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Analytical frame approach for the rotational stiffness prediction of beam-to-column angle connections

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ABSTRACT

The application of recent developed analytical methodologies, based on a plane representation of the T-stub analogy, to evaluate the rotational stiffness of top and seat angle connections with double web angle (TSDW) is dealt with in this paper. Effective width tables for stiffness calculations have been adapted for non-preloaded and preloaded joints. These analytical proposals, developed with the assessment of FE modelling and checked with the results of T-stub tests, have been introduced in a mechanical procedure following a non-aligned Eurocode model. The calculation of the rotational stiffness has been carried out with the aid of program *DAC*. This software implements these T-stub stiffness proposals linked with the effective width definitions relating to the angles and the column flange in bending. The results obtained with the proposed methodology are compared with experimental data on preloaded and non-preloaded joints showing the goodness of the frame approach to deal with angle connections. It also proves how the assembly of simple components to perform macro-components can contribute to simplify the evaluation of the joint response by means of the component method.

1. Introduction

The use of bolted connections in steel construction was gradually replaced by welding, especially since the mid-20th century, when the welding technology was improved with the invention of the processes of flux-cored and plasma arc welding, resulting in greatly increased welding speeds. Nevertheless, bolted connections in steel frameworks have economical and practical advantages, mostly in those aspects referred to construction time savings. One of the most popular bolted typologies in the North American market is the top and seat angle connection with double web angle (TSDW). This semi-rigid joint has got two additional incentives lately arisen to reconsider the use of bolted joints and to promote its introduction in the European market: first of all, bolted angle connections can play an important role in sustainable steel construction, mainly in terms of deconstruction and reuse of the components after recovery [1]; second, as it has been pointed out by Schippers et al. [2], Northridge and Kobe earthquakes, highlighted the vulnerability of welded connections in steel frames and commanded attention to the role that bolted semi-rigid joints played in the post-fracture behaviour of steel structures.

In this paper, bolted TSDW connections are considered with the focus on the evaluation of the rotational stiffness. For the estimation of the joint response, several modeling options are available: analytical, empirical, mechanical and finite element (FE) models. Simplified analytical methodologies for predicting the rotational stiffness of angle connections have been proposed by Azizinamini et al. [3] and by Kishi et al. [4], both considering the behaviour of the connection and not the column components. Although they offer the advantage of the ease of use, the range of application is limited to the joint designs used for their calibration [5]. Considering that the FE solution [6–8] has the lack of the great effort relating to the preparation process and also the computational cost they involve, the mechanical approach can be a compromise solution [5]. In that way, the Eurocode 3 [9] emphasize the need to account the influence of the sources of deformation due to the column, but it takes into account neither bolt preloading nor the web angle contribution. Faella et al. [10] have proposed a procedure that is able to account for all sources of deformation and the influence of bolt preloading by means of a coefficient that includes the modification of the degree of restraint. This approach improves previous methodologies but still with certain degree of dispersion from the average when it was applied to preloaded angle connections. Another proposal of mechanical model, in the field of the Eurocode component approach, was the one developed by Coelho et al. [11] for end plate connections. Although this alternative mechanical model does not represent exactly the actual joint behaviour, it assembles the components in a simple way and can be easily extended to angle connections [5]. On the other hand, a sophisticated mechanical model has been proposed [5,12] for the estimation of the complete moment–rotation curve. This approach includes the prying mechanism implemented in Eurocode 3 (EC3) as well as the deformations from tension bolt elongation and bending of the T-element flange. However, computer implementation is necessary for

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Nomenclature

F	external force
B	bolt force
Q	prying force
I	second moment of area
A_b	bolt area
I_b	bolt second moment of area
L_b	bolt length
L_{wa}	web angle length
K_i^{np}	bolt row stiffness relating to non-preloaded joints
K_i^p	bolt row stiffness relating to preloaded joints
K_{ta}	top angle in bending stiffness coefficient
K_{sab}	seat angle in bearing stiffness coefficient
K_{bwb}	beam web in bearing stiffness coefficient
K_{wab}	web angle in bearing stiffness coefficient
K_{wa}	web angle in bending stiffness coefficient
K_{ta}	top angle in bending stiffness coefficient
K_{cwt}	column web in tension stiffness coefficient
K_{cfb}	column flange in bending stiffness coefficient
K_{cws}	column web in shear stiffness coefficient
K_{cwc}	column web in compression stiffness coefficient
K_{bs}	bolts in shear stiffness coefficient
K_{tab}	top angle in bearing stiffness coefficient
K_{bfb}	beam flange in bearing stiffness coefficient
K_t	total stiffness of the components depending on the bolt row
$K_\phi{}^{np}$	overall rotational stiffness for non-preloaded joints
$K_\phi{}^{p}$	overall rotational stiffness for preloaded joints

Lower cases

t_f	flange thickness
t_h	bolt head thickness
t_n	nut thickness
t_{wh}	washer thickness
b_{eff}	T-stub effective width
d_b	bolt diameter
d_r	reduced bolt diameter
b_{ta}	top angle width
b_{wa}	web angle width
e_{ta1}	end distance from the center of a fastener hole in the top angle
e_{ta2}	edge distance from the center of a fastener hole in the top angle
e_{wa1}	edge distance in the web angle
e_{wa2}	end distance in the web angle
p_{wa}	distance between bolt rows in the web angle
m_{ta}	distance between plastic hinges in the top angle
m_{wa}	distance between plastic hinges in the web angle
w	distance between bolt axis in the top angle leg attached to the column
h_{sa}	distance between the center of compression and the mid-thickness of the angle leg attached to the beam tensile flange
h_1	distance between the center of compression and the first bolt row.
t_{ta}	top angle thickness
t_{wa}	web angle thickness
m_c	distance between plastic hinges in the column flange
t_{cf}	column flange thickness
b_c	column width
p_1	distance between the first and the second bolt row in the column flange
p_2	distance between the second and the third bolt row in the column flange
h_t	the lever arm

the application of this methodology since it applies an incremental T-stub model for the calculation of the non-linear force-displacement laws.

In order to achieve a mechanical proposal that takes into account compatibility requirements, prying forces and bolt elongation, but preserving simplicity, an equivalent frame representing the T-stub has been lately proposed, both in non-preloaded [13] and preloaded [14] cases. These models include an effective width for stiffness calculation based on plate finite element parametric studies.

The application of these analytical frame approaches to obtain the stiffness prediction of angle connections will be developed along this paper. The goodness of the proposal will be proved by comparison with experimental results from the literature, in the cases of preloaded and non-preloaded joints.

2. Frame approach for the stiffness prediction of T-stubs

For the recently proposed frame approaches [13,14], a 2D representation of the T-stub problem was adopted. The idealization suggested by Annex J of Eurocode 3 consists in modelling the top angle as a bolted T-stub whose width is equal to half of its geometrical width. This model has been considered and extended to the web angles. Nevertheless, the frame model representation of the angle behaviour includes the increase of deformability due to the angle leg connected to the beam, which is neglected by the Eurocode approximation.

Taking advantage of the symmetry, only one half of the geometry was modeled. The T-stub flange and the bolt were modeled as the frame assembly resumed in Fig. 1, which shows the geometrical and mechanical parameters of the frame approach for non-preloaded (*a*) and preloaded (*b*) T-stubs.

As it can be observed, the external force in the model is *F/2* and the reactions are the bolt force *B* and the prying force *Q*. On the other hand, *n* is the distance between the bolt axis and the location of the prying forces and *m* is the distance between the plastic hinges in the T-stub. Both parameters were taken as specified by EC3 [9].

Beams 1 and 2 represent the T-stub flange, where *I* is the second moment of area. Beam 3 represents the bolt, where A_b is the bolt area and I_b is the bolt second moment of area. In the case of the preloaded T-stubs (Fig. 1b), based on the assessment of advanced 3D Finite Element models [14], the preloading condition was imposed by constraining the rotational degree of freedom of the central node. In this case, the second moment of area of the bolt is disregarded.

The mechanical parameters are described as follows:

$$I = \frac{b_{eff} t_f^3}{12} \quad (1)$$

$$A_b = \frac{\pi d_r^2}{4} \quad (2)$$

$$I_b = \frac{\pi d_r^4}{64} \quad (3)$$

where b_{eff} is the effective width, t_f indicates the thickness of the T-stub flange and d_r is de reduced bolt diameter defined for commercial series of bolts as $d_r = \sqrt{0.78} d_b$ [10].