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INVESTIGATION AND FEM SIMULATION OF ADHESIVE REINFORCED KNEE JOINTS

Summary. This study includes full and detailed analysis of possibility of using glues in reinforcement of steel structures. The numerical calculations were done on the basis of the experimental investigations performed at BTU Cottbus with use of numerical programme Abaqus based on the Finite Element Method. The numerical results were compared with the experimental ones.

BADANIA I ANALIZA MES NAROŻA RAMY WZMOCNIONEGO PRZY UŻYCIU KLEJÓW

Streszczenie. Artykuł ten zawiera pełną i szczegółową analizę możliwości zastosowania nowoczesnych klejów do wzmacniania konstrukcji stalowych. Analiza numeryczna przeprowadzona przy wykorzystaniu programu Abaqus została wykonana na podstawie wyników badań eksperymentalnych przeprowadzonych na BTU Cottbus. Wyniki numeryczne zostały następnie porównane z wynikami badań eksperymentalnych.

1. Analysed structure

The analysed knee joint was made from double – tee welded section with very slender web. Additional transverse and diagonal stiffeners were applied. The web was reinforced by glued additional plate or plates. The geometry of analysed knee joint is presented in Fig. 1a. The layouts of reinforcement in every experiment called V were presented in Fig. 2.

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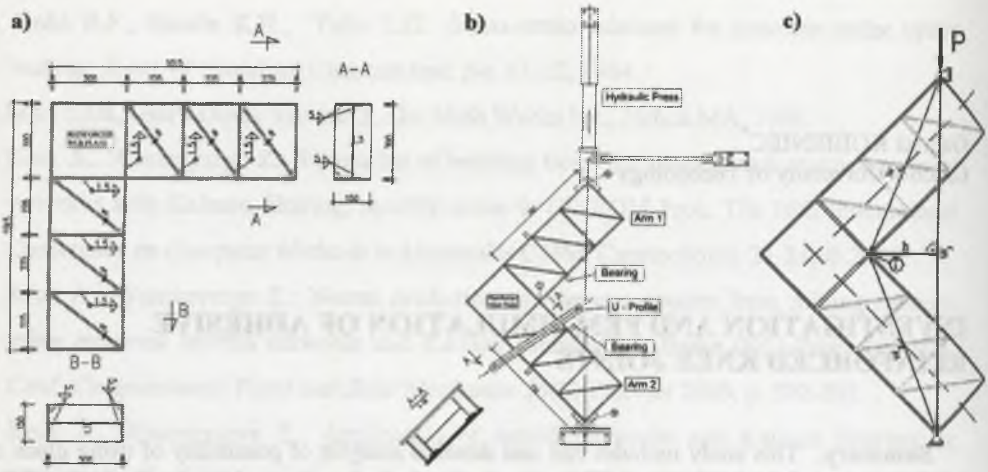

Fig. 1. The geometries of analysed models and experimental scheme
Rys. 1. Geometrie analizowanych naroży oraz schemat eksperymentalny

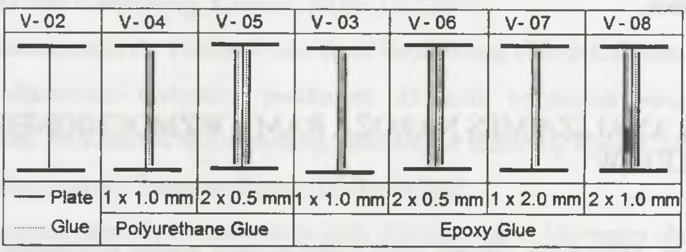

Fig. 2. Layouts of reinforcement
Rys. 2. Układy wzmocnienia

The main structure and additional plates were made from steel S235. The material properties of steel such as Young's modulus and yield stress were determined on the basis of the tension tests performed for steel plates that the main structures and additional plates were made. The material properties of main structures and additional plates were set up in Tab. 1. The glue properties were determined on the basis of experimental investigations performed at BTU Cottbus. Two types of glue were tested. The first of them was epoxy glue the second one was polyurethane glue. The stress – strain diagrams for glues were presented in Fig. 3.

Table 1

Material properties of knee joints

Name of experiment	Properties of web		Properties of flanges and stiffeners		Properties of additional plate(s)				Properties of glue		
	E [GPa]	f_y [MPa]	E [GPa]	f_y [MPa]	Number of plates	Thickness of plate [mm]	E [GPa]	f_y [MPa]	Type of glue	Number of layers of glue	Thickness of layer of glue [mm]
V-02	226.0	335.0	208.0	301.0	0	-	-	-	-	-	-
V-03	226.0	335.0	208.0	301.0	1	1.0	208.0	189.0	Epoxy	1	0.47
V-04	226.0	335.0	208.0	301.0	1	1.0	208.0	189.0	Polyurethane	1	0.66
V-05	226.0	335.0	208.0	301.0	2	0.5	234.0	219.0	Polyurethane	2	0.85
V-06	226.0	335.0	208.0	301.0	2	0.5	234.0	219.0	Epoxy	2	0.58
V-07	226.0	335.0	208.0	301.0	1	2.0	210.0	161.0	Epoxy	1	0.49
V-08	226.0	335.0	208.0	301.0	2	1.0	208.0	189.0	Epoxy	2	0.52

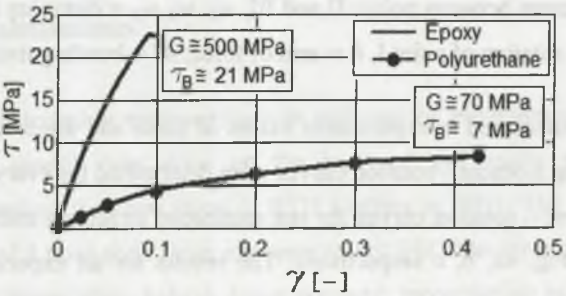

Fig. 3. Stress – strain diagrams for glues
Rys. 3. Zależność naprężenie – odkształcenie dla klejów

2. Experimental investigations

At BTU Cottbus several experiments with knee joints reinforced by additional plates glued to the web plate were conducted [2]. Every experiment was called V. Seven experiments were carried out. The first experiment concerned not reinforced knee joint while the rest of experiments reinforced knee joints. Every experiment distinguished from each other with a number and thickness of the additional plate or plates and the type of glue and the thickness of the layer of the glue. In experimental investigations these corners were under bending due to concentrated force which was applied in the right wing (Arm 1) of knee joint. The geometries of analysed models and experimental scheme were presented in Fig. 1b and the layouts of reinforcement in Fig. 2. Material properties of every experiment were set up in Tab. 1.

In every experiment the measured quantities were applied force and displacement between external points of knee joint called II and III (cf. Fig. 1c). Next with use of specific equations the bending moment and the rotation of internal point of knee joint called I were calculated (cf. Fig. 1c). These equations are:

$$\varphi = \arccos\left(\frac{w_1^{\,2} + w_2^{\,2} - (w_3 - \delta)^2}{2 \cdot w_1 \cdot w_2}\right) - \arccos\left(\frac{w_1^{\,2} + w_2^{\,2} - w_3^{\,2}}{2 \cdot w_1 \cdot w_2}\right) \tag{1}$$

$$h = \sqrt{w_1^{\,2} - \left(\frac{w_3 - \delta}{2}\right)^2} \tag{2}$$

$$M = Ph \tag{3}$$

where: δ = displacement between points II and III, w_1, w_2, w_3 = distances between points I, II, III (cf. Fig. 1c), φ = rotation of point I, h = arm of force, M = bending moment.

On the basis of measured in experiments values of force and displacement and equations (1) to (3) the bending moment – rotation curves were determined for every experiment.
The bending moment – rotation curves for not reinforced structures and for reinforced ones were presented in Fig. 4a, b, c respectively. The results for all experiments are set up in Tab. 2.

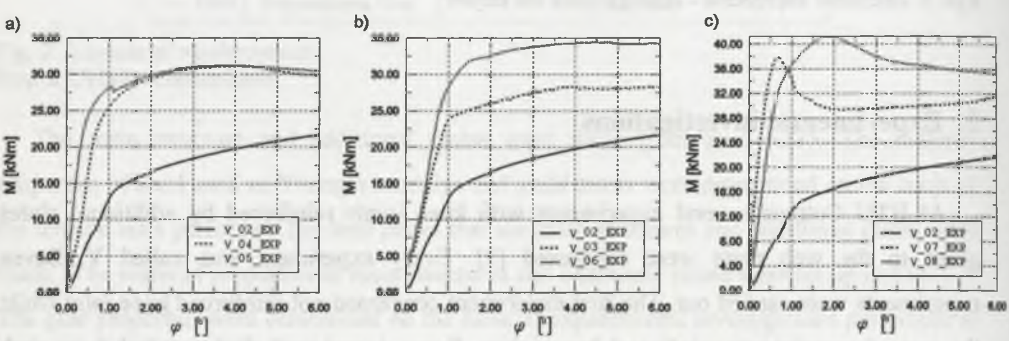

Fig. 4. Bending moment – rotation curves
Rys. 4. Zależność moment zginający – kąt obrotu

Table 2
The results for all experiments

Name of experiment	Experimental results	
	M_a [kNm]	M_u [kNm]
V – 02	-	30.56
V – 03	28.30	29.76
V – 04	31.16	32.97
V – 05	31.16	34.38
V – 06	34.54	34.86
V – 07	37.86	35.34
V – 08	41.25	39.82

3. Numerical calculations

The numerical calculation were carried out with use of programme ABAQUS [1]. The calibration of the models was done on the basis of the results of the experimental investigations performed for knee joints at BTU Cottbus in 2005. The main structures was modelled with use of 4 node shell finite elements called S4R. The layer of glue was modelled with use of 8 node linear brick, hybrid, linear pressure, incompatible modes elements called C3D8IH. The model was analysed as a simple supported one. Additional boundary conditions were applied to prevent the model from global buckling in out of plane of web direction. The layer of glue was connected with the main structures by option *TIE based on the theory of slave and master surfaces. A tie constraint ties two separate surfaces together so that there is no relative motion between them. This type of constraint allows to use together two regions even though the meshes created on the surfaces of the regions may be dissimilar. It is possible to define a tie constraint between edges of a wire or between faces of a solid or shell. Two surfaces can be tied together. Each node on the first surface (the slave surface) will have the same motion as the point on the second surface (the master surface) to which it is closest [1]. An appropriate introduction of geometrical imperfections into the numerical model should have been carefully analysed. The first step of introduction of imperfections was based on the solution of the linear buckling problem. As a result several local buckling modes were obtained (cf. Fig. 6c). In the second step a linear combination of chosen buckling (local) modes multiplied by adequate factors was created and in this way a new configuration of geometry of analysed model was achieved.

The geometrical imperfection has the following form [1]:

$$\Delta x_i = \sum_{i=1}^{n} w_i \phi_i \qquad (4)$$

where ϕ_i - i^{th} mode shape, w_i - associated scale factor.

In every experiment the measured quantities were applied force P and displacement U between external points of knee joint called II and III (cf. Fig. 1b). Next with use of equations (1), (2) and (3) (cf. Paragraph 2) the bending moment and rotation of internal point of knee joint called I were calculated (cf. Fig. 1b). All material and geometrical properties used in numerical calculations were taken from Table 1. The FEM model and graphical representation of slave and master surfaces theory were presented in the Fig. 6a and 6b respectively.

Experimental investigations showed that two maxima appeared on the bending moment – rotation curve (cf. Paragraph 2). The first maximum of bending moment called M_a is combined with destruction of bonds between glue and additional plate and the web plate. The second maximum of bending moment called M_u is combined with the Cardiff Model and describes ultimate capacity of knee joint.

It is very difficult in numerical calculations to describe behaviour of glue in elastic – plastic range thus only elastic behaviour of glue characterized by shear module G and Poisson's ratio v (cf. Fig. 3) was taken into account and that this way in this analysis only first maximum called M_a as a sufficient estimation of carrying capacity was calculated. The comparison of statical paths of equilibrium from experiment and from numerical analysis for chosen cases were presented in Fig. 8. The comparison of results for all cases are set up in Tab. 3.

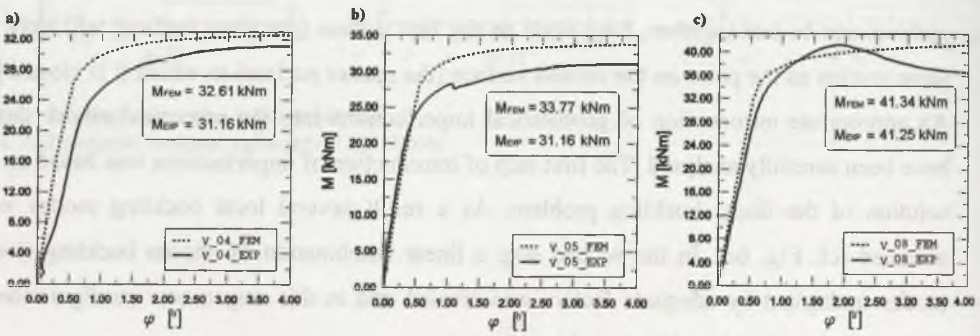

Fig. 5. Comparison of results of numerical and experimental analyses
Rys. 5. Porównanie wyników analiz numerycznej i eksperymentalnej

Table 3

Comparison of results

Name of experiment	Experimental results		Numerical results	M_{EXP}/M_{ABAQUS} [%]
	M_a [kNm]	M_u [kNm]	M_{ABAQUS} [kNm]	
V – 02	-	30.56	28.10	8
V – 03	28.30	29.76	28.83	1
V – 04	31.16	32.97	32.61	5
V – 05	31.16	34.38	33.77	8
V – 06	34.54	34.86	35.03	1
V – 07	37.86	35.34	39.25	4
V – 08	41.25	39.82	41.34	1

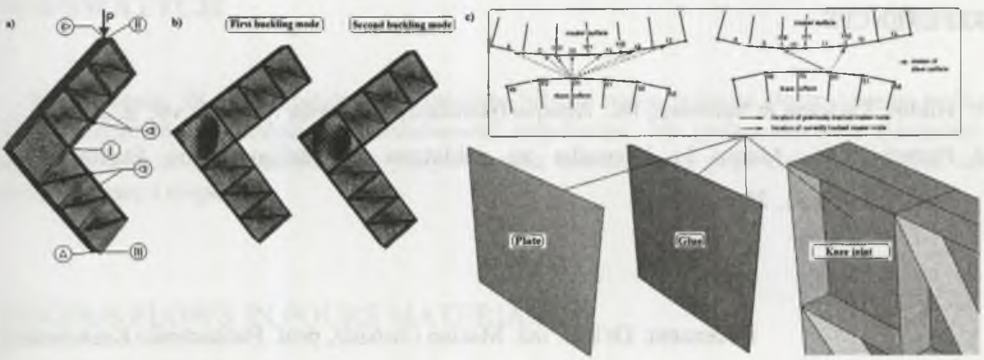

Fig. 6. FEM model of knee joint
Rys. 6. Model numeryczny naroża ramy

4. Conclusions

The experimental results showed that in case of epoxy glue the better way of reinforcement is to use two additional plates of thickness 0.5 mm instead of one plate of thickness 1.0 mm (cf. Fig. 4b). Identical conclusion can be drawn in case of experiments V – 07 (one additional plate of thickness 2.0 mm) and V – 08 (two plates of thickness 1.0 mm) (cf. Fig. 4c). Another situation happens in case of use polyurethane glue. Here two curves from different experiments superimposed thus the effect of use one additional plate is identical what in case of use two additional plates (cf. Fig. 4a).

The increase of value of bending moment M_a of reinforced knee joint in comparison with not reinforced one is significant. In case of experiments V – 03 to V – 06 the increase varies from 43% - 62% and for experiments V – 07 and V – 08 from 151% to 355% (cf. Fig. 4). Comparison of bending moment – rotation curves in case of value M_a and corresponding rotation φ for all cases are presented in Fig. 4.

The numerical calculations showed that the analysed knee joint may be effectively modelled with use of shell finite elements called S4R in case the mesh in webs is dense enough, also proved that the layer of glue can be modelled with use of solid finite elements called C3D8IH what can be an alternative for another very expensive method of modelling glues combined with creating finite spring elements. The difference between numerical and experimental results is lower than 8% in every case (cf. Tab. 3).

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