

Implementation of American weld connection standards into finite element computations

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Abstract. Presented paper summarizes the weld assessment on the basis of national standards. The approach concerning the static loading has been still not adequately developed in standards. The standard of American Institute of Steel Construction was considered as the best candidate for implementation into the finite element method using post-processing of a particular weld. A comparative analysis of maximum allowable loadings of weld connection models loaded in-plane and out-of-plane has been performed. Results obtained by the finite element method and American and Czech standards were compared and the conclusions of applicability and reliability were made.

1 Introduction

The assessment of welded structures in national standards as American Institute of Steel Construction (AISC), British Standards (BS), Czech technical standards (ČSN) and others is related only to simple weld connections. When complicated welded structure is intended to assess, it is meant in general geometry and topology, general loading or combination of general geometry and loading, there is a problem because the weld assessment is either difficult or impossible.

There are two main categories of the weld assessment – connections with either static or cyclic loading. Those are developed on different levels. Cyclically loaded welded structures are precisely documented and implemented into the Finite Element Method (FEM) in scope of assessment of complex configurations. However, the assessment of statically loaded welded connections is developed only on the basis of analytical formulas. Therefore, the implementation of standards regarding static loading into FEM is needed for assessment of complex welded structures.

2 Methods

Four basic approaches are the nominal stress, the structural stress, the notch stress and the fracture mechanics [1, 2]. The first three approaches differ in using various stresses (Figure 1). The latter approach is based on the completely different background and it is stated only for completeness. Thereafter, the stress-based methods might be distinguished in two main categories – the national standards (AISC, BS or ČSN) and special approaches, such as International Institute of Welding (IIW), Det Norske Veritas (DNV) or Forschungsbereich Maschinentechnik (FKM). The state-of-the-art suggests that the standard of AISC is probably the most suitable for assessment of complex welded structures [3].



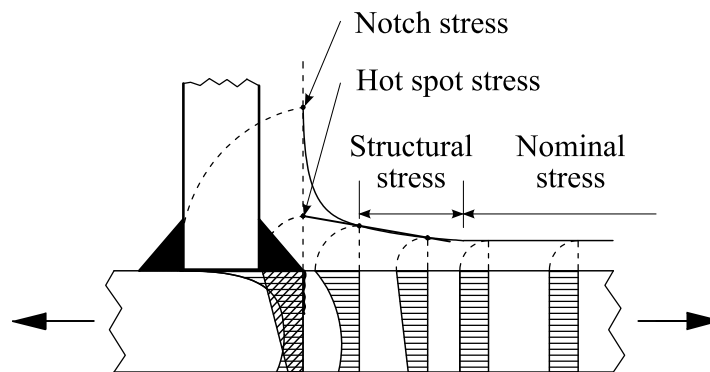


Figure 1. Approaches to the weld assessment [9].

3 Methodology

Standard configurations and loadings of welded connections are stated in the standard of AISC using the form of coefficients which are empirical. Those coefficients were obtained using Instantaneous Centers of Rotation Method (ICRM). Each part is able to withstand different loading when the weld joint is consisted of several partial welds variously oriented, and the loading can be redistributed into the whole weld group. Then, it is assumed that the whole weld group rotates around one Instantaneous Centre (IC). The principle of ICRM was described by Lesik and Kennedy [4, 11] and Miazga and Kennedy [12]. The description of the method can be summarized into following points and it can be illustratively depicted as in Figure 2. The group of fillet welds eccentrically loaded rotate around the IC which is iteratively obtained from the equations of static equilibrium. The weld is divided into the finite number of segments where the reaction forces are calculated. Maximum deformations of segments are computed in dependence of angle between the reaction forces and weld segments axes, and the critical segment is determined. The maximum external load is defined on the basis of this critical segment.

Another possible approach to assessment of welded structures might lie in deploying more sophisticated material model [5] or the damage [6], but the process would not be linear anymore.

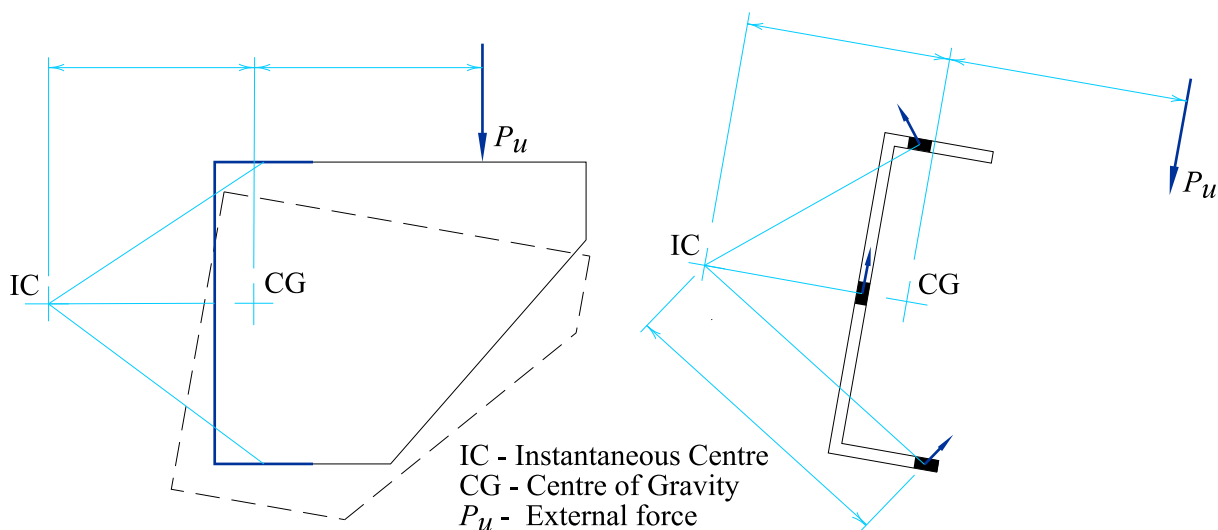
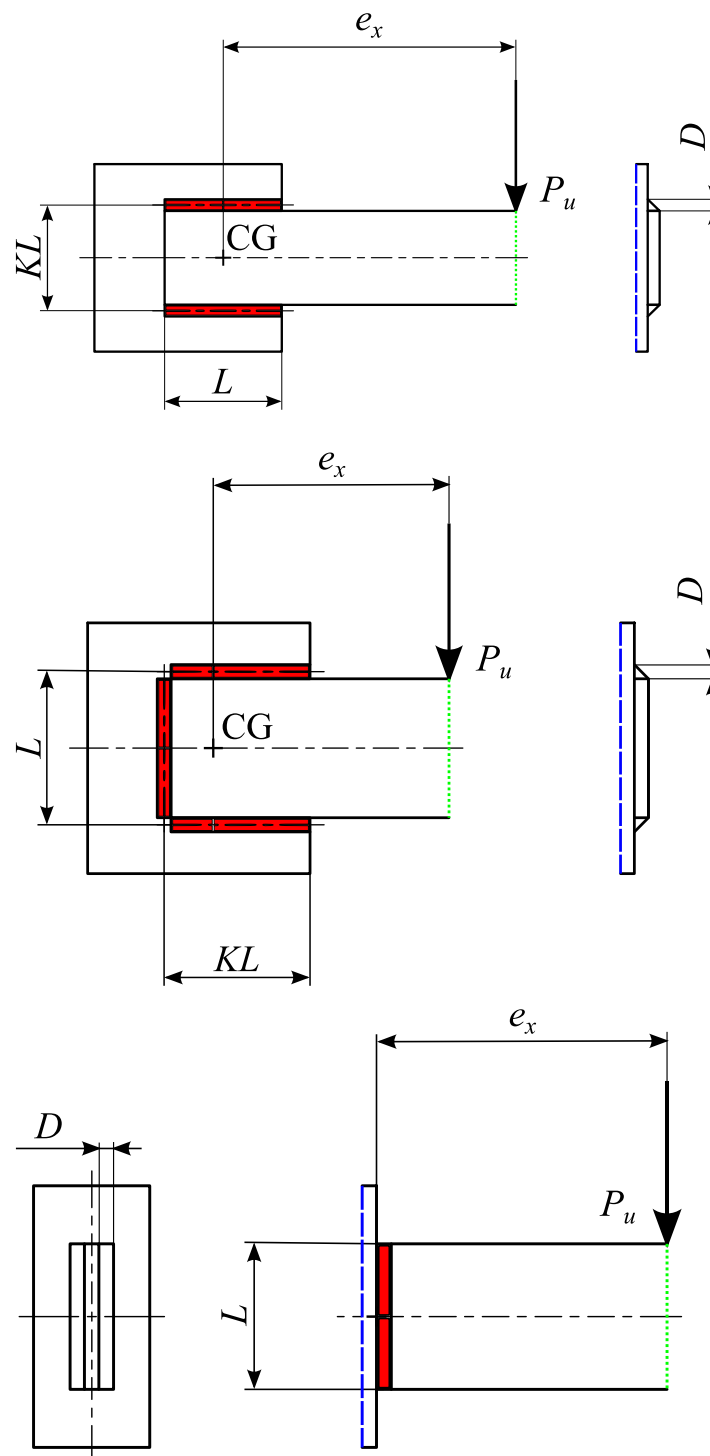


Figure 2. The principle of considered method [7].

4 Analytical solution

There were created three computational models, analytical and numerical, for comparison purposes (Figure 3). First two cases for assessment of the weld strength of joints exposed to in-plane loading and one case regarding out-of-plane loading.

**Figure 3.** Basic weld configurations [3].**Table 1.** Comparison of results from standards.

Case	AISC F_{stand} [N]	ČSN F_{stand} [N]	Δ [%]
1	65762	45067	-32
2	131312	86484	-34
3	52418	36513	-30

All the cases were assessed by standard of AISC [7, 10], ČSN [8] and by developed algorithm. Geometry was designed so as the weld strengths can be assessed by the standards, of course. The electrode E70 was used as a weld material with the strength $F_{EXX} = 480$ MPa, therefore the electrode strength coefficient was $C_1 = 1.00$. The base material was S355 steel with yield stress $f_y = 355$ MPa and ultimate tensile strength $f_u = 510$ MPa. Only the assessment of weld connections follow, so the base material was not assessed. Particular parameters for cases 1–3 are the weld size $D = 9.525$, 9.525 , 9.525 mm, $e_x = 203.2$, 203.2 , 203.2 mm, $KL = 50.8$, 101.6 , 0 mm and characteristic length of the weld group $L = 101.6$, 101.6 , 101.6 mm. Based on these dimensions, the coefficient of geometry and angle of loading of the weld group, which is tabulated, was determined as $C = 0.616$, 1.230 , 0.491 . Resulting maximum external loads of weld groups F_{stand} solved by AISC (Equation 1) and ČSN (Equation 2) are given in Table 1 where Δ represent percent difference of results. The expression for external force reads:

$$P_u = CC_1 DL \quad (1)$$

$$\sqrt{\sigma_{\perp}^2 + 3(\tau_{\perp}^2 + \tau_{\parallel}^2)} \leq \frac{f_u}{\beta_w \gamma_{M2}} \quad (2)$$

In Equation 2, σ_{\perp} is the normal stress perpendicular to the load-carrying cross-section of the weld, τ_{\perp} is the shear stress perpendicular to the weld axis and lying in the load-carrying cross-section, τ_{\parallel} is the shear stress parallel with the weld axis, $\beta_w = 0.9$ is the correlation coefficient according to the material class and $\gamma_{M2} = 1.25$ is the coefficient of weld connections reliability.

5 Numerical solution

The method taken over American standard is implemented into FEM with following advantages. There is a possibility to create an arbitrary weld, the determination of requested angles for the assessment is more accurate and there is no need to use the iterative algorithm of finding IC.

Particular computational models were defined for FEM as follows. All materials were assumed as homogeneous, isotropic and linearly elastic. The material of weld has $E = 210000$ MPa Young's modulus and $\mu = 0.3$ Poisson's ratio. The material of base metal had $E = 2100000$ MPa and $\mu = 0.3$. Boundary conditions were the same for all cases. Dashed line represents the loci where the metal was fixed and the dotted line represents the loci of applied external force (Figure 3). The discretization of model was conducted at two levels according to the standard. Each weld was divided into ten segments (Figure 4) where the reaction forces were determined. The whole model was discretized by mapped mesh with a linear 2 mm elements.

The most important part is a post-processing. Reaction forces were determined at particular weld segments on the surfaces loaded in shear – red-colored surfaces in Figure 3. All nodes belonging to particular segment were selected on this surface and components of reaction forces F_x , F_y and F_z were calculated in the Centre of Gravity (CG) of a particular surface (Figure 5). Using these forces, the angle θ between weld axis and segment force F_{dos} was computed. Based on angle θ , the maximum allowable force on particular segment $F_{pr,R}$ was computed via the Equation 3, where $\Phi = 0.75$ is the resistance factor. The Equation 3 is extended version of Equation 1.

$$F_{pr,R} = 0.6\Phi F_{EXX} [1 + 0.5 \sin^{1.5}(\theta)] \quad (3)$$

There is a criterion for estimation of maximum external force using FEM, F_{FEM} , in Equation 4. The allowable external load can be calculated for a problem with an arbitrary external load with sequential linear interpolation so as $p_{dos} = 1$ at a critical segment.

$$p_{dos} = \frac{F_{pr,R}}{F_{dos}} \geq 1 \quad (4)$$

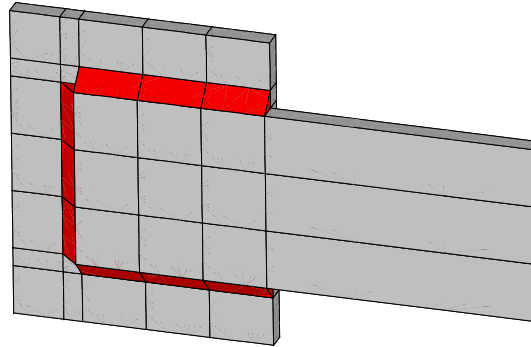


Figure 4. Division into three segments.

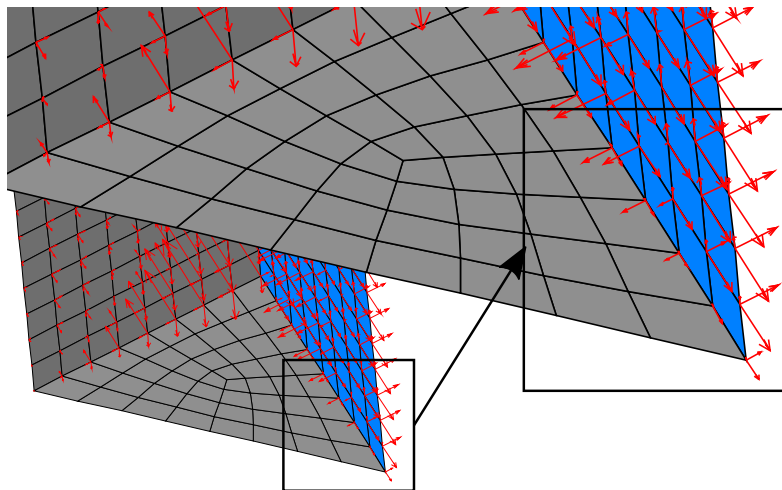


Figure 5. The estimation of forces [3].

Resulting maximum allowable external forces determined by this methodology are given in Table 2 where those are compared to values from standards. Based on these results, there was designed a weld group according to Figure 6 where the weld material is the same as in previous cases and $h_1 = 76.2$ mm, $h_2 = 101.6$ mm, $h_3 = 508$ mm, $v_1 = 50.8$ mm, $v_2 = 152.4$ mm, $v_3 = 76.2$ mm and $D = 9.525$ mm. It is not possible to assess this case according to the standard but it can be done by proposed algorithm. Results for particular loading are given in Table 3 depicting the linear dependency. The interpolation of forces so as $p_{dos} = 1$ gives maximum external force of $F_{FEM} = 178624$ N which should the weld safely withstand.

Table 2. Comparison of cases according to AISC and FEM.

Case	F_{FEM} [N]	F_{stand} [N]	Δ [%]
1	46379	65762	-30
2	118961	131312	-9
3	60000	52418	15

Table 3. Results of illustrative case.

F_{FEM} [N]	F_{dos} [N]	AISC $F_{pr,R}$ [N]	AISC θ [deg]	p_{dos} [-]
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100000	9142			1.79
200000	18285	16330	21	0.89
300000	27427			0.60

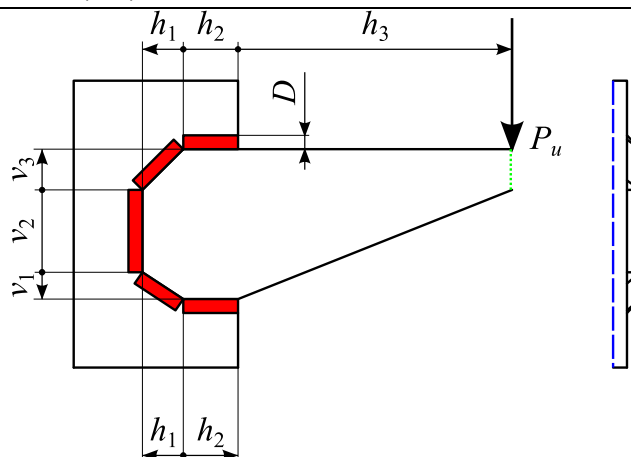


Figure 6. Non-standard weld group [3].

6 Conclusions

There has been developed the algorithm for assessment of complex welded structures loaded in-plane and out-of-plane according to American standard of AISC which is based on solution in elastic region and ICRM. The advantage is in concerning residual stress and variability of weld joint given by the term 0.6Φ in Equation 3. When certain rules are complied, the methodology can be applied to assessment of welds with results between values obtained by AISC and ČSN – which is more conservative. It is always necessary to perform experimental testing and weld inspection [12] even when the approach is derived from standard.

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References

- [1] Maddox S 1991 Fatigue strength of welded structures (England: Cambridge)
- [2] Radaj D 1990 Design and analysis of fatigue resistant welded structures (England: Cambridge)
- [3] Peč M 2015 Analysis of load capacity of selected welded structural joints under static and cyclic load (Brno: Brno University of Technology)
- [4] Lesik D F and Kennedy D J L 1988 Ultimate strength of eccentrically loaded fillet welded connections (Edmonton: University of Alberta)
- [5] Peč M, Kubík P, Šebek F, Návrat T and Petruška J 2016 Modeling of the blast load effects in explicit dynamics, Proc. of the 22nd Int. Conf. Engineering Mechanics (Svratka) eds Zolotarev I and Radolf V (Svratka: Academy of Sciences of the Czech Republic) pp 442–445
- [6] Šebek F, Kubík P and Petruška J 2014 Localization problem of coupled ductile failure models compared to uncoupled ones, Proc. of the 20th Int. Conf. Engineering Mechanics (Svratka) ed Fuis V (Svratka: Brno University of Technology) pp 632–635
- [7] American Institute of Steel Construction 1994 Manual of steel construction: load and resistance factor design (Chicago)
- [8] ČSN EN 1993-1-8 2006 Eurocode 3: Design of steel structures - Part 1-8: Design of joints (Praha)
- [9] Aygül M 2012 Fatigue analysis of welded structures using the finite element method (Gothenburg: Chalmers University of Technology)
- [10] American Institute of Steel Construction 2005 Steel construction manual (Chicago)

- [11] Lesik D F and Kennedy D J L 1990 Ultimate strength of fillet welded connections loaded in plane *Can. J. Civ. Eng.* **17** pp 55–67
- [12] Miazga G S and Kennedy D J L 1989 Behaviour of fillet welds as a function of the angle of loading *Can. J. Civ. Eng.* **16** pp 583–599