Strand7 on a PC. In all analyses in this paper, welding is assumed to be polished full penetration butt welds and consequently no factoring of the FE predicted stresses to account for stress concentrations associated with the cross sectional weld geometry or weld defects is applied.

Figure 4. Finite Element Model to calculate hot spot stresses for a K-joint with and without gusset plate

Table 1 and 2 summarise investigations undertaken to confirm that FE predictions for non stiffened joints are similar to those assessed on the basis of the parametric equations (2), (3) and (4). Table 1 summarises results from FE analyses of a series of 81 connections characterised by different values of the non dimensional parameters defining the joint geometry and using modelling techniques similar to those for the model shown in figure 4. Table 2 provides the values determined using equations (2), (3) and (4) for 9 of these models. Generally the corresponding results are within +/-20% of each other while there are large deviations at the extreme end of the parameter ranges.

From the comparison of Table 1 and 2 it is concluded that direct FE prediction of Hot Spot Stresses for non stiffened connections produces acceptable results in comparison to the use of the parametric equations. It is assumed that the FE results for stiffened connections will produce similar acceptable results.
Table 1. SCF for non reinforced K-Joints plain from Finite Element Analysis with axial, in plane bending (IPB) and out plane bending (OPB) loads

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Table 2. SCF for non reinforced K-Joints plain from Parametric Equations with axial, in plane bending (IPB) and out plane bending (OPB) loads

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5 A case study for using gusset plate in K-joint

As a case study, the K-joint connection of figure 4 typical of a shiploader connection has been modelled with and without a gusset plate. Member sizes for the case study are as following:
- Chord size 305x8 CHS with \( A = 7464 \text{ mm}^2 \), \( Z_X = Z_Y = 540000 \text{ mm}^3 \)
- Brace size 203x6 CHS with \( A = 3713 \text{ mm}^2 \), \( Z_X = Z_Y = 177000 \text{ mm}^3 \)

The local stress distribution around the K-joint is obtained using detailed finite-element analysis using separate reference load cases as:
- \( N = 1 \text{ kN} \) applied in tension to one brace and compression to the other brace.
- \( M_y = 1 \text{ kNm} \) applied as out of plane bending in reverse directions to each brace.
- \( M_z = 1 \text{ kNm} \) applied as in plane bending in reverse directions to each brace.

In assessing the nominal stress for the gusseted connection, no modification has been made for the presence of the gusset. Based on the peak Von Mises stresses around the joint in the FE model for the \( N, M_y \) and \( M_z \) taken separately, the stress concentration factors are as shown in Table 3.
## Table 3. Stress Concentration Factor for K-joint with and without gusset plate

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## 6 Conclusions and recommendations

A comparison of the maximum hot spot stress for a typical shiploader boom connection with and without stiffener gusset has been undertaken. It has been established that the gusset stiffener as frequently used by Connell Wagner provides a significant reduction in hot spot stresses for both axial loading and in plane bending. This does not imply that a connection without any stiffening will not provide adequate fatigue strength. It does imply that rigorous fatigue assessment will need to be undertaken to confirm that the simpler non stiffened connection types will have adequate fatigue strength in the context of the stress range history assessed over the design life of a particular shiploader.

## References