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Industry CPD

Numerical modelling of joints for structural design using CBFEM

This CPD module, sponsored by IDEA StatiCa UK, introduces CBFEM, a method to analyse and design connections of steel structures, which is a synergy of the standard approach to connection design (component method) and finite elements.

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Introduction

In joint design, engineers often rely on design tables, experimental results and analytical calculations to select suitable designs. These methods can be effective for common connection types, simple loading scenarios and well-documented and tested designs.

Examples of well-established joints would be those specified in SCI publications P358 and P398, which are checked for typical failure modes. The failure modes are normally directly associated with a specific load component, allowing them to be examined independently of one another, effectively neglecting interaction between them.

The methods developed for this 'component method' (CM) are, nevertheless, suited for implementation in software rather than for manual calculation. The analytical relationships mean that calculation sheets could be developed by the design engineers themselves, without having to resort to complex numerical methods. Results can easily be queried and provide an analytical methodology which can be used to verify a given design or to conduct spot-checks.

However, these methods are limited in applicability and cannot be easily extended beyond their original scope, even in simple cases.

CBFEM – Component-Based Finite Element Method

The limitations referenced above have led to the development of the CBFEM (**www.cbfem.com**), which can balance modern design requirements by combining advanced numerical methods alongside analytical calculations. In CBFEM, joint design can be generalised by using a finite element (FE) engine alongside the conventional code checks specified in the relevant guidance. The method aims to be used by engineers of any level for the design of any steel connection topology.

The overall approach in CBFEM mirrors that of the component method: joints are decomposed into components that are modelled/simulated by utilising equivalent FE formulations, with each element type chosen to overcome the limitations discussed previously. However, a single CBFEM component may correspond to multiple classical components.

These components are presented in **Figure 1**.

FIGURE 1: Connection decomposed into components reflecting component method requirements

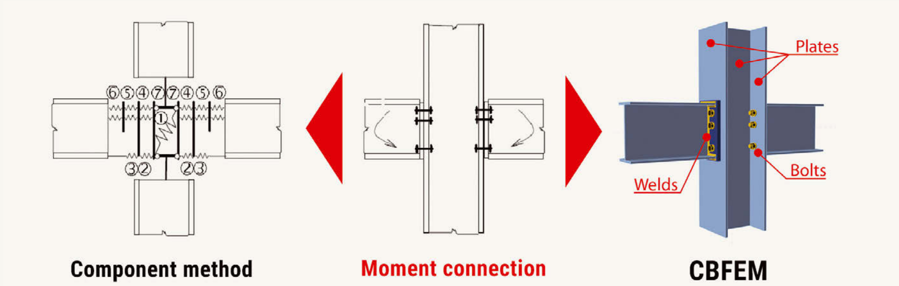
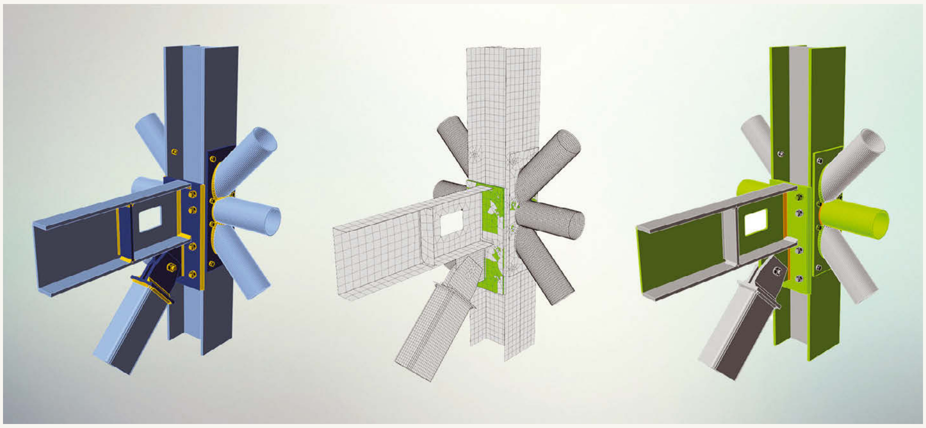


FIGURE 2: Demonstration of complex joint decomposed into separate plates with different mesh sizes, and checked according to code



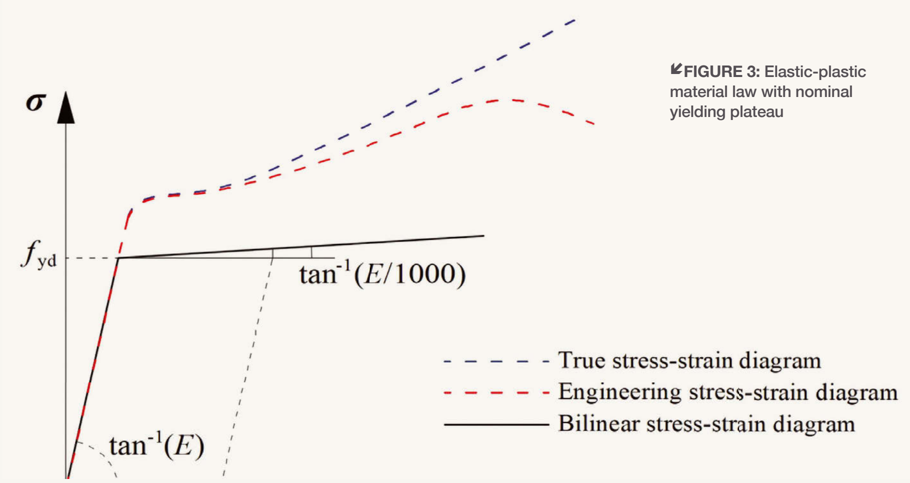


FIGURE 3: Elastic-plastic material law with nominal yielding plateau

Plate components (the material model)

A key deviation of the CBFEM from conventional methods is in how the steel plates are considered. The member sections are decomposed into plates and, along with the rest of the actual plates in a given joint model, are defined using shell element meshes, which can then be modified as required. This means that features present in the specifications can be included in the model and their impact on the joint response can then be accurately investigated as geometry requirements are fully respected **(Figure 2)**.

Additionally, a material non-linear analysis is performed to overcome the challenges posed by the discontinuity regions in these models. As CBFEM results are calibrated against the code, the elastic-plastic material with a nominal yielding plateau **(Fig. 2)** according to EN 1993-1-5, Par. C.6 (2) is adopted. This material model has a small slope to ensure calculation stability and is based on the von Mises yield criterion.

Design validity of steel plates is checked against a limit value of principal plastic strain **(Figure 3)**, and the method adopts the limit proposed in the code, equal to 5%, given that the corresponding plate is not susceptible to buckling.

The actual application at the shell element level requires their division into integration layers through the element thickness (at least five such layers). The plastic behaviour is then assessed at the integration point of each layer to determine the elastoplastic state of each shell element.

Although the magnitude of allowed plastic strain in steel can influence the joint capacity, parametric studies demonstrate that its influence is limited.

Based on material properties that are widely accepted, CBFEM is code-independent and applies as is or with minor modifications to multiple codes.

To ensure ease-of-use accuracy without requiring expertise, the methodology includes automatic mesh generation **(Figure 4)** developed after an extensive verification and validation process that guarantees results are on the safe side. These validations were performed with a maximum deviation from reference calculations of 5%, demonstrating that the proposed values performed very well without requiring modification.

Contacts

The contact between interacting plates has a major impact on the overall redistribution of forces in the connection. While not directly encountered in the standard component method, its effect is included in the code formulas. One such effect is the tensile stress increase in bolts as a result of plate surface interaction, i.e. prying forces.

In CBFEM the standard penalty method is recommended for modelling the contact between plates **(Figure 5)**. According to this methodology, penetration of nodes between plates in contact is prevented, as the solver checks their nodes during every non-linear iteration. If penetration is detected, a penalty stiffness is added via the contact springs and the contact force is redistributed between the two surfaces.

Bolts

CBFEM adopts a bolt model where every component of the bolt behaviour (tension, shear and bolt-hole bearing) is described by a set of interdependent non-linear springs.

The bolt in tension is described by a spring corresponding to its axial initial stiffness, design resistance, initialisation of yielding and deformation capacity. The axial initial stiffness is derived analytically from relevant guidance (VDI2230) and validated according to available experimental data – see Gödrich et al. (2014).

The spring model ensures that only compressive forces are transferred from the bolt shank to the bearing plate. This behaviour is implemented with interpolation links between the bolt shank nodes and hole edge nodes. The deformation stiffness of the shell element modelling the plates distributes the forces between the bolts and simulates the adequate bearing of the plate.

Additionally, standard bolt holes can transfer shear force in every direction while bolts in slotted holes allow this transfer along a single direction while moving freely along the other.

The analysis model allows for interaction between shear and axial forces within the bolts and the resulting force distribution, whereby bolts with high tensile forces have a reduced shear resistance and vice versa **(Figure 6)**.

Preloaded bolts are also supported. In this case, the shear force is not transferred via bearing but via friction between the gripped plates. Allowing for code compliance in the pre-slipping limit state as required.

Lastly, anchor bolts are modelled similarly to structural bolts fixed into concrete. For bolt stiffness calculation, the embedded length in concrete is recommended to be taken as 8·d (where d is a bolt diameter) according to the equivalent CM component (EN 1993-1-8).

Welds

Although many approaches are available for the CBFEM weld component, the most accurate one that allows the modelling of any weld geometry (partial welds, intermittent or full length) comprises a special elastoplastic element that respects the actual weld stiffness. Its thickness is calculated from

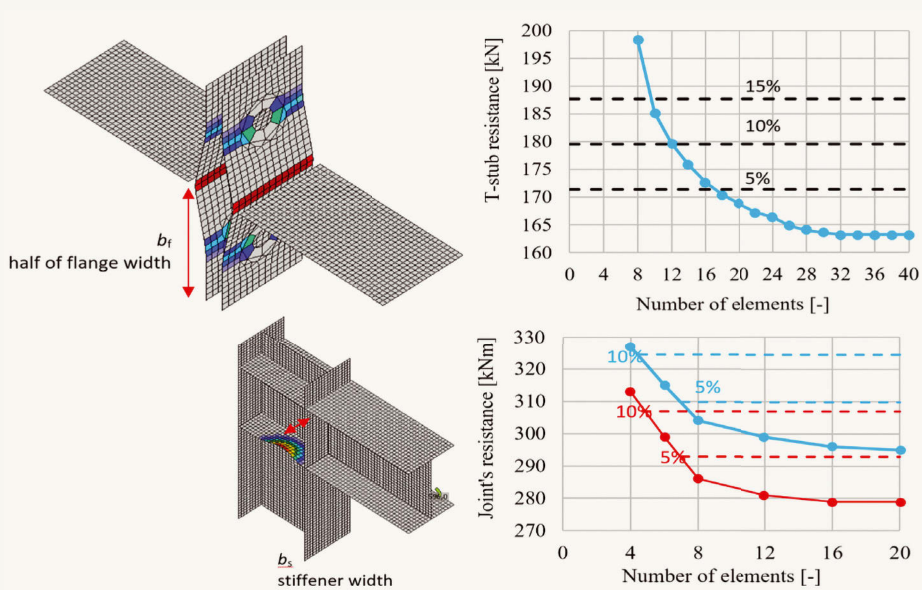
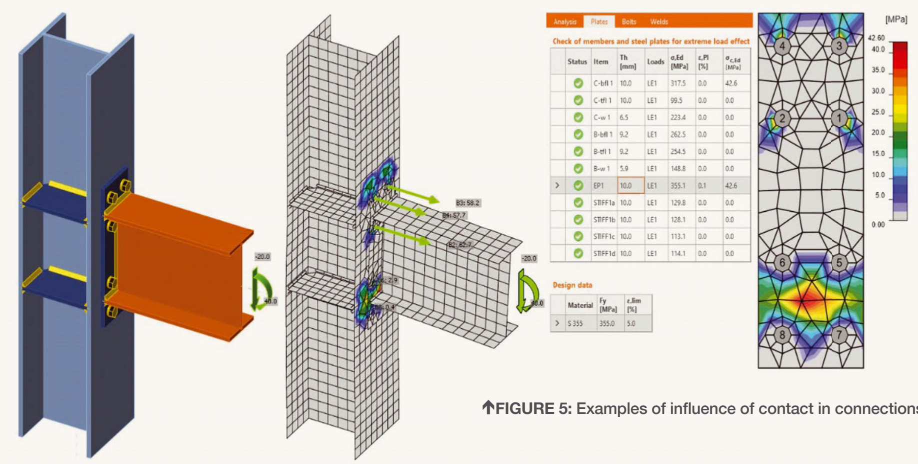


FIGURE 4: Parametric mesh sensitivity study

an equivalent weld solid following the actual weld dimensions.

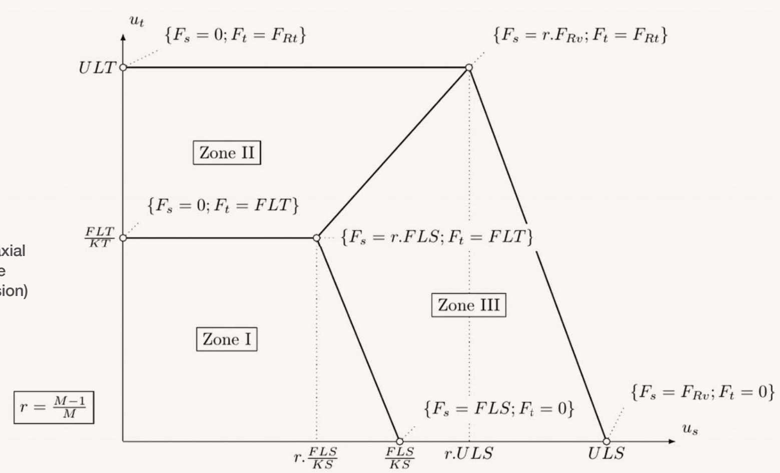
The weld plasticity state is controlled by stresses in the weld throat section and stress peaks are redistributed along the weld length when required.

The elastoplastic model of welds **(Figure 7)** provides the code-required values for weld verification directly from the analysis. The most stressed part of a weld is used for its verification with direct application of the code formulas.



↑FIGURE 5: Examples of influence of contact in connections

➔FIGURE 6: Example of interaction of axial and shear force (Eurocode version)



Analysis and loading

Joint models designed using the CBFEM approach are considered as an assembly of members in 3D space meeting at a single node. The members' orientation is not limited in 3D space, allowing the designer to model the joint as defined in the global analysis model. Loads can therefore be transferred directly from global analysis models or equivalent and, thus, applied loading respects equilibrium and reflects the boundary conditions of critical load cases accurately.

Since each joint is modelled in 3D, the precise location of joint components can be considered. This has a significant impact on the load distribution in some component types, such as bolts and welds, where the usual hand calculation results are heavily dependent on assumed stress distributions rather than calculated ones. It accounts for eccentricities that only exist in the connection model and thus impact behaviour without altering the global model, accurately reflecting boundary conditions of critical load cases and thus satisfying equilibrium criteria usually violated when using CM for ease of calculation.

In contrast to CM, CBFEM provides the designer with the capability to examine the joint behaviour under multiple critical load combinations for the true equilibrated loading without relying on overdesign.

Additional types of analysis

Buckling

Buckling should not be an issue for connection design for most cases. However, as the full development of the principal plastic strain up to its limit depends on the assumption that connection plates are not subject to buckling, a linear stability analysis is optional but recommended.

This calculation produces buckling modes under a critical load multiplier (α_{cr}). Using the resulting buckling modes and the relevant load multipliers, the designer can decide if the connection design is subject to buckling or requires stiffening to be able to develop the prescribed behaviour.

This methodology is also code-independent. However, code compatibility requires the adoption of different load multiplier limits for different codes.

Eurocodes, for example, recommend a critical load multiplier higher than 15 for steel structures. If the critical load multiplier is higher than 15, the model is considered safe.

For joints, however, there is no specific recommendation, and the above limit appears to be quite conservative. As such, guidance from research papers was adopted, leading to the use of load multiplier limits as low as 3 for local buckling modes (modes that correspond to failure that does not lead to structural collapse; **Figure 8**).

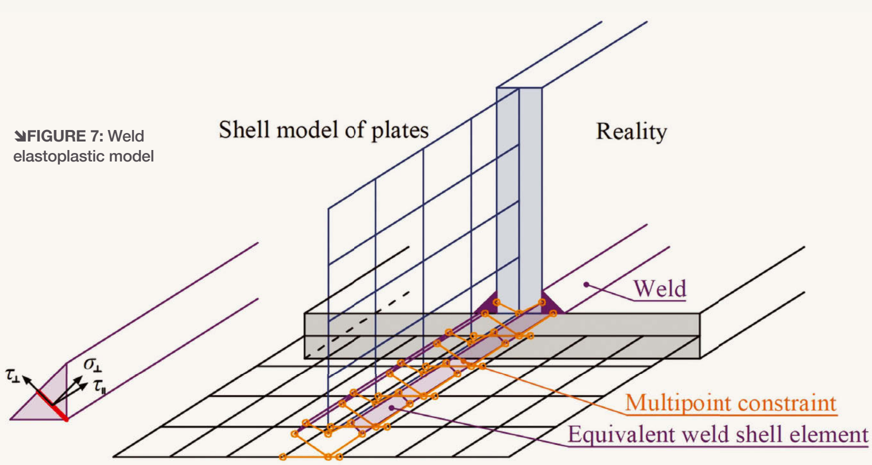
Stiffness analysis

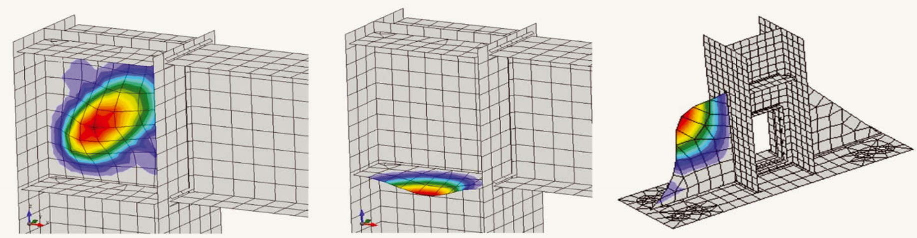
The Eurocode requires the joint classification according to its stiffness as rigid, semi-rigid or pinned. Further to this, classifying a joint as semi-rigid has implications for the analysis and design of the connected structural member: its actual stiffness must be considered in the global model as rotational springs corresponding to that connected member's relevant degree of freedom.

CBFEM supports this type of analysis for each connected member. The joint model changes in relation to the one used for the strength analysis by supporting every member other than the one analysed **(Figure 9)**. In line with the code requirements, stiffness analysis must be performed separately for each of the connected members.

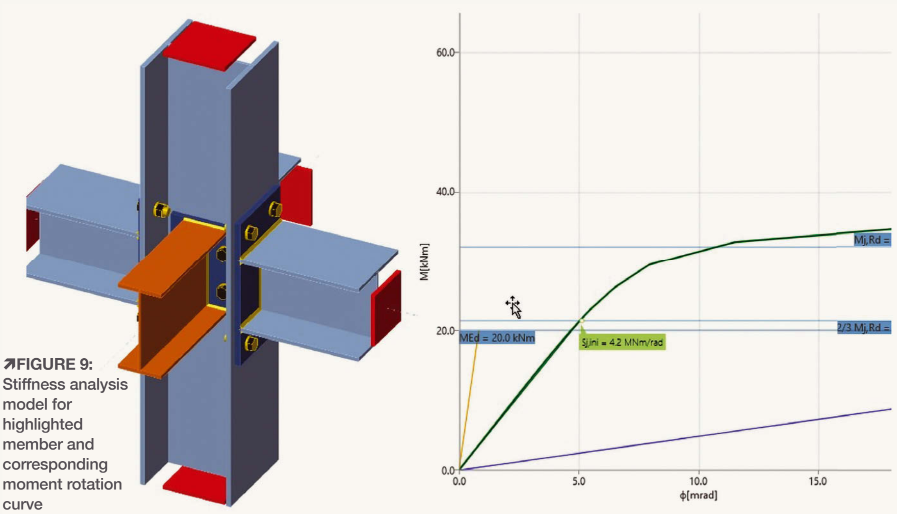
Then a non-linear analysis follows until failure due to violation of the principal plastic strain limit. For each analysis step, the moment rotation value pairs are recorded and, at the end of the analysis, plotted. Along with the moment-rotation curve, the stiffness classification limits are drawn for the

↘FIGURE 7: Weld elastoplastic model





↗**FIGURE 8:** Buckling modes corresponding to local modes of failure where load multiplier $\alpha_{cr} \geq 3$ is applicable



↗**FIGURE 9:** Stiffness analysis model for highlighted member and corresponding moment rotation curve

corresponding rotational component giving good insight into the connection behaviour.

A side-effect of the numerical analysis is that CBFEM can also calculate the axial and torsional joint stiffnesses. These could be useful in some cases; however, there is no guidance for their use in the context of the current codes.

Other types of analysis

The CBFEM approach provides a framework that has since been expanded to other types of analysis and cannot be covered in detail in this article:

- capacity design for assessment of the joint performance in seismic designs
- fatigue analysis
- joint resistance analysis, whereby the applied loads are increased proportionally until failure.

Conclusion

Using CBFEM, users can obtain results and conduct code checks of any connection topology while complying with the guidance requirements. Strict adherence to the existing provisions is favoured over a precise simulation of the physical model as part of the underlying method validation.

The overall impact of this is that users can optimise joint designs iteratively and integrate joint design prototyping as part of their standard design process.

Questions

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1) Which of the following are valid for the CBFEM analysis? (Select all that apply.)

☐ In principle, it decomposes the connection into components, just like the component method
☐ The methodology is limited and applies to specific connection geometries
☐ The mesh of the FE model must be manually defined by the user depending on the size of the joint
☐ This method strives for strict adherence to the guidance requirements

2) CBFEM is based on a material non-linear analysis. This analysis utilises a principal plastic strain limit for plate failure which (select all that apply):

☐ Was derived by research to precisely simulate the actual behaviour of steel connections
☐ Is taken from the current edition of the Eurocodes
☐ Is recommended to be modified by the designers according to their needs
☐ Applies to any code as it is a property of the material

3) Which are the major advantages of CBFEM regarding joint loading? (Select all that apply.)

☐ It utilises envelope loads to ensure a high safety margin
☐ Load can be defined under equilibrium reflecting an actual limit state derived from the global analysis
☐ Minor member eccentricities that are neglected in the global analysis are automatically accounted for
☐ The transfer of multiple load combinations from the global analysis is not recommended and can lead to overdesign

4) How are the prying forces accounted for in the context of CBFEM?

☐ They are neglected as their contribution to the capacity of bolts and plates is negligible
☐ Through the contact elements that are created between bolted plates, with the contact action increasing the tensile bolt force
☐ Tensile bolt forces are increased by a fixed percentage
☐ Specific formulas are used for different cases

5) Which of the following points hold for the stiffness analysis and classification of a joint? (Select all that apply.)

☐ Stiffness classification is a code requirement that does not have any impact on the original design
☐ CBFEM allows the classification of the member stiffness as rigid, semi-rigid or pinned
☐ The current Eurocode covers the calculation of bending, torsional and axial stiffness classification
☐ CBFEM calculates the stiffness of the joint separately for all the members

6) Which of the following is true for the weld component of the CBFEM?

☐ Welds are verified against specifically developed formulas that are part of the CBFEM method
☐ The most accurate approach is the one that redistributes excessive stress using elastoplastic elements following the actual weld behaviour
☐ Weld stress calculation follows an assumed distribution along the joint
☐ These elements do not respect the stiffness of the actual welds

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