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SINGLE THROUGH BOLT CONNECTIONS WITH GAP

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Abstract. *In order to account for the growing economic importance of labour costs in construction projects, designers are seeking innovative connection typologies that simplify the works on site. These innovative connections are often under loads that are not directly classified in the design specifications. This paper presents the analysis of a single through bolt connection with a large gap and no inner nut. A numeric investigation of the bending effects that occur on the bolt is performed, along with comparison studies between the analyzed connection and connections with similar typologies where tests results are available and the differences are pointed out. It is suggested an analytical verification strategy in order to adhere to the current specifications. The authors suggest that laboratorial studies be conducted for its ultimate validation.*

1 INTRODUCTION

The evolution of the structural steel market has seen over the last decades in the composition of the entirety of the total construction costs a decrease in the relative materials cost in relation to the labour costs. While in 1983 the materials costs accounted for 40 percent of the total construction cost, in 1998 it only accounted for approximately 25 percent, whereas the labour in the form of fabrication and erection operations typically accounts for approximately 60 percent of the total investment [1]. This change has to be considered by both the structural designer and the detailer, since decisions taken in the concept phase of the project have a large impact on the financial outcome of the whole construction.

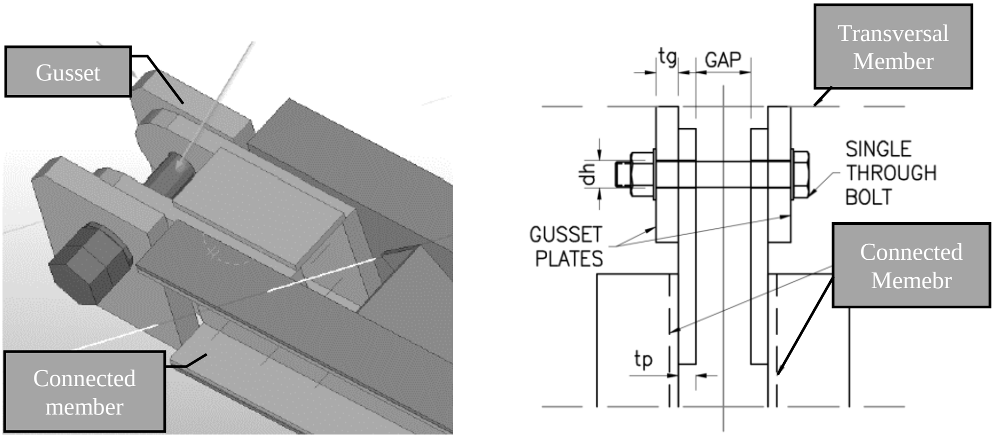
The most direct aspect of the design that has a large impact in both the fabrication and erection costs is the connection design [1]. For an optimized design, it does not suffice that the strength requirements of the connections are met. The simplicity of fabrication and installation are very relevant factors cost-wise and thus are strongly recommended to be improved during the design phase [2].

Therefore, structural designers and the detailers are looking into non-customary typologies of connections that bring benefits for the erection [3]. While this effort is beneficial, designers and detailers must be attentive to the fact that non-customary connections may be subject to structural effects that are not directly classified on the design specifications and therefore must be cautiously analysed.

This paper presents the thorough analysis of a connection typology that simplifies the erection works and is statically determinate but that also has special considerations such as possible excessive bending of the bolt and impossibility of pretensioning that must be considered by the designer when this connection typology is used in order to ensure the safety requirements.

2 CONNECTION TYPOLOGY DESCRIPTION

The connection is composed of two separate pair of plates with a gap between them, as illustrated in Figure 1. On each pair, the external plate is a gusset welded to a transversal member and the internal plates are both welded to the member to be connected. A single bolt closes the connection by parring through all the plates.



(a) (b)

Figure 1: Connection Typology. (a) General View of the Connection. (b) Schematic View of the Typology.

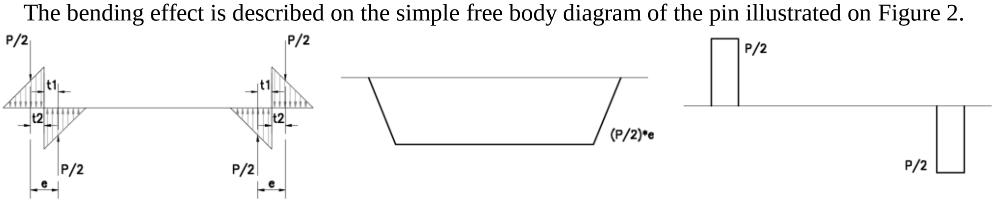
The typology as shown in Figure 1 has the advantage that, in the field, only one single bolt is required to perform the installation of the member and secure the connection. The fabrication of the connection is also rather simple, for it is made of gussets and connection plates that are directly welded to the members.

On the other hand, the designer may be reluctant to use this kind of connection due to the size of the gap, since it is too large to allow the installation of filler plates. If a single plate would be used as filler, its thickness would be too large. In the case of usage of several different plates, their installation would be too cumbersome in the field.

The existence of the gap renders impossible the application of the nominal pretensioning in accordance with the Table J3.1 of the AISC 360-10 specification [4]. The pretension on the bolts as specified in the TableJ3.1 are very high (70% of the minimum tensile strength) and would bend the connection plates along their minor axis since the plates are not touching one another.

Since there is a geometric similarity, the designer may use the strategy to evaluate the connection as two separate lap joints (double lap joints), where the additional tensile component on the bolt due to bending is considered negligible. It is said in the Guide to Design Criteria for Bolted and Riveted Joints [5], published by the AISC, that, although the bending can result in an additional tensile component in the fastener, this tensile component is often of minor importance and does not affect significantly the ultimate strength of the connection. Another strategy possible would be the consideration of the typology as a double shear connection without the inner fillers. Tests results are available for both the aforementioned connection.

The bending effect is described on the simple free body diagram of the pin illustrated on Figure 2.



(a) (b) (c)

Figure 2: Acting loads on the bolt. (a) free body diagram. (b) bending moment. (c) shear actions.

The connection typology discussed in this article differs from the double lap joint because the inner plates are free to displace and rotate towards the inner side, since no nut is present inside the gap area. The bolt can't be considered as snug-tight against the plates, since the condition as per the specification of having the plies in firm contact is never achieved. Also a relevant prying action as shown on [6] inputs a tendency for the inner plates to displace towards the center of the connection, resulting in an even higher bending effect on the bolt. That displacement does not occur in a double lap joint, since the inner nut restrains the inner plate movement, nor in a double shear type with fillers, since the inner fillers are in contact. Those previous arguments bring uncertainty on the verification of the analyzed connection as related to one of those tested types.

In the following sections the bending effect is assessed using a comparative finite element analysis approach.

Since no specific tests results were found during the authors research for the specific connection typology, a conservative analytical approach for the assessment of the connection capacity is presented in item 4.

3 FINITE ELEMENT ANALYSES FOR BENDING EVALUATION

In order to investigate if, for this connection, the tensile component of the bolt caused by its bending may relate to an existent tested case, the two connection were modelled through a finite element package: the connection with gap and a similar double lap joint.

Model #1 is a direct modelling of the connection typology as illustrated in Figure 1. Model #2 has an internal nut on both sides simulating a double lap joint.

The main two aspects investigated are the importance of the inner nut on the following aspects: (1) to restrain the inner plate prying effect; (2) to provide a restriction on the rotation of the pin on the inner part of the connection.

4.1 Models Characteristic

Both models have the following general characteristics, which are described in Table 1. The geometry modelled in described in Table 2.

Table 1: Model Characteristics.

Item	Description
Element type	Brick 3D element formulation without midside nodes.
Mesh characteristics	Mesh average side size of 4mm. Mixture of bricks (8 nodes, 94.3% of volume), Wedges (6 nodes, 3.1% of volume), Pyramids (5 nodes, 1.5% of volume) and Therahedra (4 nodes, 1.1% of volume). Approximate number of elements: 20k
Material modelling	Isotropic materials with non-linear von-mises isotropic formulation and bilinear strain-stress curve to consider plastic behaviour. The values listed in **Error! Reference source not found.** have been reduced by the factor 0.9 in accordance with the Annex 1 of the AISC specification [4, p. 16.1–474]. Also in accordance with the annex, no strain hardening was considered.
Contact	Surface contact modelling without friction consideration. Contacts on (1) the surface between the two plates, (2) outer surface and bolts head, (3) inner plate's hole and bolt's shaft and (4) outer plate's hole and bolt's shaft.
Poisson's Ratio ν	$\nu = 0.29$ for both the materials of the plates and the pin.
Young's Module E	$E = 180000N/mm^2$ for both the materials of the plates and the pin. Alco accounts for the factor of 0.9 as per Annex 1 of the AISC specification [4, p. 16.1–474] for plastic analyses.

Table 2: Geometric Characteristics.

Variable	Value	Description
a	34.713 mm	Shortest distance from edge of pin hole to edge of member measured parallel to the direction of force.
b	59.713 mm	Shortest distance from edge of pin hole to edge of member measured perpendicular to the direction of force.
d	28.575 mm (1 1/8 in)	Bolt diameter.
d_h	30.575 mm	Hole diameter.
w	150 mm	Plate width.
t_g	25 mm	Plate thickness – Truss side – Outer plate
t_p	19 mm	Plate thickness – Double channel side – Inner plate
GAP	60 mm	Gap between the inner plates.

Table 3: Material Properties.

Material	Specified minimum yield stress F_y	Specified minimum tensile strength F_u
Plates – USI CIVIL 300 [7]	300 MPa	450 MPa
Bolt – A325 – d=1 1/8 in [8]	558.48 MPa (81 ksi)	723.95 MPa (105 ksi)

4.2 Model #1 General View

Figure 3 illustrates the general view of model #1. Noteworthy is, in Figure 3 (a), that the inner part does not have a nut.

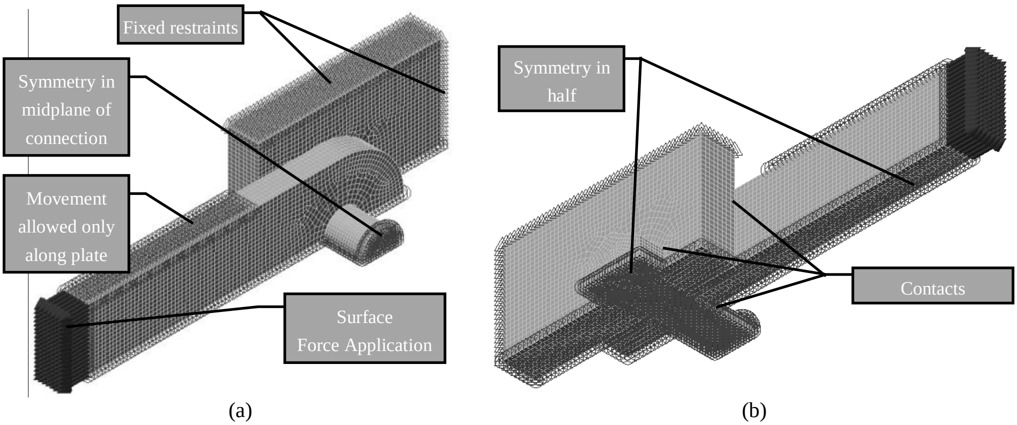
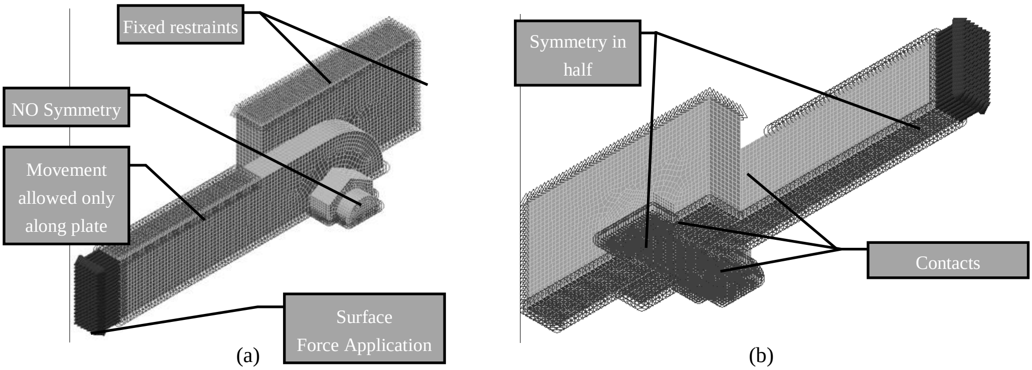


Figure 3: Model #1 FEM general view. (a) View from inner side. (b) View from outer side.

4.3 Model #2 General View

Figure 4 illustrates the general view of model #2. Noteworthy is, in Figure 4 (a), that the inner part does have a nut and that the symmetry is removed from the center of the bolt. This effectively simulates as if the connection was a double lap joint.



(a) (b)

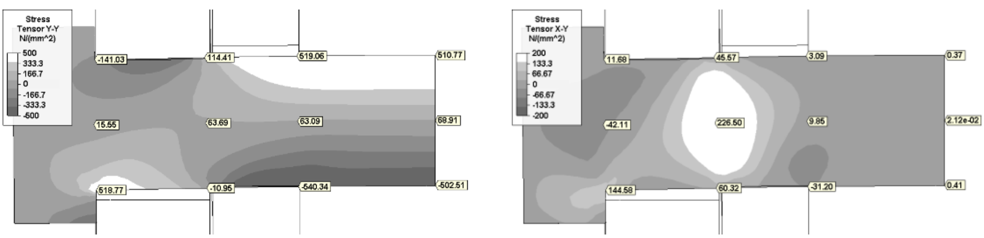
Figure 4: Model #2 FEM general view. (a) View from inner side. (b) View from outer side.

4.4 Models' Result Comparison

To allow comparison of the stress levels that exist in the models with and without the nut, both models #1 and #2 have been arbitrarily loaded with $5.75tf$ equally distributed in the surface in accordance with Figure 3 and Figure 4. Due to the symmetry, this load represents a total of $23tf$ in of axial load in the connection.

Figure 5 exhibits the stress results for Model #1, while Figure 6 presents the stress distributions for Model #2.

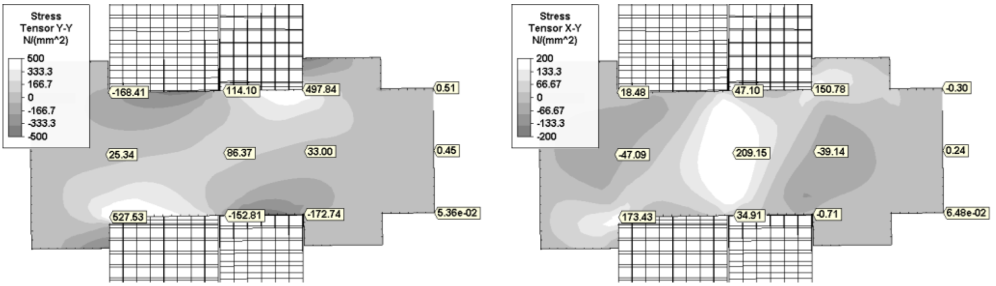
Important notes for Figure 5 and Figure 6: (1) they show the stresses at the symmetric plane of the model, i.e. the midsection of the pin. (2) the plate that appears on the right is the member connection plate (inner plate), whereas the plate that on the left below is the gusset plate (outer plate). (3) The plates in do not have values contours and only have their mesh displayed transparently, i.e. their white colour is not to be taken as values as exhibited in the legends.



(a) (b)

Figure 5: Model #1. (a) Tensors on the axial direction of the bolt. Values from $-500N/mm^2$ [dark gray] to $500N/mm^2$ [white]. (b) Shear Tensors transversal to the bolt (shear). Values from $-200N/mm^2$ [dark gray] to $200N/mm^2$ [white].

The comparison of the finite element analysis results yields interesting insights. The first insight is that the tensile component due to the bending of the bolt as predicted in item 1 does appear. This can be clearly seen in Figure 5 (a) and Figure 6 (a), where the region near the symmetry plate of the bolt presents both tensile and compression stresses that are higher than $500N/mm^2$ (plastification on the bolt occurs for that load).



(a) (b)

Figure 6: Model #2. (a) Tensors on the axial direction of the bolt. Values from $-500N/mm^2$ [dark gray] to $500N/mm^2$ [white]. (b) Tensors transversal to the bolt (shear). Values from $-200N/mm^2$ [dark gray] to $200N/mm^2$ [white].

The tensile component distribution in the Model #1 is different when compared with the tensile stress that is found by the calculations when the connection is modelled with its inner nut (Model #2). Figure 6 (a) displays that the tensile stress due to the bending endured by the bolt is affected by the tension on the bolt that arises from the prying effect that exists when the nut is present. Also, the rotation restrain that the nut provides affect both the bending and shear distribution of Model #2.

The different tensile stresses that are seen in both cases, allows to assert that the test results found in [6] and [9] would need to be reevaluated for the typology presented in this article.

A comparison between the Model #1 and a model of a double shear bolt with fillers completing the gap was not performed, since the authors expected the result for tensile stress to be close. But yet, an evaluation for the prying effect on the critical situation near the bolt rupture would only be able to be assessed by tests results. That effect is of large relevance for flexible inner plates.

4 PROPOSED ANALYTICAL CALCULATION

As stated in item 1, no specific testes results are presented for this typology. It is still necessary to investigate by tests results how the bolt would mechanically behave on the situation near the rupture, where full plasticity of the bolt section and large displacements are presented and the prying action for the inner plates are on its upmost situation, enlarging the eccentricities presented on the bolt.

So, in order to conservatively fully take into account the yet uncertain bolt capacity under bending effects, a “pin-connection” evaluation for the bolt and the plates is below presented.

Considering that the connection is composed of one single through bolt and that the plates are not snug-tight, its plates and the bolt were analysed not as a bolted double lap joint connection under pure shear, but as if the connection was of a “pin-connected” member with the characteristics as described as displayed in Table 2**Error! Reference source not found.**.

The verification of the connection plates in accordance with section D5 of the AISC code [4, pp. 16.1-29] must consider the limit states for tensile rupture, shear rupture, bearing and yielding. They have been calculated for the plate with the lowest thickness and are presented in Table 4. An example of the calculation may be found in [10, pp. D-20].

The materials of the connection are considered as stated in Table 3**Error! Reference source not found.**.

Table 4: Limit states for the pin-connected tension member.
Duplicated since the connection has two symmetric sides.

Strength	AISC [4] Section	Value (N) LRFD	Value (tf) LRFD
Tensile Rupture	D5.1	1385100	141.28
Shear Rupture	D5.1	754118	76.92
Bearing	J7	439769	44.86
Tensile Yielding	D2	1539000	156.98

According to the data exhibited in Table 4, the governing strength of the pin-connection plates is the bearing limit state and therefore the design tensile strength of the connection is $44.86\ tf\ LRFD$.

For the bolt itself verification, considering it as a bended round pin and the eccentricities, moments and shear found on Figure 2, a combination of tension and shear is to be verified.

The equation C-J3-6a in the commentary of the specification where used instead of equation 1J3-2, for in the commentary the equation is in its non-simplified format.

$$F_{nt} = 543M\ Pa\ ;\ F_{nv} = 408\ MPa\ ;\ \Phi = 0.75\ (LRFD) \tag{1}$$

$$e = \frac{t_g}{3} + \frac{t_p}{3} = 14.67mm\ ; Z_{pin} = \frac{d^3}{6} = 3888.73mm^3 \tag{2}$$

$$f_t = \frac{P}{2}\frac{e}{Z_{pin}}\ \ ;\ \ f_v = \frac{P/2}{A_b} \tag{3}$$

$$\left(\frac{f_t}{\Phi F_{nt}}\right)^2 + \left(\frac{f_v}{\Phi F_{nv}}\right)^2 = 1 \tag{4 – AISC Spec. C-J3-5a}$$

$$P_{max} = 2\sqrt{\frac{1}{\left(\frac{e}{Z_{pin}\Phi F_{nt}}\right)^2 + \left(\frac{1}{A_b \Phi F_{nv}}\right)^2}} = 189150N = 19.29tf \tag{5}$$

Where F_{nt} is the nominal tensile stress as per equation C-J3-2 [4] (threads excluded from shear plane), F_{nv} is the nominal shear stress as per equation C-J3-3 [4] (threads excluded from shear plane), A_b is the nominal unthreaded body area of bolt, Φ is the resistance factor, e is the eccentricity existing between the plates, Z_{pin} is the bolt's plastic section modulus and P is acting load on the connection.

Therefore, if the tension component that is caused in the bolt by the bending suffered due to the eccentricity is considered, the bolt's design tensile strength would be, in this example, governed by the bolt's capacity and would be of $19.29tf$.

5 CONCLUSION

The typology presented in this paper has erection advantages and therefore has the potential of bringing economic benefits to the steel construction projects. Even if simple to install in the field, the single thorough bolt connection presents bending effects and the impossibility of pretensioning that may render the designer reluctant on its recommendation.

This paper exhibits that, although differing from double lap joints by not having an opposite nut on the inner part of the plates and not being snug-tightened, the analyzed connection is statically determined and a conservative analytical verification can be performed taking fully into account any bending effects as shown on item 4. Even without the snug-tight condition, it can be locked by installing an additional nut.

The comparative numerical results of item 3 indicate that the bending effects on the proposed typology are different than those present on a similar lap joint typology that had its capacity tested. If compared to a double shear with fillers typology, the effect of the prying action that displaces the inner plate and enlarges bending can only be fully accessed by tests results. Since no specific tests were performed for the connection analyzed, doubts on the bending influence are still present. The authors strongly suggest that strength resistance laboratorial tests of the connection typology be conducted to assess the bending influence and obtain certain prescriptions for this typology of connection. Until then the procedure shown on item 4 is recommended.

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