Corrigendum: Numerical Analysis of Initially Imperfect Pretensioned Bolted Connections (2021 IOP Conf. Ser.: Mater Sci Eng. 1150 012020)

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Page 1:
In the Introduction section 1, the following text appears:

"Threaded connections, in particular bolted joints, are a common engineering feature found in most equipments and structures. In preloaded joints the bolts are first tightened sufficiently to establish closure of the joint with alignment of the mating components producing the required bolt preload and (more importantly) a compressive load at the faying surface. The faying surface is the joints prepared contact face. Preloading is intended to maintain closure of the joint and make it perform as a single continuous member."

This should read:

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Page 612
In the References section, the following reference was omitted, and should read:

"[13] Welch, M. (2018), "Classical analysis of preloaded bolted joint load distributions", International Journal of Structural Integrity, Vol. 9 No. 4, pp. 455-464. https://doi.org/10.1108/IJSI-07-2017-0045"
Numerical Analysis of Initially Imperfect Pretensioned Bolted Connections

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Abstract. Bolted steel end-plate rigid connections are used to transfer straining actions between different parts of steel structures. However, during structural assembly some of these connections are erected with initial imperfections in form of gap between connected parts. This paper investigates numerically initially imperfect end plate connections subjected to major external bending moment and major shearing force. A finite element model (FEM) is developed to represent the behavior of these initially imperfect connections. The presented FEM is verified against experimental testing presented by the authors in previous work. The effect of the gap angle between connected parts on the connection bending strength and moment-curvature relationship is investigated by varying its value from 1.5° to 6°. The results of initially imperfect connections are compared to those of perfect ones and it is concluded that the loss in bending strength of imperfect connections varies from 11.5% to 22% for gap angles from 1.5° to 6° respectively.

1. Introduction

Threaded connections, in particular bolted joints, are a common engineering feature found in most equipments and structures. In preloaded joints the bolts are first tightened sufficiently to establish closure of the joint with alignment of the mating components producing the required bolt preload and (more importantly) a compressive load at the faying surface. The faying surface is the joint's prepared contact face. Preloading is intended to maintain closure of the joint and make it perform as a single continuous member.

It has been observed that in many cases the end plates cannot come to full contact although bolts are fully tightened to their required pretension value, this imperfection can either be in joint's tension side or compression side, loaded or unloaded structures (load independent). Fig. (1) shows connections with initial imperfection in existing structures, an illustration of initially imperfect connections is presented in Fig. (2).
Many research projects were carried out in the past few decades to classify the connection types [1 and 2], to develop the mathematical model for connection stiffness [3], and to study the influence of joint flexibility on the behaviour of steel framed structures [4]. However rather less work has been done to evaluate the initial imperfection of the end-plate that is observed after construction and causes a separation of the connection sides at the contact interface on the behaviour of the connections. Based on the finite element analysis, Wheeler [5] studied the influence of the initial imperfection of the end-
plate on the behaviour of the tubular moment end-plate connections. and found that the initial stiffness of the connections tended to decrease by introduction of imperfection in the end-plates.

In 2007, Chen and Du [6] studied the residual deformation of welding and its effect on the capacity and behaviour of the bolted end plate. They performed an experimental work on 21 specimens of which 3 were control ideal specimens while 6 specimens were with V-shaped initial imperfection with various degrees, 6 specimens with W-shaped initial imperfection with various degrees and 6 specimens with C-shaped initial imperfection with various degrees, with a total of 21 specimens as shown in Fig. (3):

![Figure 3. V shape, W shape and C shape imperfection respectively as studied by [6]](image-url)

It was concluded from their work that in case of imperfection, limited to the criterion that depth of imperfection is less than or equal H/300, gives 4.7% to 8.5% reduction in the rotational stiffness in case of V-shape, while in W-shape about 18% to 19% reduction in the rotation stiffness was observed. Duana et al. [7] studied the initial imperfection of bolted end-plate connection where the thickness of end-plate and column flange can’t meet the code provisions based on a field investigation. The authors performed reliability analysis of steel portal frames, then the Monte Carlo simulation technique was used to estimate the failure probability of steel portal frame system. They concluded that:
1. The assumption of fully rigid connections in the reliability analysis is quite unsafe and can lead to underestimating the failure probability.
2. Insufficient thickness of column flange has a significant effect on safety of portal frame for both flush and extended connections.
3. The insufficient thickness of end-plate has slight effect.

2. Research Significance
For end plate with high strength pretensioned bolts, the current codes and design guidelines [8-10] do not include the case of initially imperfect end plate connections, these codes neither set criteria for accepting or rejecting the initial imperfection as shown in Fig. (1-2), nor state a method of assessing the effect of initial imperfection on the ultimate load capacity of the connection. So, in this paper, a FEM model is developed to study initially imperfect connections and a limited parametric study is also presented to quantify the effect of the gap angle on the bending strength.

3. Finite Element Modelling of Connections
In 2020, Abdallah et.al [11] conducted an experimental program on a group of initially imperfect connections to study their moment deflection behaviour of the initially imperfect connections and bending strength and compare them with ideal connection. They tested four specimens fabricated as a plate girder, namely (I240 BUS of web200x10mm and flanges 120x20mm). The specimens consisted of an ideal connection, and three connections with 2°, 4° and 6° initial imperfection gap angle. Each was loaded up to bolt(s) failure, schematic of the test data are shown in Fig. (4-5).

Bolts used were with nominal diameter of 12mm and nominal grade of 8.8 pretensioned type bolts. The tightening stage was performed with a manual torque wrench to provide a pretension load of 37kN. The steel used for all parts of specimens was S355 (360/520 MPa).
Stiffeners were provided at location of supports and at location of load application.

**Figure 5.** Beam cross section and specimens end plate details used in [11]

### 3.1. Finite Element Model Description

Two groups of models were developed to simulate the behavior of the connections using a finite element package, commercially known as ABAQUS v6.12 [12]. The first group of models, verification models, which were built to verify the FEM of the experimental program described by [11] using the load deflection behavior results discussed, while the other group was built for conducting the parametric studies, where multiple degrees of initial imperfection and different bolt diameters were considered for reaching comprehensive conclusions.

### 3.2. Material Properties Definition

For bolt material, the bolt tensile test data were available in [11], and the considered Poisson’s ratio was ($\nu = 0.3$), the actual stress strain curve was obtained from the previously mentioned experimental program. While for steel sections properties, the yield stress of 360 MPa and ultimate stress of 520 MPa with ultimate strain at failure of 16% were considered.
3.3. Assigning Interaction Properties Between Parts

Tie constraint was considered when no slip or separation is allowed whatever the stress state or straining actions are, this was used between beam flanges and web, beams sections and end plates, and stiffeners and stiffened elements. While interactions were assigned to define the inter-surface behaviour, such as the interaction between end plates at the faying surfaces, and interaction between bolts and end plates including end plates outer surfaces and end plates holes circumferal area. Generally in ABAQUS software, the interaction is defined by assigning behaviour in normal direction and in tangential direction, these behaviours were assigned as follows:

i. Normal behaviour: was assigned as hard contact that allows separation after contact; meaning it fully transfers compression stresses but doesn't transfer tensile stresses.

ii. Tangential behaviour: using coefficient of friction of 0.3 with sliding permitted.

3.4. Load Application

In order to precisely simulate the actual loading sequence, where bolts are first tightened before full utilisation of the structure, two steps of loading were defined, the first one is the step in which pretension force was applied on bolts, then the second step is the one in which the external load was gradually applied.

3.5. Element Type

The degrees of freedom are the fundamental variables calculated during the analysis, displacements or rotations are calculated at the nodes of the element. At any other point in the element, the displacements are obtained by interpolating using the nodal displacements. Hence, the higher number of nodes means more computational cost of the analysis.

ABAQUS software package has the capability of mixing different meshes types together in the same model, where low computational cost elements, like the tetrahedral elements, can be used in the model in regions of low interest, while regions of high interest can be modelled with higher computational cost elements.

In this paper the FE modeling of connections was developed using continuum (solid) elements for all parts of the connection. This kind of elements is capable of providing sufficient degrees of freedom to model contact, deformations and plasticity effects.

Because of their capabilities to mesh highly complex geometries with greater ease than C3D8 elements, the C3D6 wedge elements or tetrahedral C3D4 elements (Fig. (6)) were used to model beams, stiffeners, and end plates, while C3D8 elements were used for modeling the bolts.

After some trials, the suitable mesh size for the bolts was found to be 3-4 mm, while for end plates region of contact the mesh size could be increased to be of 18-20 mm in order to reduce computational cost, and size of the mesh could be increased to around 50-60 mm for the remaining beams portions. Assembled model is shown in Fig. (7).
3.6. Results Comparison

3.6.1. Failure Load Values

The comparison between experimental failure load of the specimens tested by Abdallah et. Al [11] and failure loads acquired from FEM are presented in table (1), while model deformed shapes are shown in Fig. (8):

|                | I240 Ideal | I240 2° | I240 4° | I240 6° |
|----------------|------------|---------|---------|---------|
| Experimental Failure Load (kN) Abdallah et. al [11] | 151        | 129     | 126     | 118     |
| Current FEM Failure Load (kN)                      | 160.1      | 138.1   | 136.8   | 134.6   |
| Percentage Difference (%)                          | 6%         | 7.1%    | 8.5%    | 14%     |

Fig. 8. a) FEM of I240 Ideal specimen at failure  
Fig. 8. b) I240 6° specimen at failure

3.6.2. Moment Deflection Curves

The comparison between experimental and FEM moment deflection curves are presented in Fig. (9-12).
3.7. Verification Process Conclusion
The comparison between FEM and experimental results revealed good agreement, which ensures the accuracy and suitability of the developed FEM for performing the numerical study on reliable basis.

4. Numerical Study of Imperfect Connections

4.1. Numerical Study Introduction
To further investigate the behavior of the initially imperfect connections, a group of connections with various parameters were modelled using FEM. The main purpose of this numerical study is to discuss the effect of the connections with initial imperfections gap angle on the behavior of the steel structure in terms of moment deflection relation.

4.2. Numerical Study Outlines
The structure considered was a cantilever beam connected to a column with the connection of interest, where the variables considered were bolt diameter and degree of initial imperfection, a layout of the connections considered is presented in Fig. (13), and the details of the connections are presented in Fig. (14).

![Figure 13. Layout of connections considered in parametric study](image)

![Figure 14. Details of connection considered](image)

Beam used: a built-up section of flanges 200mm in width, 25mm in thickness, while web was 450mm in length and 16mm in thickness. Beam was of length 1100mm while loading was at distance 1000mm from the column external face, the beam was provided with sufficient stiffening below loading point to prevent excessive stresses. Column used was HEM 400 of length 1000mm, that was fixed at the start and at the end. The column was provided with sufficient stiffening at the connection region, right opposite to the beam flanges to prevent excessive stressing.

In order to effectively investigate the imperfect connection, four values of degrees of initial imperfection were considered; 1.5°, 3°, 4.5° and 6°, each with two values of bolts diameters were considered; 20&22mm, bolts were HSB type grade 8.8.

The summary of the parameters is presented in the following table.

| Table 2. Numerical study summary and model nomenclature: |
|----------------------------------------------------------|
| Ideal | 1.5° | 3°  | 4.5° | 6°  |
|-------|------|-----|------|-----|
| M20   | M20-1| M20-1.5 | M20-3 | M20-4.5 | M20-6 |
| M22   | M22-1| M22-1.5 | M22-3 | M22-4.5 | M22-6 |

An illustration of the assemblies and meshed models are presented in Fig. (15-16).
Figure 15. Assembled model

Figure 16. Meshed model

4.3. Numerical Study Results

A sample model state of stress is presented in Fig. (17-18), while a summary of the numerical study results is presented in table (3).

Figure 17. Connection M20-I stress state at maximum load (MPa)
Figure 18. Connection M22-6° stress state at maximum load (MPa)

Table 3. Numerical study results:

|                  | Ideal | 1.5° | 3°  | 4.5° | 6°  |
|------------------|-------|------|-----|------|-----|
| **M20**          |       |      |     |      |     |
| Max. Deflection (mm) | 14.8  | 18.7 | 25.5| 29.6 | 31.1|
| Ult.Moment (kN.m) | 688.4 | 609  | 592.2| 591.2| 536.8|
| % loss in capacity | ___   | 11.53%| 13.97%| 14.12%| 22.02%|
| **M22**          |       |      |     |      |     |
| Max. Deflection (mm) | 16    | 22.5 | 28  | 34.4 | 33.7|
| Ult.Moment (kN.m) | 794.8 | 685.1| 667.1| 650.2| 641.2|
| % loss in capacity | ___   | 13.8%| 16.06%| 18.19%| 19.32%|

To better assess the effect of initial imperfections on connection, moment deflection curves of the imperfect connections as well as their ideal counterparts were plotted on the same graphical representation as shown in Fig. (19-20)
In real-life structures, the occurrence of the imperfect connections is unplanned, one can obtain deflection and moment capacity of an ideal connection but not of an imperfect connection, so for better normalization, the actual deflection of the structure with initially imperfect connection was divided by the corresponding deflection of the ideal connection structure at same load level, then the acting load was divided by the ultimate moment capacity of the connection, and these two ratios ($\frac{M_{\text{Acting}}}{M_{\text{Ultimate of Ideal}}} (%)$ and $\frac{\Delta_{\text{Imperfect}}}{\Delta_{\text{Ultimate of Ideal}}} (%)$) were plotted as shown in Fig. (21-22).
Conclusions

1. A reduction in load capacity of the initially imperfect connection ranging from 11.5% to 22.1% than that of the ideal connection with same bolts was noticed.
2. An increase in maximum deflection of the imperfect connections ranging from 26.35% to 110.6% more than ideal ones were noticed i.e.; more ductile behavior.
3. Maximum deflection increases with increasing the degree of initial imperfection.
4. The beam deflection of the imperfect connections is of larger magnitude compared to ideal counterpart at same moment level with a percentage ranging from 40.6% to 110.1%. i.e.; the stiffness of imperfect connection is less than the ideal ones.

Reference

[1] Reidar Bjorhovde, Andre Colson, and Jacques Brozzetti. "Classification system for beam to column connections" Journal of Structural Engineering, Vol. 116, No. 11, November, 1990. ©ASCE.
[2] Bahaari MR, Sherbourne AN. "Computer modelling of an extended endplate bolted connection". Computers and Structures 1994;52(5):879–93.
[3] Baharri MR, Sherboure AN. "Finite element prediction offend plate bolted connection behavior II: Analytical formulation". Journal of Structural Engineering, ASCE 1997;123(2):165–75.
[4] Masika RJ, Dunai L. "Behaviour of bolted end-plate portal frame joints". Journal of Construction Steel 1995;32(2):207–25.
[5] Wheeler AT, Clarke MJ, Hancock GJ. "FE modelling of four-bolt tubular moment end-plate connections". Journal of Structural Engineering, ASCE 2000;126(7): 816–22.
[6] Shiming Chen, Gang Du (2007). “Inflence of initial imperfection on the behaviour of extended bolted end-plate connections for portal frames” Journal of Constructonal Steel Research 63 (2007) 211–220.
[7] H. J. Duana, J. C. Zhao and Z. S. Song “Effects of Initial Imperfection of Bolted End-plate Connections in the Reliability of Steel Portal Frames” Procedia Engineering 14 (2011) 2164–2171.
[8] Murray, T., M. and Shoemaker, W.L., “Steel Design Guide Series 16, Flush and Extended Multiple-Row Moment End-Plate connections”, AISC, Chicago, IL, 2002.

[9] American Institute of Steel Construction (AISC), Steel Design Guide Series 4 (2003), “Extended End-Plate Moment Connection,”, Chicago, IL.

[10] Eurocode 3: Design of steel structures- Part 1-8: Design of joints”, ISBN 0580 46081 9.

[11] Mostafa Nour Eldin M., Emad Salem, Sherif M. Ibrahim, Abdelrahim K.Dessouki, Experimental Investigation on Initially Imperfect Rigid Connections, International Journal of Advanced Research in Engineering and Technology (IJARET) Volume 11, Issue 12, December 2020, pp.474-483, Article ID: IJARET_11_12_051 DOI: 10.34218/IJARET.11.12.2020.051

[12] ABAQUS Documentation Analysis User's Manual (2006).