PERIODICA POLYTECHNICA SER. MECH. ENG. VOL. 49, NO. 1, PP. 47–58 (2005)

INVESTIGATION OF MINOR AXIS AND 3D BOLTED END-PLATE CONNECTIONS – EXPERIMENTAL AND NUMERICAL ANALYSIS – LOAD TESTS

Katalin VÉRTES and Miklós IVÁNYI

Department of Structural Engineering
Budapest University of Technology and Economics,
H-1111, Bertalan L. u. 2., Budapest, Hungary
E-mail: vertes@vbt.bme.hu
Tel.: +36-1-463-1741, Fax: +36-1-463-1784

Received: March 12, 2005

Abstract

Minor axis and 3D connections are widely used in the practice, still the behaviour and calculation process of these types of joints are not clearly described in the codes. The behaviour of a joint can be determined through numerical, experimental and analytical method. This study introduces numerical and experimental investigations of minor axis and 3D joints and provides proposal for the extension of the component method of the Eurocode 3.

Keywords: minor axis, 3D, joint, component method.

1. Modelling of Steel Structures and Joint Behaviour

The recently widely used computer programme for structural analysis assume the structural joints to be rigid or pinned. However, usually it is possibile to define separate joint elements (partially continuous frame) and prescribe individual properties.

Mostly computational methods are based on the calculation of those nodal displacements, deflections and the derivatives of the deflection, which fulfil the compatibility condition, while the satisfaction of the equilibrium conditions are assured by the constitutive laws. This process is called the displacement method.

The structural Eurocodes (EC3) do not emphasize the adaptation of any of the calculation processes, although the calculation process described in Annex J which discusses the joint behaviour, uses the notion of joint stiffness for the defining of the joint's initial behaviour. This means definitely the displacement method.

2. Description of the Joint Behaviour for Frame Analysis

The traditional methods of steel construction design assume the connection between the structural bars as rigid or pinned. The behaviour of structural joints – according also to tests – exhibit different, so-called semi-rigid connection behaviour.

Joint Classification according to Stiffness

The easiest way to consider the connection in a global analysis is the assumption of an equivalent spiral spring as linking element. From the stiffness point of view ‘rigid’, ‘pinned’ and ‘semi-rigid’ connections are distinguished. In the case of frames with semi-rigid connections always develop M_j moments and F_j relative rotations through the loading.

Joint Classification according to Deformation Capacity

Concerning the joint deformation or rotation capacity, the joints can be classified similar to the cross-sections considering the resistance against local instabilities or more general against brittle failure.

Joint Classification according to Resistance

According to resistance ‘full-strength’ and ‘partial strength’ joints are distinguished accordingly as the joint resistance reaches the resistance of the connected element or not.

3. Selection of the Right Joint Model for the Structural Analysis

EC 3 Annex J recommends and proposes the component method for the calculation of steel frame connections [1]. Annex J discusses primarily the so-called major axis joints, and describes a detailed calculation process for the analysis of a connection where the beam is connected to the strong axis of the column.

The aim of the research project is the analysis of the behaviour of 3D steel connections with the extension of the Eurocode’s component method.

In our research the application of all three methods, namely the experimental method, the numerical method and the analytical method are included.

The experimental and the numerical analyses made possible the full study of the effects of geometrical arrangement and various loading. The investigation of the elastic, elastic-plastic and failure mode was carried out [2].

From practical point of view the development of an analytical method was required, therefore there was necessary to generalise the results and make them suitable for practical application.

4. The Research Program

The experimental program was set up in a way to be able to get as much information as possible about the behaviour of 3D steel connections. *Fig.1* summarizes the test program. Specimen 1 and 2 were necessary for the analysis of major axis joints which is detailed in EC3 Annex J. Specimen 3 was for minor axis joint analysis. Specimen 4 and 5 were set up to analyse both major and minor axis joints together.

The experiments were carried out in two parts:

S (stiffness) program: elastic experimental study:
S1 small axial load on the column, bolts are screwed by hand
S2 large axial load on the column, bolts are screwed by hand
S3 small axial load on the column, bolts are stressed
S4 large axial load on the column, bolts are stressed.

During loading, only elastic deformations developed. Those relations were observed which can influence the joint stiffness. They are the normal force in the column, the prestress of the bolt and the effect of the normal force in the column and the prestress of the bolts together [3]. (Altogether $4 \times 10 = 40$ tests)

R (resistance) program: failure experiments:

During the experiments R1-R5 we intended to get as wide ‘picture’ of the joint behaviour as possible and to get new information on the joint stiffness resistance and deformation capacity. (Altogether 10 tests)

Together with the experiments the connections were modelled by FEM (Ansys 7.0 [Ansys Inc. 2002]) as well. The FE model was built up by nonlinear 8-node BRICK 45 elements in order to be as accurate as possible. The whole specimen was modelled through the numerical analyses. Different material models were defined for the steel material and for the bolts.

The supports of the models were the following: at the column base the whole section was fix supported. The top of the column was supported against displacements in major axis and perpendicular directions (the vertical displacements and the rotations around the axes were allowed). The lateral torsional buckling of the beams was restrained by side supports. The beams were loaded at the end cross-section in the middle of the upper flange. The load intensity was increased continuously.

The key of the numerical calculations was the appropriate modelling of the bolted connection. Thus contact surfaces were defined between the shank and the bolthole the endplate/column flange or web and the bolthead and between the endplate and the column flange or web. *Fig.2–11* show the obtained force-displacement curves.

Fig. 12 shows the ultimate deformed shape and the distribution of the Mises stresses obtained from the FE analyses.

It is clearly visible, that the ultimate deformed shapes correspond with each other and moreover from *Figs. 2–11* it is also readable that the global behaviour obtained by the test and the numerical simulation fits well.

The results of the numerical calculations correspond with the tendency of the experimental ones. The results of models R1 and R2 are in accordance with the

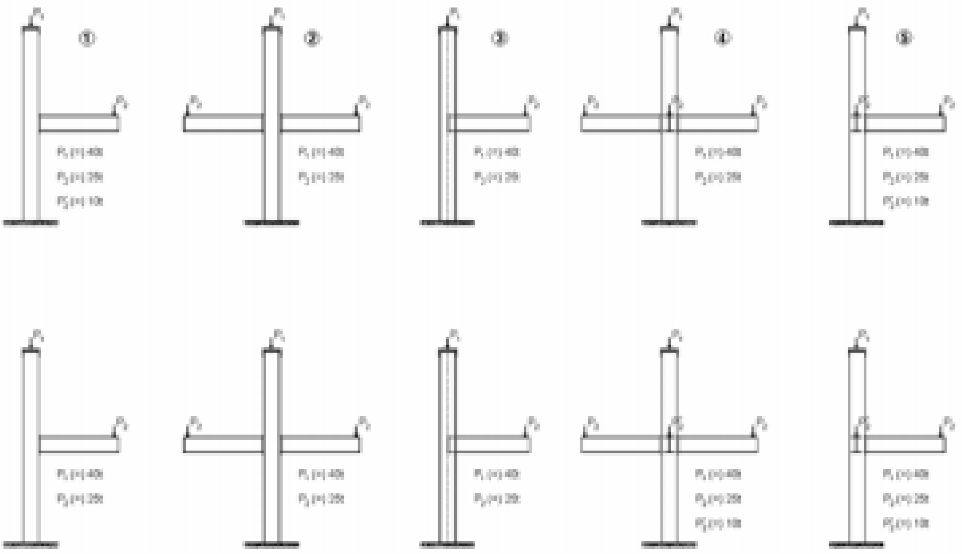

Fig. 1. Test program

results of Eurocode 3's component method. The obtained stress distributions

of models R1 and R2 reflect the defined components of Eurocode 3 and in the case of models R3-R5 the component of the minor axis bending – column web in tension and compression – appears as well.

The ultimate resistance results obtained by the tests could not be obtained exactly by the FE models. The reason of it is that the model was not able to follow such large deformations [7].

5. Design of Steel Stuctural Joints through the Spatial Component Method

The design of steel structural joints is carried out with the internationally accepted and in Eurocode adopted component method [4]. The component method discusses the determination of the joint stiffness and resistance. The Eurocode 3 provides a detailed description of the major axis joints but only general advices are available in connection with the calculation of minor axis and 3D joints (joints with both minor and major axis beams). That is why the research took on the analysis of these problems.

5.1. Determination of the Stiffness of Minor Axis and 3D Joints through Spatial Component Method

When evolving the spatial component method the following points have to be taken into account:

(a) the principles of the EC3's component method
(b) for the generalization the methods and recommendations of EC3 have to be applied.

In accordance with to the above statements the basics of our recommendation the MSz ENV 1993-1-5: 1999

> Eurocode 3: Design of Steel Structures
> Part 1.5 General rules. Supplementary rules for planar plated structures without transverse loading (March, 1997) [Ref.: EC3 (1.5)]

and
MSz ENV 1993-1-7: 1999

> Eurocode 3: Design of Steel Structures
> Part 1.7 General rules. Supplementary rules for planar plated structures with transverse loading (March, 1997) [Ref.: EC3 (1.7)]

If the beam-to-column connection is so-called minor axis joint, all components but the component of the column web (which is called the basic element of the minor axis joint) can be obtained according to EC3 Annex J. The column web is locally bent by the endplate of the beam. This bending can be divided into tension and compression zones. (*Fig.* *14*).

The analysis of the obtained plate component can be done according to EC3 (1-7) as a perpendicularly loaded plate. So the minor axis joint stiffness can be determined, since for k_i stiffness factors $F/(E\delta)$ is needed. The web plate of the column – as the basic component of the minor axis joint – can be analysed and the other components can be derived according to EC3 Annex J.

The components of a 3D joint can be obtained from EC3 annex J except the column web component. This plate is loaded by the major axis beams beside the minor axis beam.

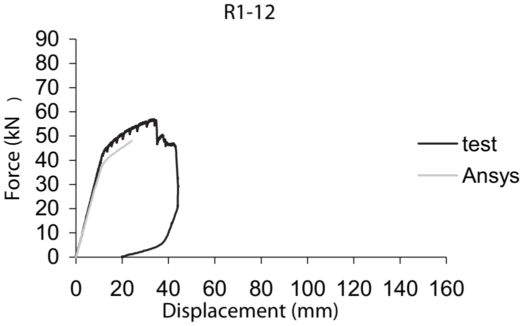

Fig. 2. Load-displacement curve

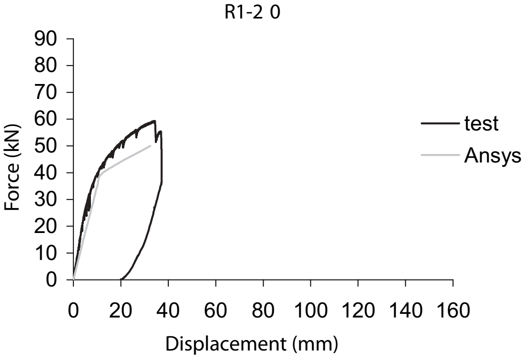

Fig. 3. Load-displacement curve

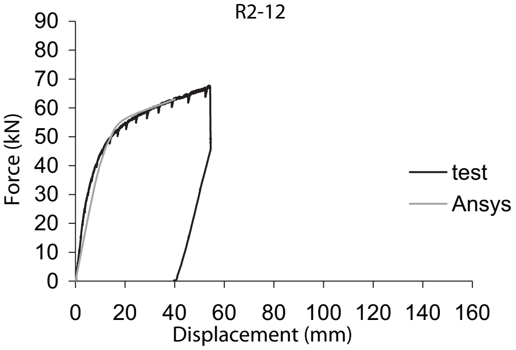

Fig. 4. Load-displacement curve

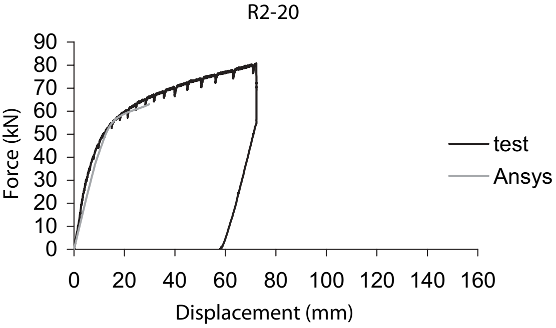

Fig. 5. Load-displacement curve

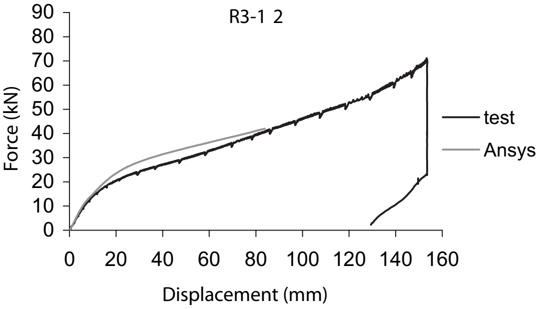

Fig. 6. Load-displacement curve

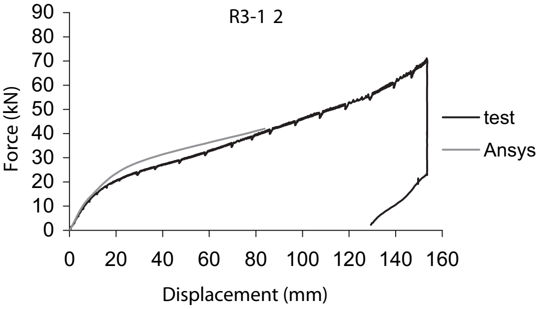

Fig. 7. Load-displacement curve

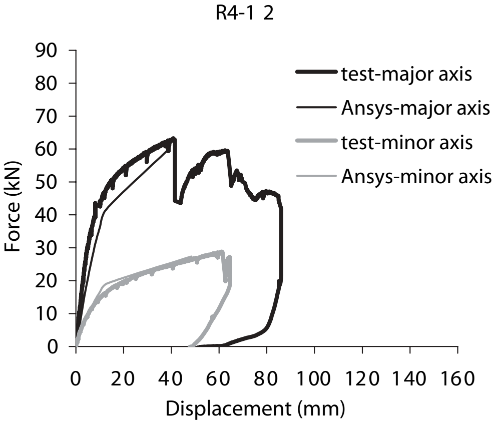

Fig. 8. Load-displacement curve

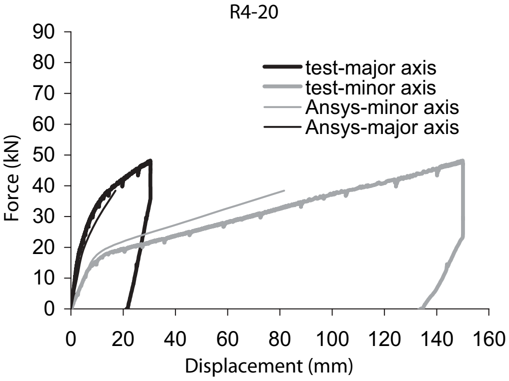

Fig. 9. Load-displacement curve

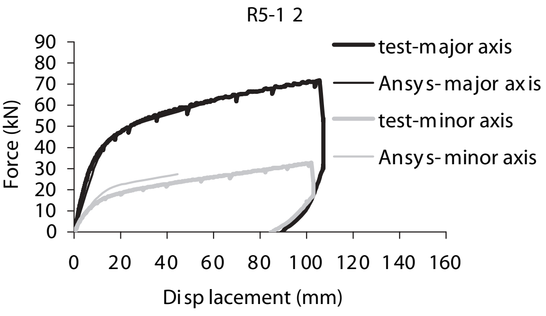

Fig. 10. Load-displacement curve

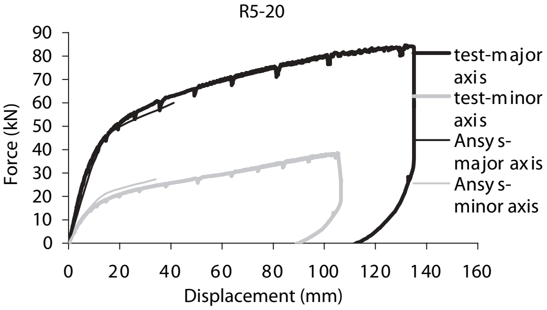

Fig. 11. Load-displacement curve

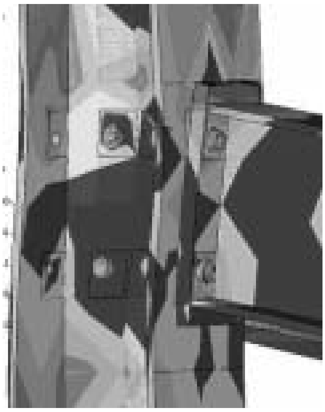

Fig. 12. Ultimate deformed shape and the distribution of the Mises stesses (R5-20) [3]

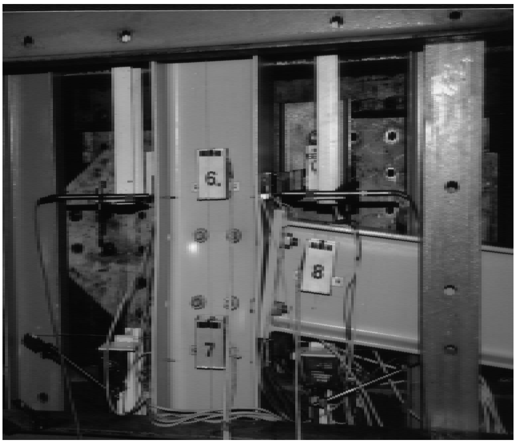

Fig. 13. Ultimate deformed shape (R5-20) [3]

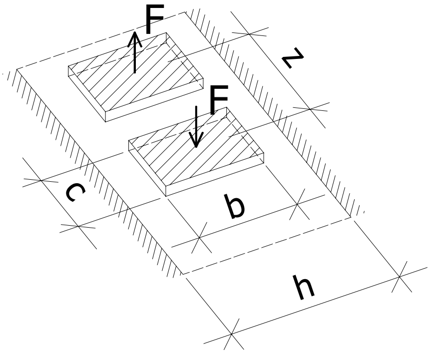

Fig. 14. Loads of the column web

The plate of *Fig.* 14 is loaded by additional effects such as bending and shear and the local loads of the major axis beams. In the case of the basic plate component, which is transversally loaded by the minor axis beam the effect of the 'shear-lag' and the major axis beam can be taken into account because of the general moment and shear loads. EC3 (1-5) Chapter 4.4 introduces the determination of the web's resistance for in-plane loading.

Of course as an effect of the in-plane and transverse loads the deformations perpendicular to the plate increase, which develop perpendicular to the column web from the effect of the minor axis beam. This increase can be calculated with the common formula which takes into account the second order effects. Thus, in the case of $F/(E\delta)$ belonging to k_i:

$$\bar{\delta} = \delta \cdot \frac{}{1} 1 - \frac{F_s}{F_{Rd}}$$

where

δ	the deformation of the column web under the effect of the minor axis beam
F_sg	force from the major axis beam
F_{Rd}	in-plane force perpendicular to the web's longitudinal axis

5.2. Determination of the Resistance of Minor Axis and 3D Joints Using the Component Method

The resistance of the minor axis joint can be determined according to EC3 Annex J. The design resistance [5]:

$$M_{j \cdot Rd} = z \cdot F_{Rd}$$

where

z	the lever arm of the joint
F_{Rd}	the resistance of the weakest component at the minor axis joint

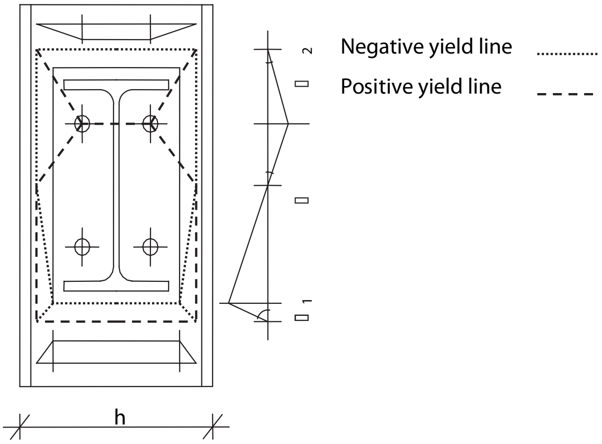

Fig. 15. Global yielding mechanism

The resistance of the different components can be: column web under bending and punching, bolts under tension, end-plate under bending, beam web under tension and beam flange under compression.

The above written components can be determined according to EC3 Annex J except the column web under bending. The yielding mechanisms of the column web can be put into two classes.

Local mechanism: the yield lines are localized around the tension or compression zone. This mechanism is analysed by $F_{Rd.\mathrm{local}}$.

Global mechanism: the yield lines extend to both the tension and compression zones. This mechanism is analysed by $F_{\mathrm{global}.Rd.}$. The analysed form of the global mechanism is shown in *Fig.* 15.

However in case of a 3D joint if $F \neq 0$ there was interaction between $F_{v.\mathrm{pl}}$ minor axis force and $V_{F.\mathrm{pl}}$ shear resistance. Theoretically this interaction can be taken into account by the Ilyushin yield criteria.

In the case of the 3D connection develops a load state where the local buckling of the column web can lead to failure. The resistance analysis can be done according to EC3 (1-7) Chapter 5.4.

6. Conclusion

The EC3's component method for the calculation of major axis joints can be generalized and in that way applied for minor axis and 3D joints. The stiffness and resistance can be determined according to the standards EC3 (1-5) for in-plane loaded plates and EC3 (1-7) for plates loaded perpendicularly.

Acknowledgement

The financial support for this research given OTKA grants No. T 048814 is gratefully acknowledged.

This paper has been established in the frame of the Hungarian-Finnish scientific and technological co-operation with the support of the Centre for International Mobility, the foreign partner of the National Office for Research and Technology.

References

[1] STEENHUIS, M. – JASPART, J-P. – GOMES, F. C. T. – LEINO, T., 1998. Application of the Component Method to Steel Joints, COST C1 *Proceedings of the International Conference, Control of the Semi-Rigid Behaviour of Civil Engineering Structural Connections*, Ed. By Maquoi, R., Liege, 17-19. September 1998, pp. 125–143.

[2] NEVES, L. F. C. – DA SILVA, L. S.– WELLASCO, P. G. S., Experimental Behaviour of End-plate Minor-axis Steel and Composite Joints under Static Monotonic loading, *'Eurosteel' Conference Proceedings, Coimbra, Portugal*, 2002. pp. 1101–1110.

[3] Hungarian National Project: NKFP 2002/16 e-Design K+F Proceedings, Description of the Behaviour of Steel Connections by the Developed Spatial Component Method (in Hungarian), 2003.

[4] JANSS, J.– JASPART, J-P.– MAQUOI, R., Strength and behaviour of in plane weak axis joints and of 3-D joints, Connections in Steel Structures Behaviour, Strength and Design Ed. Bjorhorde, R., Brozzetti, J., Colson, A., Elsevier Applied Science, London 1988., pp. 60–68.

[5] GOMES, F. C. T. – JASPART, J-P. – MAQUOI, R., 1996. Moment Capacity of Beam-to-Column Minor-Axis Joints, *Proceedings of the IABSE International Colloquium: Semi-Rigid Structural Connections, Turkey*, September 1996, pp. 319–326.

[6] STOCKWELL, F. W. JR., Yield line Analysis of Column Webs with Welded Beam Connections, *AISC Engineering Journal* 1st. quarter 1974. p. 6.

[7] VÉRTES, K. – IVÁNYI, M., Numerical Analysis of Bolted End-plate Connections, MAGÉSZ 2004, Special Edition.