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FINITE ELEMENT MODELING OF ANGLE BRACING MEMBER BEHAVIOR IN EXPERIMENTALLY TESTED SUB-FRAME SPECIMENS

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Abstract. *This paper summarizes experimental and numerical investigations on the behavior of steel sub-frame specimens braced with use of a diagonal angle member. The laboratory tests were designed to investigate the effect of bracing member end connections (bolted asymmetric and welded symmetric) and the effect of bracing member slenderness on the frame behavior in the whole range of frame load-displacement characteristics. An advanced finite element numerical model is developed with use of commercial ABAQUS code. Elastic buckling modes are evaluated. Displacement controlled Riks geometrically and materially nonlinear analysis is carried out for the reproduction of the behavior of specimens tested in laboratory. Numerical frame load-displacement characteristics are compared with experimental ones. A simple analytical model of the compression member behavior developed elsewhere is compared with experimental angle brace characteristics. Practical recommendations are formulated.*

1 INTRODUCTION

Steel truss bracing systems are commonly used for the enhancement of sway performance of structural frames in multi-storey buildings. Vertical truss bracings are composed of diagonals made of rolled profiles, single or compound. In typical braced frames of moderate height, diagonals are made of single angles connected through bolted asymmetric joints or welded symmetric joints to continuous columns, or columns and beams, of the primary load bearing frame.

The behavior of structural members is usually examined experimentally as isolated elements; see Gizejowski et al. [1]. This type of experiments is helpful in predicting the effect of member slenderness on the buckling strength but is not adequate to model the member performance as an element of structural systems, especially with reference to the influence of real end conditions of bracing members on their buckling strength and force-deformation characteristic. The behavior of members acting integrally as elements of braced frame structures has been less investigated.

Analytical models, one based on tangent modulus theory and the second - on the evaluation of overall member force-deformation characteristic, have been developed by Barszcz and Gizejowski in [2] for the prediction of buckling strength according to Eurocode 3. Model based on the evaluation of overall member force-deformation characteristic for the assessment of load-displacement characteristic of more complex structures was presented in [3]. The above mentioned analytical model of the member behavior is further verified in this paper for angle bracing members tested as components of sub-frame specimens.

A summary of experimental work concerned with the behavior of angle member as an element of braced sub-frame portal specimens is presented hereafter. The experimental load-displacement behavior of tested specimens is compared with the FE results obtained with use of commercial ABAQUS code. Experimental force-deformation characteristics of the brace angle are compared with the analytical model dealt with in [2] and [3]. Conclusions directed towards the practical application of developed analytical model for modeling of the behavior of bolted and welded angle braces are drawn.

2 EXPERIMENTAL INVESTIGATIONS

Tests were designed to examine experimentally the behavior of two sets of braced sub-frames that are presented in figure 1. Figure 1a illustrates the general layout of sub-frame specimens BL with the angle brace jointed to gusset plates with use of high-strength bolts though close tolerance holes, and figure 1b – specimens WL with the angle brace welded to gusset plates. Details of both types of the connection are given in figure 2a and b, respectively.

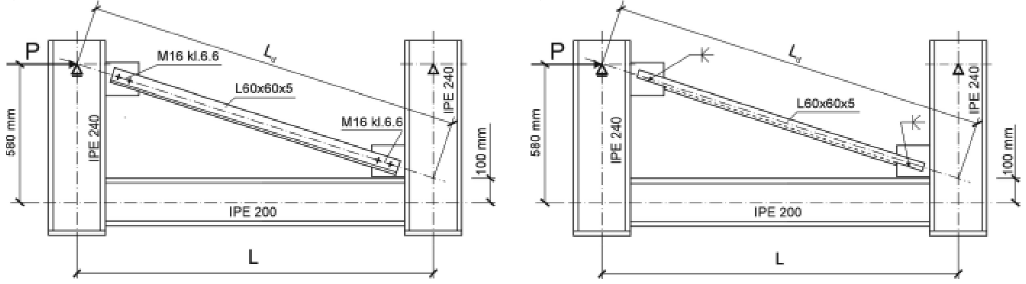
a)
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Figure 1: Geometry of tested sub-frame specimens; a) BL specimens, b) WL specimens.

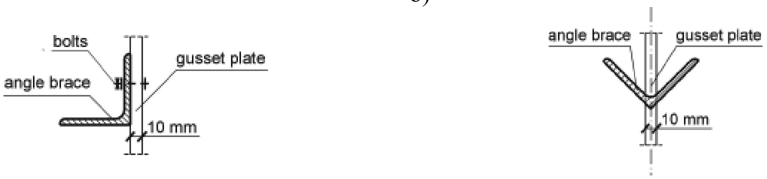
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Figure 2: Details of angle bracing connection; a) specimens BL, b) specimens WL.

Each set of tested specimens consists of three subsets characterized by different beam length *L* and the diagonal distance L_d. Notation for each subset of specimens is given in table 1. In each subset of BL and WL specimens, three specimens were tested.

Table 1: Description of tested specimen subsets.

Characteristic subset parameter	BL 1320 WL 1320	BL 1520 WL 1520	BL 1925 WL 1925
L	1320	1520	1925
L_d	1405	1595	1985

Tests were conducted for sub-frames mounted in an upside-down position. In the upper left node, the bracing member axis coincided with the left column axis and the node was held in position but allowed for the in-plane rotation. The same boundary conditions were applied to the upper right node of the right column end. The upper left node was loaded with a horizontal load *F* and the upper right node was subjected to a reactive force. The beam of sub-frame specimens was restrained in the out-of-plane direction in order to ensure that the frame deflects primarily in-plane. The incremental displacement controlled loading program, corresponding to the horizontal load *F*, was applied. Details of test rig, testing procedure and measurement devices were described in [4].

3 INVESTIGATIONS OF THE FRAME BEHAVIOR

Numerical investigations are conducted with use of commercial software ABAQUS. All the rolled double tee and angle section walls are modeled with use of thin shell four node finite elements S4R5 from the ABAQUS library. This element is only suitable for thin elements with small strain using the thin shell theory, however, large displacements are allowed for. The S4R5 elements are significantly less expensive since they use the reduced integration rule (Gauss integration). They are also cost-effective for large models with small strain and have good hourglass control. The aspect ratio of the mesh was kept close to 1.0 throughout.

a) BL 1320: F_{cr}=203,1 kN

d) WL 1320: F_{cr}=211,9 kN

b) BL 1520: F_{cr}=178,0 kN

e) WL 1520: F_{cr}=202,8 kN

c) BL 1925: F_{cr}=129,4 kN

f) WL 1925: F_{cr}=171,2 kN

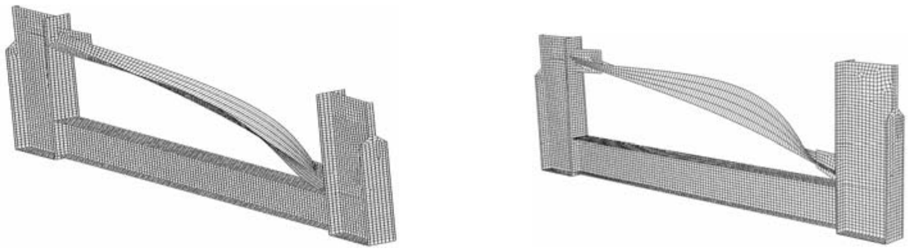


Figure 3: Frame critical loads and buckling modes from numerical simulations.

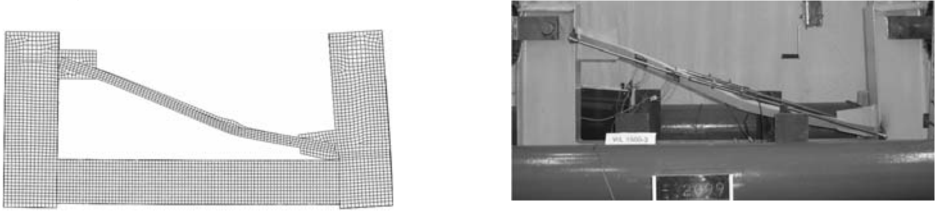
The multi point constraints option (MPCs) available in ABAQUS code is used to model the bolts in the braced sub-frame specimens BL. For each bolt MPC, rigid beam like constrains are created at matching nodes of two mid-surfaces of the angle brace leg and the gusset plate around the bolt shank circumference approximated by a square in order to simplify capturing the behavior of two plate elements jointed with high-strength close tolerance bolts. This helps also to avoid early analysis termination in case of excessive plastic deformations in concentrated bearing zones, between the bolt shank and connecting plate elements. Such a modeling technique seems to be accurate from engineering point of view.

The angle brace welded to gusset plates is modeled with connecting the angle brace to gusset plate directly via common nodes along the intersection line between the angle brace and the gusset plate. It is strongly believed that this modeling technique is quite accurate for the welded joint as long as no fracture is developed in the area of weld material or its neighborhood.

In order to estimate the elastic failure loads and to find the sensitivity of tested specimens to buckling effects, eigenproblems are solved. Critical loads F_{cr} and buckling modes are evaluated. Figure 3 illustrates the buckling modes and the values of critical loads. It is observed that for the short-beam specimens a distortional form of bracing member buckling governs while for the longest beam specimens - an overall buckling mode is detected. It is clear that buckling is associated primarily with the bracing member deformations and rather a negligible contribution of the frame beam and column deformations to the buckling profile is observed.

a) WL 1320: F_{ult}=124,6 kN

b) WL 1520: F_{ult}=124,4 kN



c) WL 1925: F_{ult}=115,3 kN

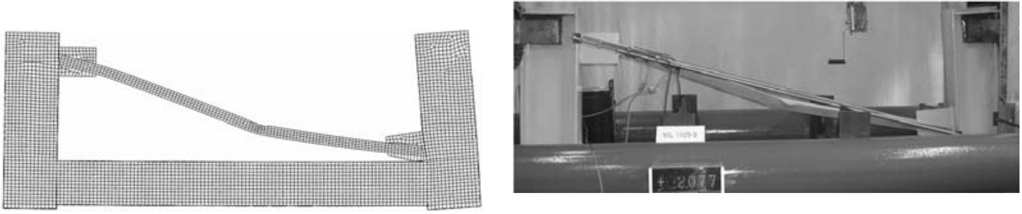
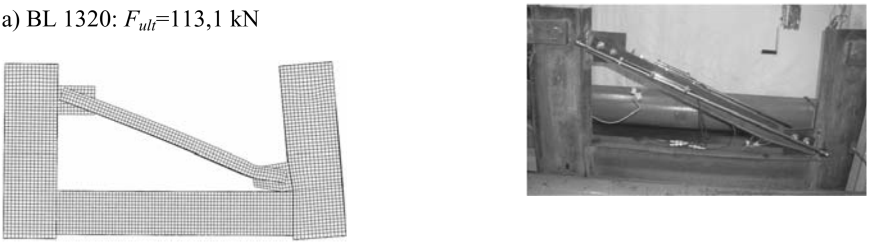


Figure 4: Frame deformation of welded brace specimens from tests and numerical simulations.

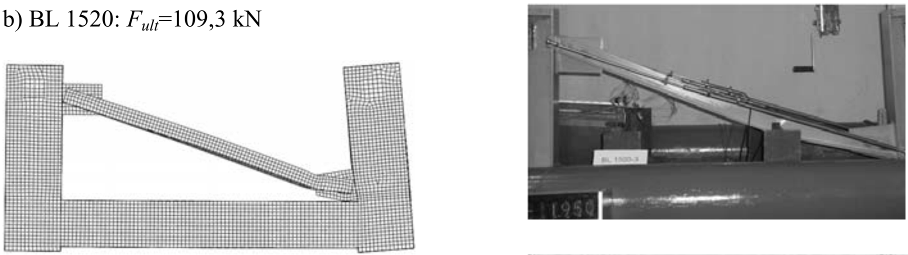
Finally, ultimate loads and deflected profiles are evaluated from fully nonlinear Riks analysis using ABAQUS code. Figure 4 gives the values of the frame ultimate loads F_{ult} and illustrates the deformed profiles of inelastic WL sub-frames at failure, comparing them with those recorded during tests. One can observe that the deflected frame profile is characterized by localized plastic deformations of the lower node of the right column. Since bracing members in these specimen subsets are connected concentrically, their deflected profile is associated with buckling deformations. The maximum coordinate of buckling profile shifts from the lower joint for a shorter brace length to the mid-length for a longer brace length.

Figure 5 gives the values of the frame ultimate loads F_{ult} and illustrates deformed profiles of inelastic BL sub-frames at failure, comparing them with those recorded during tests. One can observe that the deflected frame profile of BL specimens is similar to that of WL sub-frames. Since bracing members in all BL subsets of tested specimens are connected eccentrically, their deflected profile is associated with bending and torsion, without distinguished buckling in-plane deformations.

a) BL 1320: F_{ult}=113,1 kN



b) BL 1520: F_{ult}=109,3 kN



c) BL 1925: F_{ult}=105,8 kN

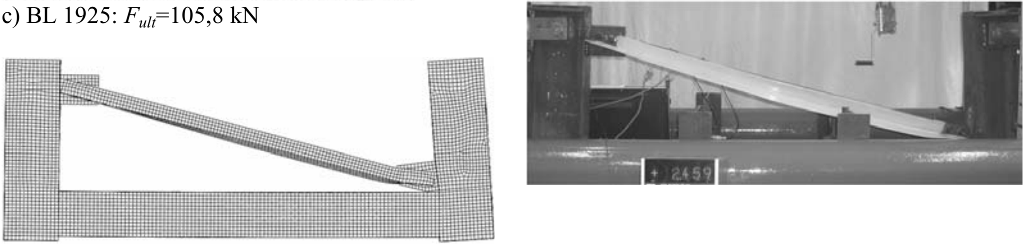


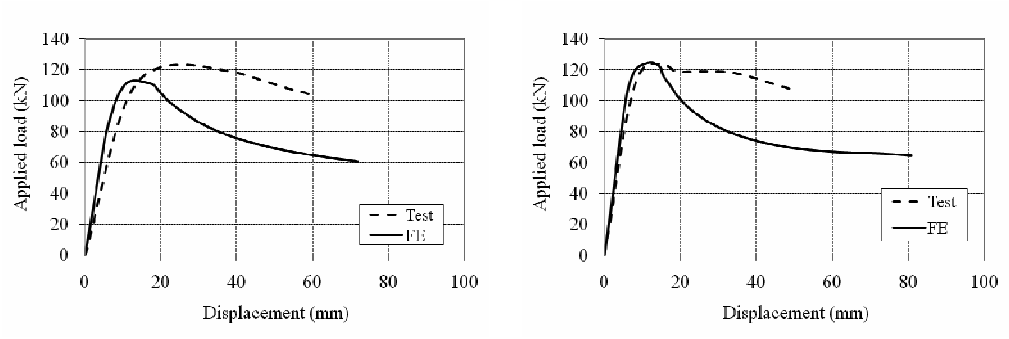
Figure 5: Frame deformation of bolted brace specimens from tests and numerical simulations.

The most stressed joint in all the tests appeared to be the right lower frame joint at which three elements are connected – the frame beam and column, and the bracing member. The detailed deformation of this joint obtained from laboratory tests and from numerical modeling is shown in figure 6.

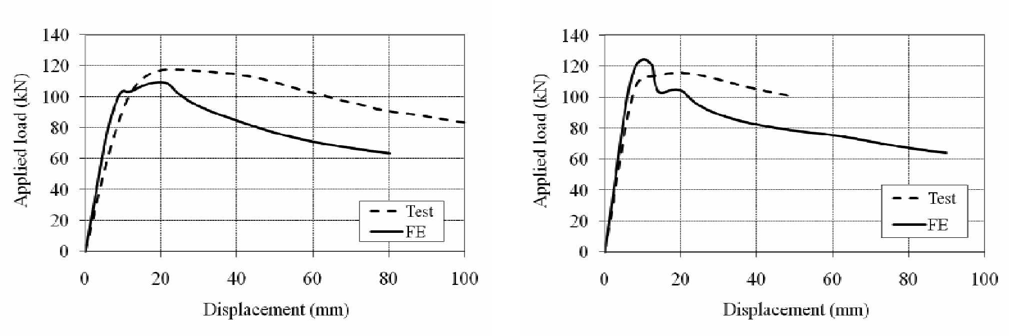
Figure 6: Details of WL 1320 column-beam-bracing joint deformations from tests and simulations.

Frame load-displacements characteristics from laboratory tests and from numerical modeling are presented in figure 7. All six frame experimental characteristics are evaluated as average curves from three tests of each subset. Since numerical modeling is carried out for initially perfect specimens, the accuracy of computer simulations is of a different degree depending on the sensitivity to imperfections and type of bracing member connections.

a) BL 1320 d) WL 1320



b) BL 1520 e) WL 1520



c) BL 1925 f) WL 1925

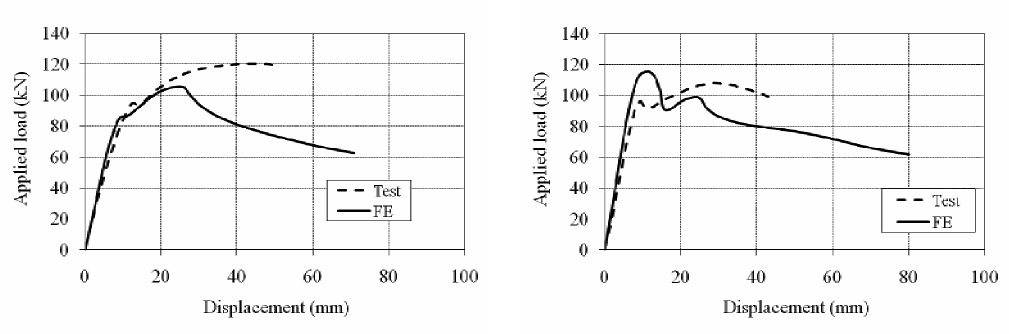


Figure 7: Frame load-displacement characteristics from tests and numerical simulations.

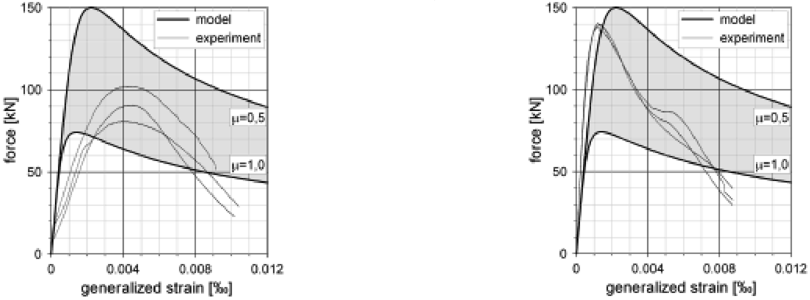
The following observations are made:

a) For frame specimens BL with eccentric connections of the bracing member, computer simulations lead to a higher initial stiffness and a noticeably lower ultimate loads as well as a lower placement of the post-limit branch of equilibrium path if compared with those obtained experimentally. Effect of geometric imperfections of the bracing member does not play important role in this case since the member is under combined bending, torsion and compression from the beginning of loading process.

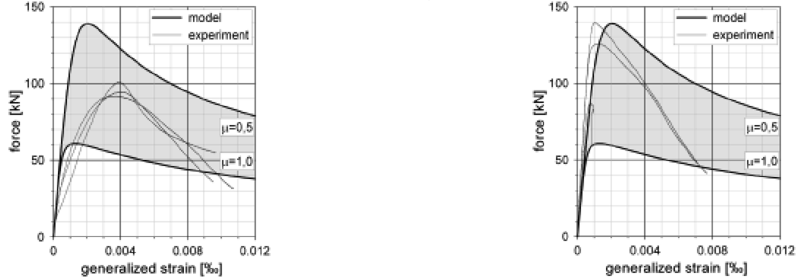
b) For frame specimens WL with concentric connections of the bracing member, computer simulations lead to a very close estimation of the initial stiffness but a higher ultimate loads and a lower placement of the post-limit branch of equilibrium path if compared with those obtained experimentally. Higher values of the ultimate load from computer simulations can be attributed to the effect of geometric imperfections of the bracing member that is not accounted for in analysis. Since the bracing member is concentrically connected with regard to out-of-plane deformations, it is predominantly axially loaded almost up to the attainment of the frame buckling strength. A sharp drop in the value of applied load is observed in the post-limit range. A more close estimation could be expected if the effect of geometric imperfections is accounted for in computer simulations.

3 INVESTIGATIONS OF THE BRACE BEHAVIOR

a) BL 1320 d) WL 1320



b) BL 1520 e) WL 1520



c) BL 1925 f) WL 1925

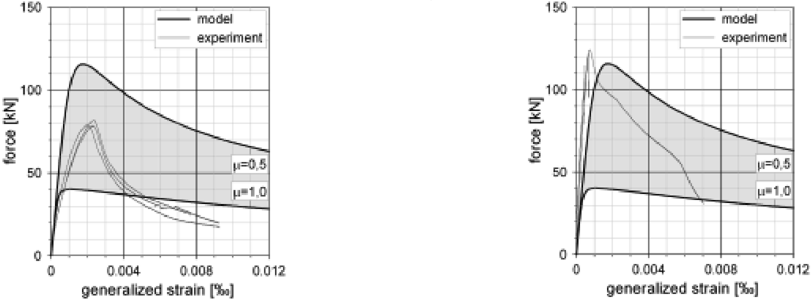


Figure 8: Bracing member force-deformation characteristics from tests and analytical model.

Finally, the behavior of bracing member assessed on the basis of test results is compared with simple modeling of force-deformation characteristic developed in [2]. Force-deformation characteristics presented in figure 8 are constructed in terms of the member axial force and member generalized strain (shortening due to compression and bending divided by the length). Results of three experimental curves are plotted for each subset of tested frame specimens. The upper bound of analytical solution is constructed for the effective length factor μ=0.5 while the lower bound it corresponds to the effective length factor μ=1.0.

The following observations are made:

a) The evaluation of welded connection bracing member behavior is reasonable enough using the upper bound analytical solution. It indicates that that the force-deformation characteristic of the welded type of member connection may be evaluated with the effective length factor equal 0.5.

b) The bolted connection bracing member behavior can not be evaluated so accurately using the cited analytical formulation. The values of experimental initial stiffness are lower than those from analytical solution for both values of the effective length factor. The experimental buckling strength is placed between those corresponding to two extreme values of the effective length factor, i.e. for two different types of boundary conditions assumed for the connection of brace member. This clearly indicates that the strut model developed in [2] has to be refined in case of bolted connections in order to account for the effect of connection eccentricity.

4 CONCLUSIONS

This paper presents experimental, numerical and analytical results of investigations aiming at the development of a simple and yet reliable model for the angle member behavior in bracing systems of structural frame structures. Welded brace angle force-deformation characteristics may be evaluated using directly the analytical formulation presented in [2] for the effective length factor equal 0.5. Bolted brace angle force-deformation characteristics can not be evaluated so accurately using the formulation presented in [2]. The refinement is needed with regard to the effect of connection eccentricity and inclusion of corresponding bending deformations in the evaluation of member generalized strain. This would affect predominantly the region of pre-buckling deformations and the level of buckling strength, resulting in lowering of the member force-deformation curve and bringing the analytical curves closer to the experimental ones. A more accurate model would therefore be developed and the effective length factor suggested accordingly.

The development of a refined model of the angle strut behavior in case of bolted connections is being underway, and better prediction of the bolted brace force-deformation characteristic is expected.

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