Structural Analysis and Design of Steel Connections Using Component-Based Finite Element Model

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Abstract: This paper introduces CBFEM (component-based finite element model) which is a new method to analyze and design connections of steel structures. Design focused CM (component model) is compared to FEM (finite elements models). Procedure for composition of a model based on usual production process is used in CBFEM. Its results are compared to those obtained by component method for portal frame eaves moment connection with good agreement. Design of moment resistant column base is demonstrated by a case loaded by two directional bending moments and normal force. Interaction of several connections in one complex joint is explained in the last example. This paper aims to provide structural engineers with a new tool to effectively analyze and design various joints of steel structures.

Key words: Steel structures, structural connections, finite element model, component model, analytical model, design model.

1. Introduction

One of the key parts of structural analysis and design of a steel structure is calculation of joints. Structural engineers have plenty of calculation tools for members and their cross-sections. Despite that majority of construction defects are caused by a bad structural design of a joint, tools for their analysis, calculation and design are much less widespread and their functionality is limited to several types of joints.

Many authors aim to resolve this issue by introducing a new method that is:

• general so that it is useable for most of joints, anchors and details used in building practice;

• simple and fast so that it provides results in time comparable with currently existing methods and tools;

• comprehensible so that structural engineer gets clear information about joint behavior, stress, strain and reserves of individual components and about overall safety and reliability.

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2. Component and Finite Element Models of Connections

Component model of connections builds up on standard procedures of evaluation of internal forces in connections and their checking. Zoetemeijer [1] was the first who equipped this model with prediction of stiffness and deformation capacity. The elastic stiffness was improved in the work of Steenhius et al. [2]. Basic description of components behavior in major structural steel connections was used by Jaspart [3] for beam to column connections and by Wald et al. [4] for column bases. The model was generalized by Da Silva [5]. Method implemented in the current European structural standard for steel and composite connections [6, 7] can be applied in majority of software for structural steel used in Europe. Procedure starts with decomposition of a joint to components (Fig. 1), followed by their description in terms of normal/shear force deformation behavior. After that, components are grouped to examine joint moment-rotational behavior and classification/representation in a spring/shear model and application in global analyses (Fig. 1).

Advantage of the component model is integration of current experimental and analytical knowledge of connections components behavior (bolts, welds and plates). This provides very accurate prediction of behavior in elastic and ultimate level of loading. Verification of the model is possible using simplified calculation. Disadvantage of component model is that experimental evaluation of internal forces distribution can be done only for limited number of joint configurations. In temporary scientific papers, description of atypical components is either not present or has low validity and description of background materials. Models of hollow section connections are described in Chapter 7 of EN1993-1-8 [6] by curve fitting procedures: Their compatibility with component model is unreliable. The CMs (component models) are rather complex for hand calculation, resulting in a need to use tools/design tables.

FEM (finite element models) for connections are used from the 1970s and they are research-oriented. Their ability to express real behavior of connections is making them a valid alternative to testing—standard and expensive source of knowledge of connection's behavior. Native process of computer-based design is VaV (validation and verification) of models [8]. Application of VaV to steel connections design is limited to a few published benchmark studies [9]. Comparison of VaV to different engineering application is still to be done [10]. Material model for

FEM uses true stress-strain diagram (Fig. 2). Strain is recommended to be limited to 5% [11]. Implementation of safety into advanced design models under ultimate limit state design is summarized in Ref. [11]. Standard procedure with partial safety factors for material/connections may be applied. More advanced and accurate solution, which takes into consideration the accuracy of model and material separately, gives more accurate and economical solution of structural connections.

3. Composition of CBFEM Model

CBFEM (component-based finite element model) is based on decomposition of the whole joint into separated components—steel plates, welds, bolts, anchors and concrete block. Each component has its own analysis model:

• 2D plate/wall finite elements for steel plates of stubs of hot/cold formed cross section;

• force interpolation constrains for welds;

• nonlinear springs for bolts and anchors;

• contact elements between plates in connections;

• Winkler/Pasternak subsoil for concrete blocks.

First step in creating of the model is preparation of its geometry. Structural engineer creates the structural joint by applying manufacturing operations using these components (Fig. 3). Meshing of the components is automatically done by software.

The plates connected by welds are modeled separately.
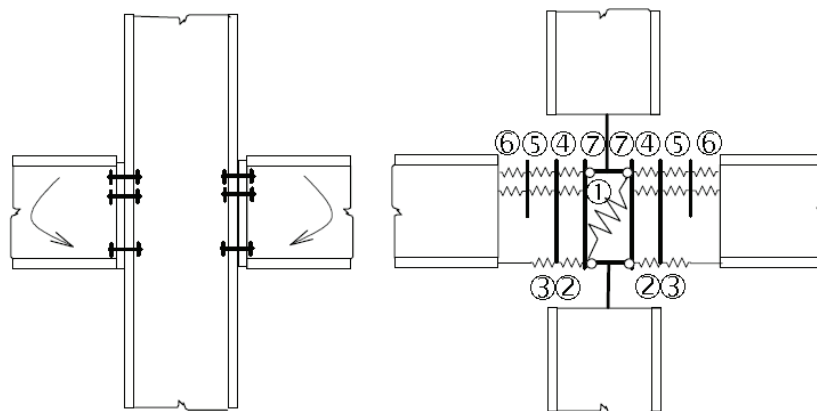
Fig. 1   Component model of symmetrical beam to column connection with end plates (1—column web in shear; 2—column web in compression; 3—beam flange and web in compression; 4—column flange in bending; 5—bolts in tension; 6—end plate in bending; 7—column web in tension).
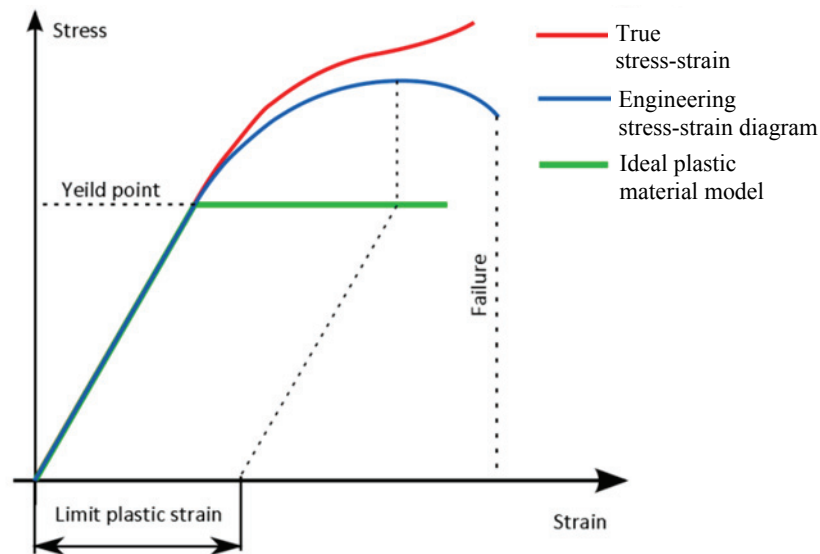
Fig. 2   Material models of steel for research and design oriented methods.
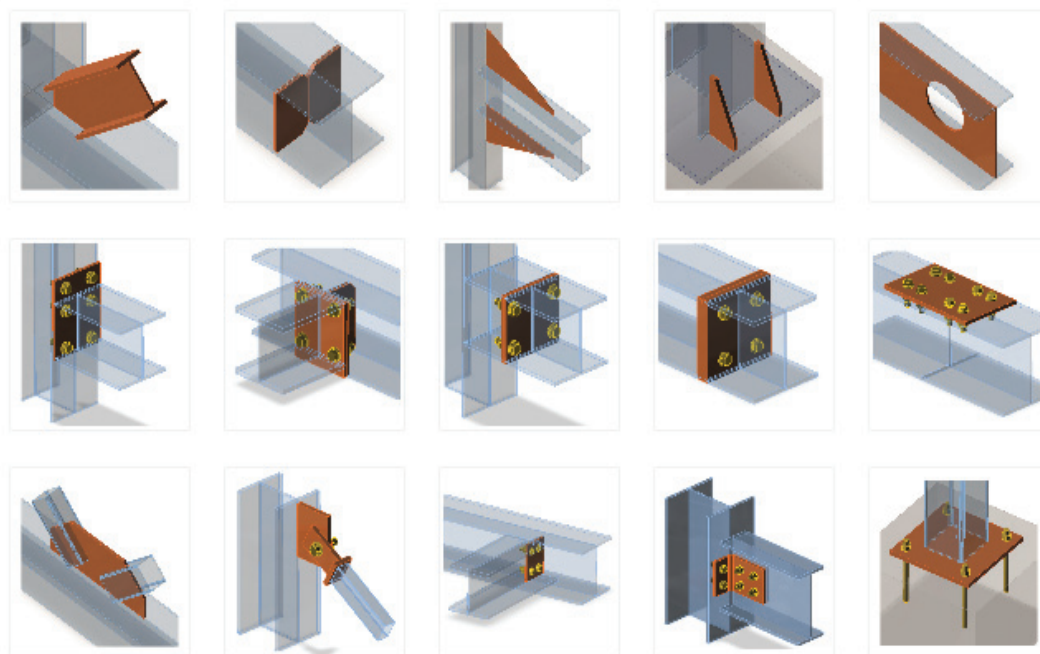

Fig. 3   Manufacturing operations applicable to the structural joint.

They are connected by weld component only, which is characterized by weld in plane and out of plane tensile stiffness and resistance. The bolts are modeled as two fans of interpolation links with its tensile and shear trilinear stiffness and adequate resistance. Slender compressed plates are checked for local buckling. Possible post buckling behavior of thin-walled sections is introduced by effective stress of each compressed plate.

4. Case Studies

4.1 Welded Portal Frame Eaves Moment Connection

The CBFEM model of the portal frame eaves moment connection with parallel stiffeners was verified by the CM. Results show a good agreement between two models. After that, sensitivity study was performed. Beam IPE (standard name of European hot-rolled I-sections) cross-section size is variable

parameter shown on horizontal axis (Fig. 4). Column HEB (standard name of European hot-rolled I-sections) 260 was considered. The resistance shown on vertical axis represents force couple of bending moment in plane M_y and vertical shear force V_z for which the ultimate limit state was reached. It is assumed that bending moment and shear force values are equal. Resistance of the connection was governed by two components, column panel in shear and beam flange in compression. Comparison of critical component for both CBFEM and CM models was made. The same component was critical in both models for all parameters. Results of both models are very similar and differences in resistance are up to 7% and only in uncommon cases, e.g., column HEB 260, beam IPE 500. To cover the CBFEM model uncertainty,

factor α_1 will be determined according to sensitivity studies [11].

Study of the moment connection in the corner of portal frame is visualized in Fig. 5. Design resistance and distribution of internal stresses are shown for three types of a joint with unstiffened beam web, parallel stiffeners and inclined stiffener in compressed part of column web. These models were verified against CM with good accuracy. However, reaching this results using CM to the joint with inclined stiffener is very time consuming and with limited optimization features. The numbers below diagram indicates different capacity of the joint based on various location of stiffeners. The biggest capacity is in Fig. 5c where two stiffeners (one inclined) are used. Maximal stress is marked in red, minimal in blue.
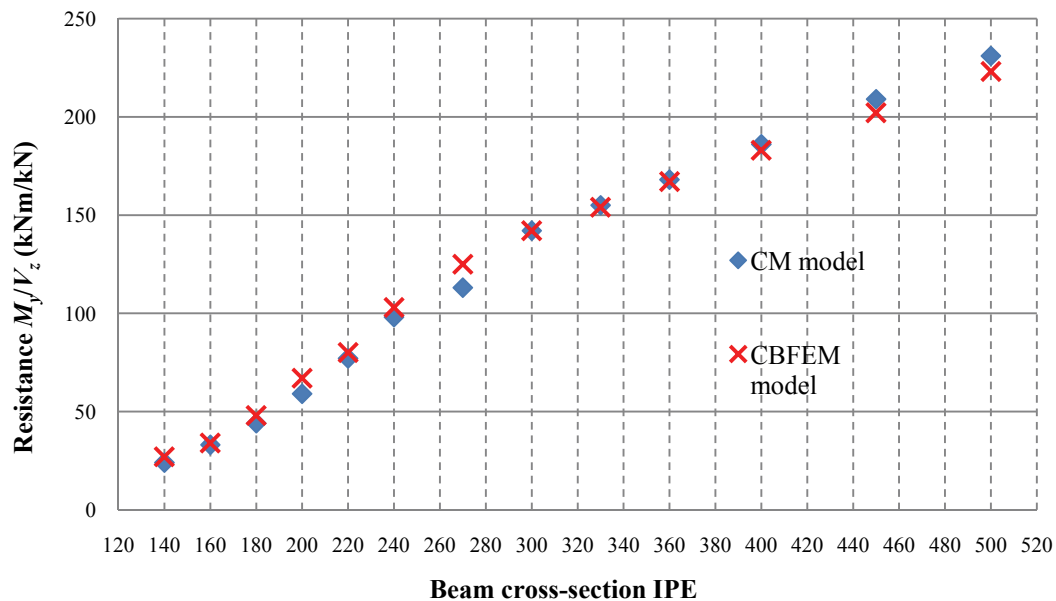
Fig. 4   Sensitivity study (Column HEB 260), variable parameter is beam cross-section size.
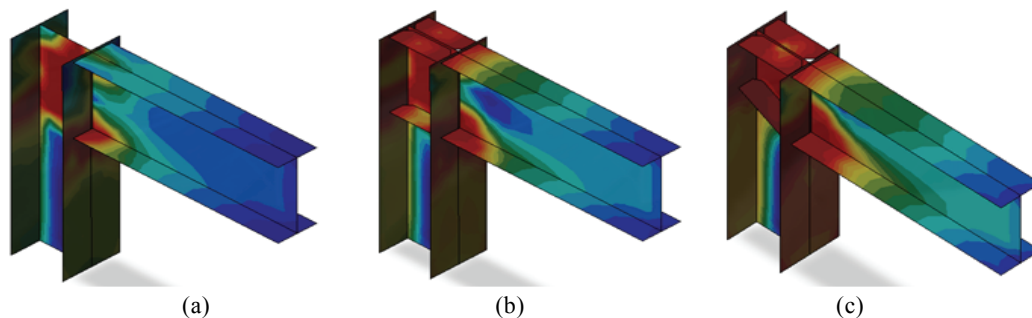
Fig. 5   Influence of the shear stiffener to rotational capacity of eaves moment connection: (a) *Mu* = 46.5 KNm; (b) *Mu* = 61.3 KNm; (c) *Mu* = 73.0 KNm.

4.2 Column Base with Base Plate

Nowadays, tools using CM support column base with base plate design with or without stiffeners. The example is calculated with loading in two perpendicular principal directions. In case of loading by bending moments in general plane, the result is obtained by interaction [6]. The accuracy of interaction is limited to linear behavior and may result in 30% overestimation. The CBFEM method was validated with good accuracy using experiments both from literature and carried out specifically for this purpose by the authors. The verification of cases loaded by moment in major/minor axes performed against CM gives good results (Fig. 6). The CBFEM model, directly performing calculation under general loading,

allows engineers to optimize stiffeners and plate (Fig. 7).

5. Analysis of a Complex Steel Joint

Interaction of several connections in one joint is very hard to solve using CM. Analytical CM needs to be created manually for every type of the joint. On the other hand, there are no limitations for typology and number of members used in CBFEM method.

General effectiveness of the method is shown in an example of a frame joint (Fig. 8). There are following members in the joint: connection on bolted end-plate with ribs, connection on shifted end-plate with stiffener, connection of skewed beam on short end-plate, rectangular hole in the web and several stiffeners. All

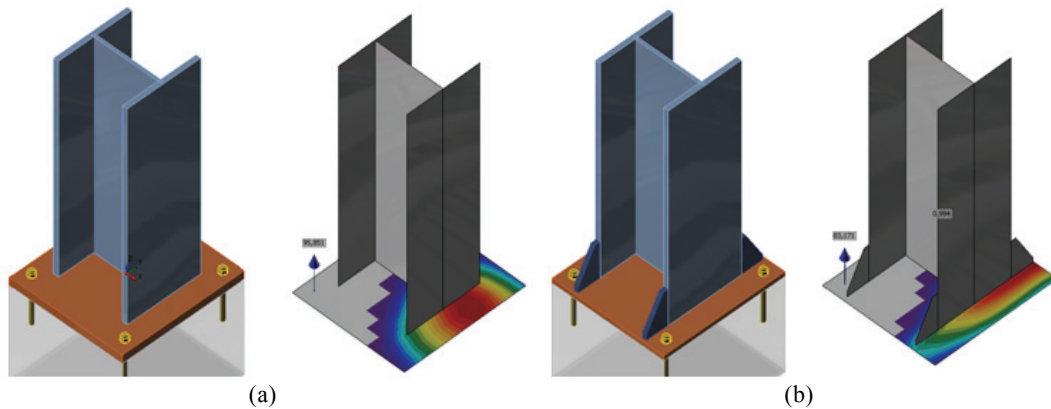(a)   (b)

Fig. 6   Contact stress in concrete loaded by general moment: (a) unstiffened plate 35 mm; (b) stiffened plate 22 mm.

(a)   (b)
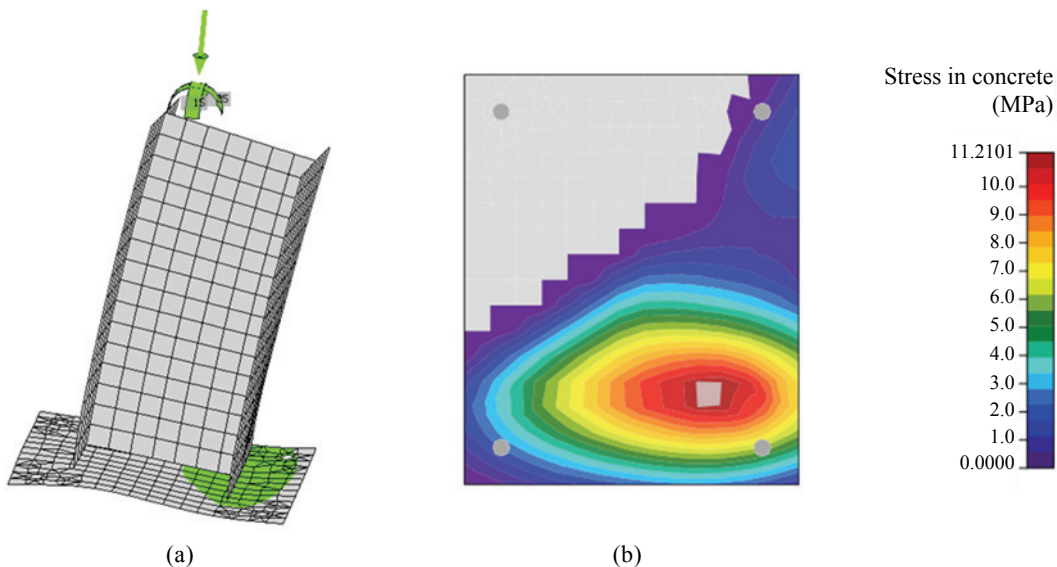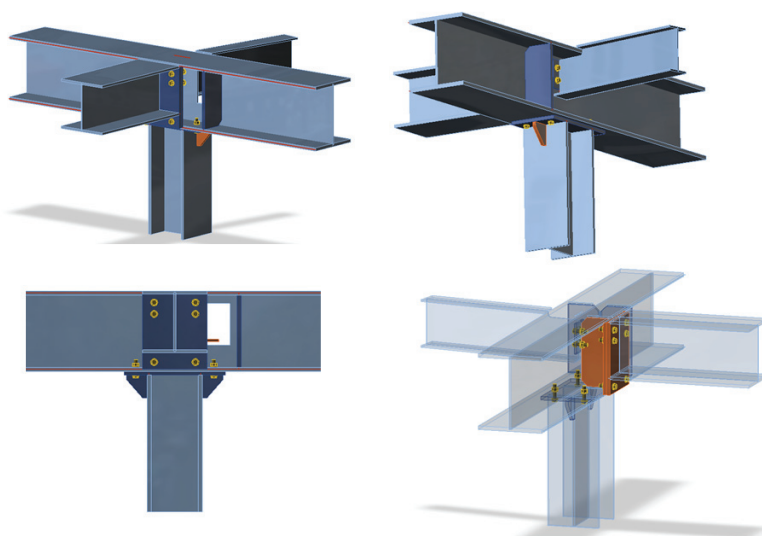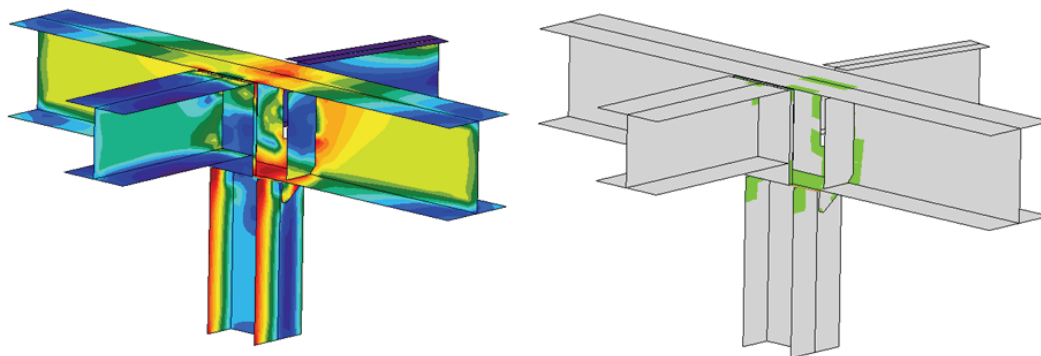
Fig. 7   Base plate loaded by normal force and two bending moments: (a) deformed shape; (b) stress in contact area.

Fig. 8   Complex frame joint—interaction of more connections.

Fig. 9   Stresses and plastic zones in complex steel joint.

these members can be solved separately by CM but the overall capacity of the joint is also defined by their interactions—true capacity of a given connection cannot be defined without analysis of a connection located next to it.

Presentation of calculated results is very important for clear understanding of CBFEM method. Fig. 9 shows stresses in steel plates and developing of plastic zones in different parts of the joint.

6. Conclusions

Structural engineers often face a challenging task when analyzing, calculating and designing joints of steel structures. Commonly used CM is laborious for calculation and its application by design tools in practice is limited to certain types of connections and their loading. On the other hand, sophisticated 3D

volume finite element models are too complex for use in daily practice for structural engineers.

Authors of this paper developed new method called CBFEM [12]. It can be used for majority of joints, anchoring and details of various topology, which give results in time comparable with existing simplified methods and provide clear information about behavior of the joint. CBFEM method enables structural engineers to accurately analyze joints that had to be simplified or estimated so far [13].

Acknowledgments

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