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A design methodology for side wall failure of RHS truss X-joints accounting for compressive chord pre-load

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ABSTRACT

This paper presents a design methodology for equal-width RHS X-joints failing by side wall buckling, with a particular focus on the effect of a compressive chord pre-load. A slenderness parameter is thereby defined based on the elastic local buckling stress of the side wall, idealized as an infinitely long plate under a patch loading transferred from the brace member in combination with a uniform chord pre-load. A Rayleigh-Ritz approximation is used to obtain a closed form solution. The proposed design equation is verified against finite element results over a wide range of wall slenderness values and is demonstrated to yield excellent predictions. Finally, a reliability analysis is performed using the first order reliability method (FORM) within the framework of both the Eurocode and the AISC Specification to ensure the proposed equation possesses the required level of safety. The proposed equation strongly outperforms the current CIDECT design rule for side wall buckling and also further extends the range of applicability to a wall slenderness ratio of up to 50.

1. Introduction

Structural hollow sections with a rectangular, square or circular cross-section are widely used in engineering structures because of their favourable properties, such as a high structural efficiency in compression and bending, a high strength and stiffness in torsion, an aesthetic appeal, a reduced exposed area and a reduced drag coefficient in fluid flow [1]. Rectangular hollow sections (RHS) are often favoured over circular sections because of the reduced complexity of manufacturing the connections. RHS have important applications in truss structures which are often found in large roof spans, pedestrian bridges, walkways and offshore structures. In the design of these trusses the joints require particular attention as they are susceptible to a number of particular failure modes. Research on welded hollow section joints has been carried out for many decades and CIDECT (Comité International pour le Développement et l'Etude de la Construction Tubulaire) has been very instrumental in this. The design rules for hollow section joints issued (and regularly upgraded) by CIDECT have been adopted by all major design standards around the world. The most recent version of the design rules can be found in [2].

This paper focuses on right angle X-joints between equal-width RHS truss members subject to brace compression and a compressive chord pre-load. It is noted that this paper follows the established CIDECT nomenclature, where h_0 and h_1 are the chord height and the brace height, respectively, b_0 and b_1 represent the chord width and the brace width, respectively, and t_0 and t_1 refer to the thicknesses of the chord wall and the brace wall, respectively (Fig. 1).

For these types of joints, side wall failure of the chord member is critical, either by buckling or by localized plastification under the brace (bearing failure). In the current CIDECT design rules, this is essentially accounted for by isolating a vertical strip in the chord side wall and designing it as a column [3]. A chord load function Q_f is then applied to account for the effect of a chord pre-load. While defendable because of its simplicity, this approach obviously ignores the two-dimensional character of the side wall which acts as a plate under bi-directional stresses.

It is common in experimental work to determine the capacity of an X-joint as the minimum of either the peak load or the load corresponding to the $0.03b_0$ deformation limit [4] after carrying out a test on an isolated connection. However, recently a compelling case has been made to limit the joint capacity to the load at which side wall buckling first occurs [5,6]. This rationale is based on the observation that, in the design of CHS and RHS trusses, completely separate and uncoupled checks are carried out for the stability of the truss members on one hand and the capacity of the truss joints

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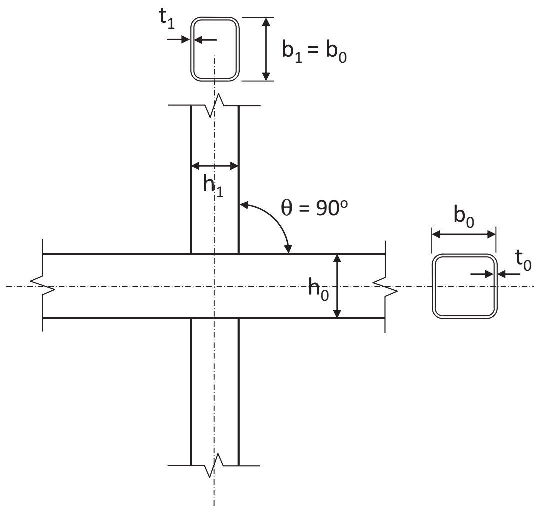

Fig. 1. Connection geometry.

on the other. It is thereby entirely conceivable that a truss member is continuous over a joint (e.g. in the case of a chord member or a through-member in an X-brace) without the truss member being supported out-of-plane at that particular joint. The out-of-plane effective length of that specific truss member would thus include one or more joint locations. If side wall buckling were to take place in one of those joints, it would locally severely reduce the longitudinal compressive capacity of the side walls (theoretically in the order of 60% for the elastic case and idealized boundary conditions [7]) and, by consequence, the out-of-plane buckling capacity of the truss member through the introduction of a weak link. Since the truss member checks are carried out based on the assumption of a 'sound' cross-section displaying no local buckling, a safe (although in most cases somewhat conservative) design approach consists of limiting the joint capacity to the side wall buckling load. This philosophy has been adopted in the here proposed methodology.

Furthermore, it has been known for some time that the current CIDECT design rules for chord side wall failure are quite conservative, and more so as the chord wall slenderness h_0/t_0 increases [8]. The aim of this paper is therefore to present an alternative design equation for chord side wall buckling, equally simple in its application as the current CIDECT rule, but founded on a rational plate buckling model and verified against numerical and experimental data.

In previous research, 31 tests on equal-width X-joints were carried out by Packer [3]. The brace members thereby consisted of either RHS members or simple plates welded to the chord. Both hot-formed and cold-formed RHS tubes were considered and the wall slenderness values (h_0/t_0) in the tests ranged from 15.3 to 42.2. The effects of the brace member angle θ (Fig. 1) and the compressive chord pre-load were investigated and the research resulted in the proposition of a unified equation for both T- and X-joints. However, neither the chord depth (h_0) nor the axial chord preload were explicitly included in the equation, as they were believed to have little effect on the ultimate strength of the joints. At a later stage, Davies and Packer [9] rejected this conclusion and instead postulated that the joint strength depends on the chord slenderness (h_0/t_0) and the non-dimensional bearing length (h_1/h_0).

Wardenier [10,11] conducted tests on RHS T- and X-joints, with the brace members loaded either in tension or compression, but without a compressive load in the chord. Both hot finished and cold finished hollow sections of grades S235 and S275 were included in the programme. It was concluded that for equal-width X-joints, the compressive strength of the joint is limited by either a bearing or a buckling failure mode in the chord side walls. The authors provided a unified equation for both failure modes, in which the buckling stress is derived from the model of a pin-ended strut with an effective length of $(h_0 - 2t_0)$. This approach formed the basis of the current CIDECT design rule.

Through a series of experimental and numerical studies on RHS X-joints carried out by Yu [12], it was found that the effect of an axial chord pre-load on the ultimate capacity of an X-joint decreases with increasing β values, where $\beta = b_1/b_0$. For full-width X-joints (β = 1) the effect was found to be very small. At the same time, however, it was discovered that the influence of the axial pre-load increases with increasing side wall slenderness. The numerical results by Yu [12] formed the basis of the chord stress function Q_f for side wall failure in the CIDECT design guide [2].

Recently, experimental and numerical studies have been carried out by Becque and co-workers [5,6] to develop an alternative design equation for chord side wall failure of equal-width RHS X-joints, founded on a rational plate buckling model. The proposed design equation showed excellent agreement with experimental and numerical results, but did not account for a compressive chord load. In this paper, the research is extended and a model founded on the same principles is developed which also includes the effect of a compressive chord pre-load. Detailed numerical models, first validated against experimental data, were employed to carry out parametric studies and generate numerical data. These data were subsequently used to validate the proposed design model.

2. Analytical model

A rational model was developed in which the chord side wall was idealized as an infinitely long plate simply supported along both longitudinal edges and subject to a transverse localized stress σ_1 (originating from the brace members) and a longitudinal compressive stress σ_2 (Fig. 2). The plate was assumed to be made of a linear elastic, isotropic and homogeneous material with thickness t_0. The loads and boundary conditions were idealized as follows:

1. It was assumed that the vertical load transferred from the brace side wall is uniformly distributed over the brace width h_1. The total vertical load carried by the connection (two side walls) is then given by:

$$P_1 = 2\sigma_1 t_0 h_1 \tag{1}$$

2. The chord preload P_2 is uniformly distributed over the cross-section of the chord member:

$$P_2 = 2\sigma_2 t_0 (h_0 + b_0) \tag{2}$$

3. The plate is hinged along both longitudinal edges. This is a conservative assumption, neglecting any restraint provided by the

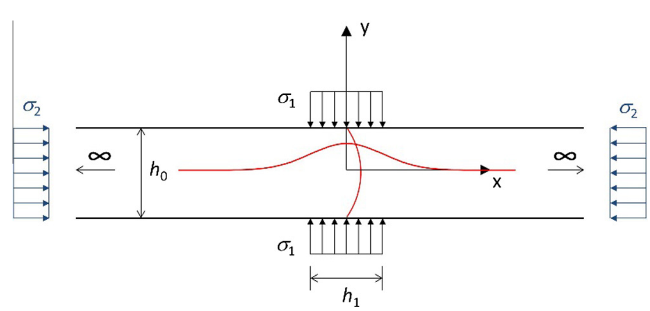

Fig. 2. Idealized model.