

Investigation of conjugation nodes of a structure's loadbearing elements in the nonlinear formulation

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Abstract. When designing beam grids and frameworks for industrial and public buildings, contemporary engineering makes use of finite-element complexes. Loadbearing structures are usually modeled with beam-type finite elements. The joints between elements are typically modeled as perfect hinges or entirely rigid. Nodes are designed separately depending on the previously obtained loads aided by different tools, ad-hoc software among others. The actual behavior of nodes is different from that of a perfect model. This necessitates a research on the effect the assumptions and simplifications make on the stress (strained) condition of loadbearing structures and nodes. The paper scrutinizes the behavior of hinged nodes. The research is centered around a welded steel I-beam hinged on both sides. The beam was modeled in two ways: using rod finite elements supported with perfect hinges on both sides and via dimensional finite elements, where modeling in its own right was performed for the hinged nodes located on the welds. The structure was stressed evenly with a distributed one-parameter load increasing from zero to a certain finite value at which the beam collapses. The beam is considered to fail as soon as fiber yielding behavior arises in the flanges of the welded I-beam. The calculation was run in the multipurpose software complex LS-DYNA employing explicit and implicit finite element methods as well as nonlinear static techniques. The research has revealed that the actual hinged node is not a perfect hinge and has a certain finite rigidity. Thus, the actual beam, as opposed to a perfect beam, will exhibit a bending moment, while the moment will have a smaller value across the span. Since the node was designed for a transverse force only, the real behavior of the weld exhibits plastic deformations driven by the bending moment. Moreover, deformations arise in the gusset plates and in the web of the welded I-beam where the maximum strain caused by bending moments manifests itself. Research has discovered that failure does not happen due to the minuteness of such deformations. Thus, the conclusion can be made that a hinged beam can be designed as a beam with perfect hinges, but it will at the same time modeled with a surplus. The results obtained are backed up by the data given in various sources.

Keywords. hinged node, hinged beam, steel beam, perfect hinge, weld

1. Introduction

When designing the connections of elements of beam framings and frameworks of industrial and public buildings and structures, designers usually use standard or similar solutions for beam and column connection nodes presented in [1-12]. In so doing, the element connections are assumed to be ideal, i.e. either hinge joints or absolutely rigid connections [13-16].



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Analysis of design documentation of buildings and structures indicates that the most frequently encountered solution for beam and column connections is the node presented in Figure 1.

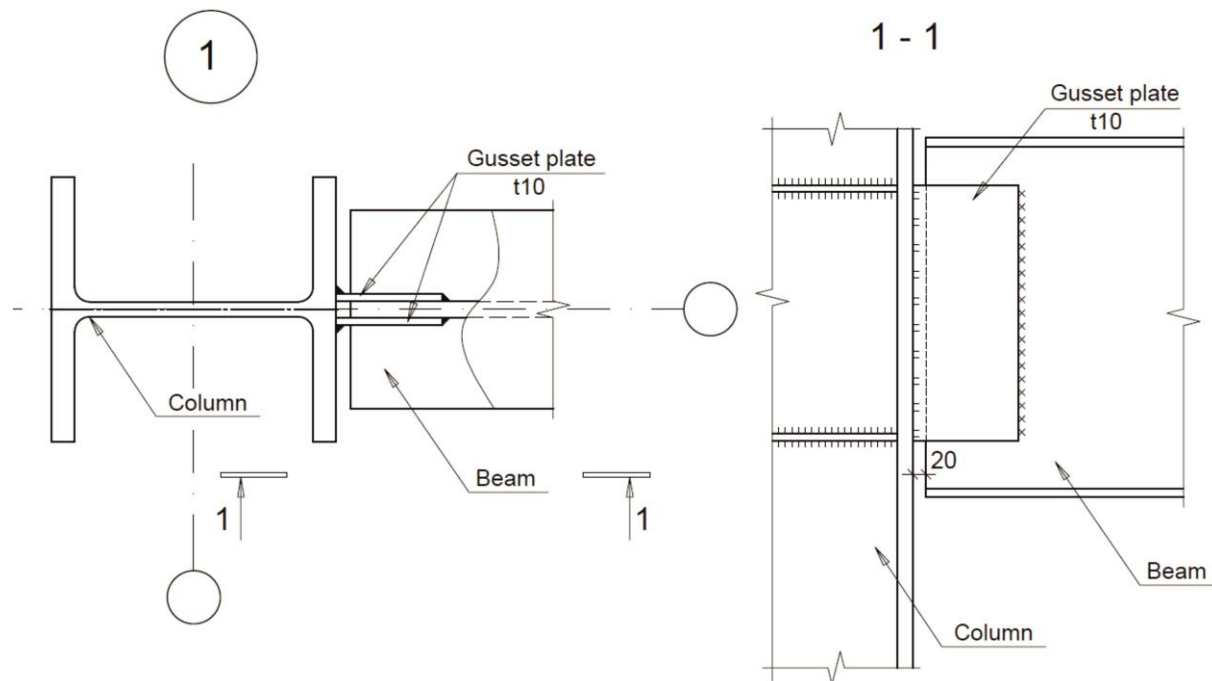


Figure 1. Standard hinge node for beam and column connection

According to standard (off-the-shelf) solutions [7, 8], this node belongs to the hinge joint type. However, existence of a pair of weld seams practically along the whole height of the I-beam wall signifies that the proposed node will have a significant value of bending rigidity even with the presence of gaps in the beam ribs. Thus, besides the lateral forces, there will be a bending moment appearing on the beam supports, which will be taken up by gusset plates and weld beams of the node. This assumption is corroborated by experimental research presented in [11].

The purpose of this research is to determine bearing capacity of the presented node and the structural element in the form of the steel beam resting on hinge joints at its two ends.

To assess the impact of adopted assumptions and simplifications of the off-the-shelf solution, it is necessary to perform testing of the stress-deformed state of the bearing structures and the nodes per se.

2. Methods

The article studies functioning of the hinge nodes. Calculations were performed for a steel beam made of welded I-beam, resting on hinge joints at its two ends.

The beam section and the node elements were selected according to [17-22], based on the adopted initial conditions:

- uniformly distributed load on beam of 55750 N/m;
- beam span of 3 m;
- beam and gusset plate material – steel S255 [19];
- welding electrode grade – E42A [19];
- the node has been designed by analogy with the standard hinge node (Figure 1).

As a result, the selected cross-section was in the form of welded I-beam with the web of 200x10 mm and flanges of 100x10 mm. Gusset plates of 100x100x10 mm were selected for the node. Gusset

plate welded joints with the I-beam web and with the column were assumed with a leg of 3 mm. The web and flange connection seams were not taken into account in the calculation.

The beam was modeled and estimated in a physically and geometrically non-linear setting by two methods. In the first case - rod finite elements with ideal hinges at the ends. The design diagram is presented in Figure 2. In the second case - volume finite elements with direct modeling of hinge nodes and welded connections (Figure 3). In this respect, two options for fastening gusset plates to the column were examined - absolutely rigid connection and with a welded seam.



Figure 2. Hinge beam modeled with rod finite elements

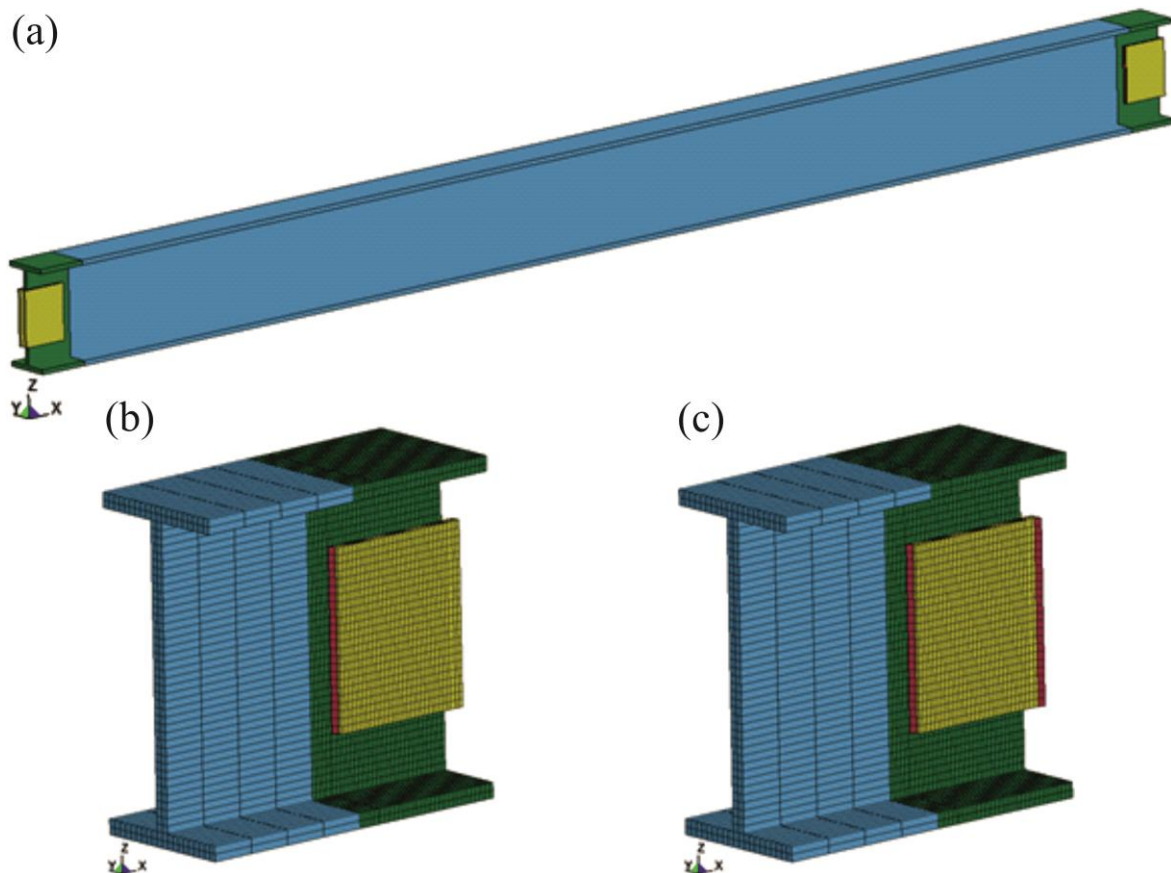


Figure 3. Hinge beam modeled with volume finite elements: (a) – general view of the model; (b) – fastening of gusset plates to the column is absolutely rigid; (c) – fastening of gusset plates with a welded seam

The LS-Dyna software package was used for the research. It applies non-linear static methods and non-linear dynamic methods with the use of explicit and implicit schemes of direct integration of motion equations.

The structure was loaded with a uniformly distributed single-parameter load, increasing from zero to a certain final value at which the beam failure occurs. Beam failure was considered to be the appearance of fiber fluidity in the welded I-beam flanges.

Numerical methods of structural mechanics are used, as a rule, for solution of non-linear differential equations. Usage of any of these methods leads to a resolving system of non-linear algebraic equations of displacement method [23]. This system may be presented in the form of a matrix equation:

$$[\mathbf{R}(z)]\vec{z} = \vec{R}_p \quad (1)$$

where $[\mathbf{R}(z)]$ - is the square matrix of the system reactions (rigidity), the elements of which depend not only on the structure material, but on its stress-deformed state as well; \vec{z} - vector of unknown values (displacements); \vec{R}_p - vector of load values.

The equation may be solved by different methods, for example, by the Newton-Rafson method.

The beam, gusset plate and weld seam material was modeled with the help of an elastoplastic model. The material behavior diagram is presented in Figure 4.

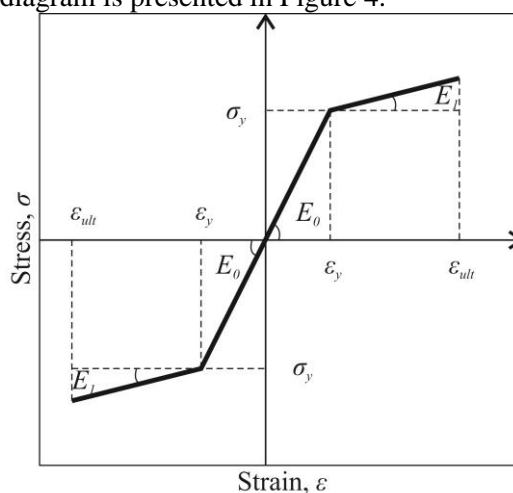


Figure 4. General view of the beam, gusset plate and weld seam material diagram

3. Results

In the estimation of the rod hinge beam, as was assumed from the SP estimation, fiber fluidity in the welded I-beam flange appears at the load which equals the initial load (the load parameter is equal to 1). The stress intensity and plastic deformation charts are shown in Figure 5.

Examination of the beam with direct modeling of nodes indicated that the real node does not constitute an ideal hinge and that it has a certain finite rigidity. It can be seen in Figure 6 that the gusset plates are partially preventing turning of the I-beam, due to which pulling (compressing) stresses appear in them. Thus, contrary to a beam with ideal hinges, there will be a bending moment appearing on the real beam supports.

Since the node was designed only for lateral force, plastic deformations occur in the weld seam during real operation due to the appearance of the bending moment. Notably, plastic deformations in the seam occur even at load parameter equal about to 0.1 (i. e., at 10% of full load value). In the course of further loading, plastic deformations also appear in the gusset plates and in the I-beam web at weld seam locations. Research indicates that, due to minuteness of these deformations (not more than 8% at

the time of the beam failure), no disintegration occurs. Figure 7 presents isofields of plastic deformation in the beam node at load parameter equal to 1.

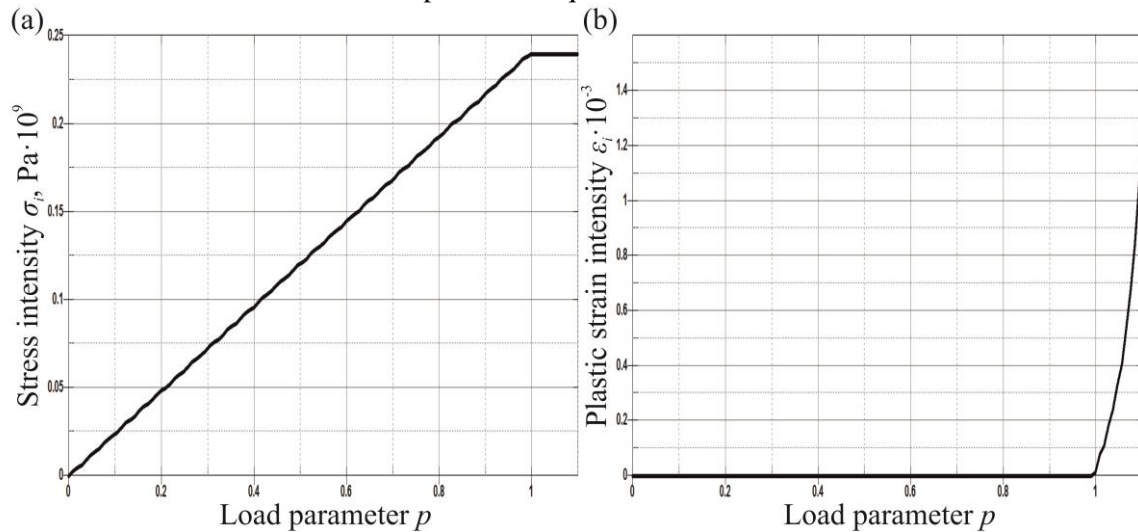


Figure 5. The stress and plastic deformation intensity charts of the span center of the rod hinge beam: (a) – stress intensity; (b) – plastic strain intensity

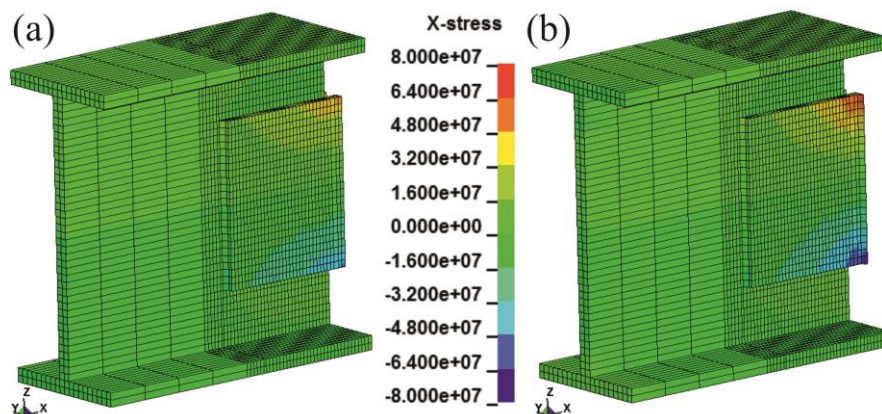


Figure 6. Isofields of X-stress at load parameter p equal to 1: (a) –fastening of gusset plates to the column is absolutely rigid; (b) – fastening of gusset plates with a welded seam

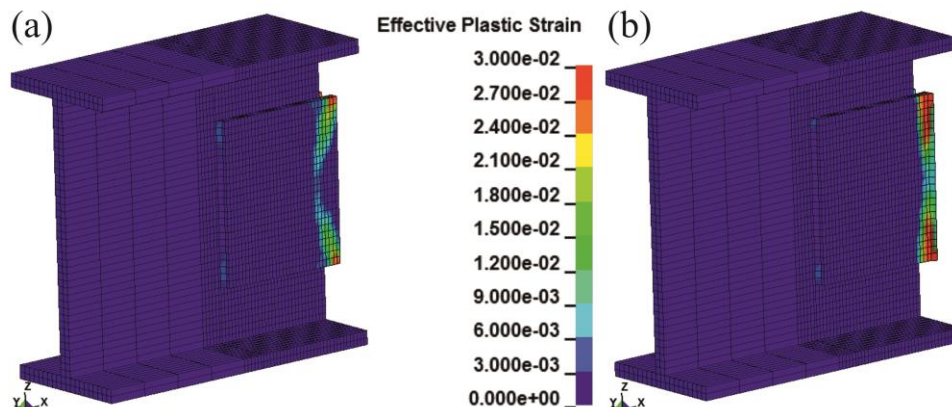


Figure 7. Isofields of plastic deformation intensity at load parameter p equal to 1: (a) –fastening of gusset plates to the column is absolutely rigid; (b) – fastening of gusset plates with a welded seam

Due to the fact that real beam nodes have a certain rigidity, deflection and moment in the span will be reduced, compared to the hinge beam. To assess the deflection values, additional research was performed on a rod model of a beam rigidly fixed at two ends, similar to the hinge one. Figure 8 presents charts of the span center deflection depending on the load parameter. The charts are plotted to the point of appearance of fiber fluidity in the I-beam flanges.

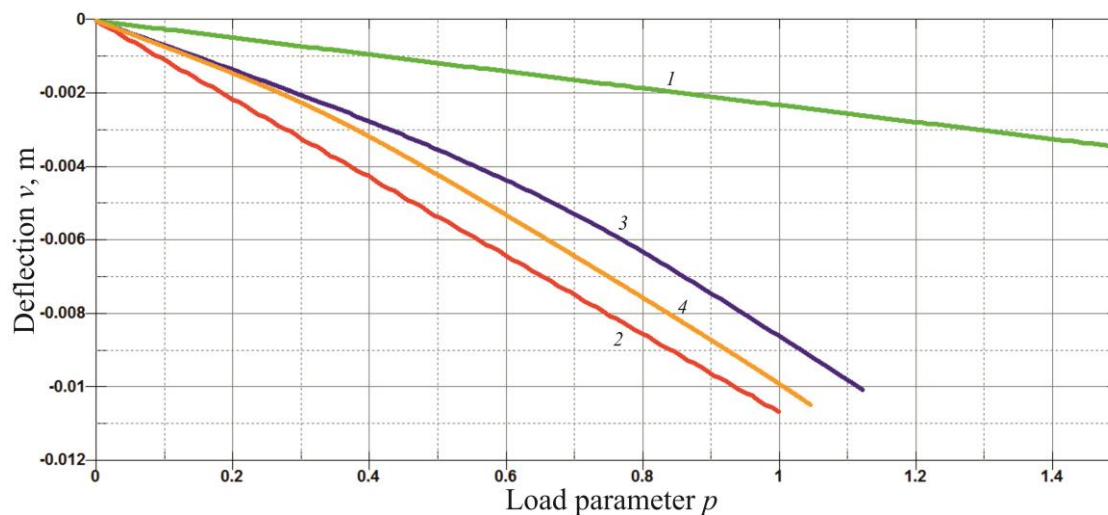


Figure 8. Charts of the span center deflection depending on the load parameter p : 1 – rod rigidly fixed beam; 2 – rod hinge beam; 3 - fastening of gusset plates to the column is absolutely rigid; 4 – fastening of gusset plates with a welded seam

Thus, when modeling real behavior of the node, the beam's bearing capacity turned out to be greater than bearing capacity of the beam with ideal hinges. Specifically, for a beam with absolutely rigid fastening of gusset plates to the column by 12%, and for a beam with gusset plate fastening using weld seams by 5%.

4. Discussion

The nature of the charts obtained using the span center deflection values depending on the applied load matches the data presented in [11] quite well (Figure 9). Thus, it is possible to draw the conclusion that the accomplished numerical research can be confirmed experimentally.

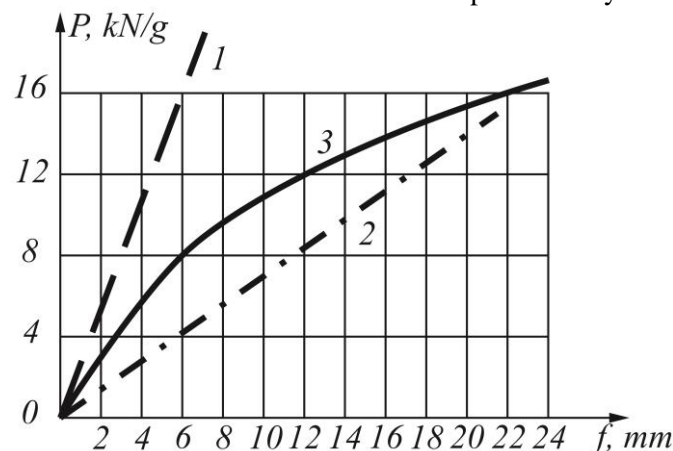


Figure 9. Charts of the span center deflection [11]: 1 – rod rigidly fixed beam; 2 – rod hinge beam; 3 - experiment

The paper [24] studied the elastoplastic behavior of a beam resting on hinges with finite rigidity of its nodes. In this respect, the study was performed for a cross-beam connection with the column without the use of gusset plates. The paper [24] also records appearance of plastic deformations in the node which appear at the load of 32% of the full value. According to the results presented in our studies, plastic deformations appear at the load which equals 10% of the full value. Therefore, when design is performed according to existing norms, plastic deformations may occur in nodes of various structural schemes at loads that are significantly smaller than design values, and this must be taken into consideration when designing the nodes.

5. Conclusions

As a result of the accomplished research, it is possible to draw the conclusion that a beam resting on hinges with the use of the node type presented on Figure 1 may be designed as a beam with ideal hinges. In this case, in real-life operation the design sections of beam bearing elements in the center of the span will have a certain margin of bearing capacity; however, plastic deformation may occur in connection nodes of the bearing elements. It is necessary to perform additional design research for each specific case in the process of designing structures and their nodes.

Acknowledgments

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