CAPACITY DESIGN OF STEEL JOINTS

PROGETTAZIONE IN CAPACITÀ DEI GIUNTI IN ACCIAIO

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ABSTRACT

Joints in seismically active zones are designed with sufficient ductility to avoid brittle failure modes. Plastic hinge is assumed in one selected weakest element, e.g. a beam or an end plate. In the capacity design, the load resistance of all other elements is checked against forces which are necessary to create this plastic hinge. The selected weakest element is assumed with increased yield strength and with the assumption of strain-hardening. In the paper, application of the capacity design using the Component Based Finite Element Method is presented. The workflow is explained and verification using prequalified beam-to-column joints is provided.

SOMMARIO

Nelle zone sismicamente attive, i giunti sono progettati con una duttilità sufficiente per evitare modalità di rottura fragile. Si assume che la cerniera plastica si formi nell’elemento più debole selezionato, ad es. una trave o una piastra di estremità. Nella progettazione in capacità, la resistenza al carico di tutti gli altri elementi viene verificata rispetto alle forze necessarie per formare la cerniera plastica. Viene assunta una maggiore resitenza allo snervamentto e un comportamento incrudente per l’elemento più debole selezionato. Nell’articolo, viene presentata l’applicazione della progettazione in capacità utilizzando il Metodo a Elementi Finiti basato sulle Componenti. Il workflow è spiegato attraverso l’ultilizzo della verifica di nodi trave-colonna prequalificati.

1 INTRODUCTION

Buildings in seismically active zones must be safe even during a serious earthquake. Certain damage may be assumed on a structure but it must not collapse as a whole. Steel structures are suitable in earthquake zones because yield zones are able to dissipate a large amount of energy. Seismicity induces dynamic loads but practically, the seismic loads are assumed as static and part of the design seismic load combination according to EN 1990 [1].

Ductility class is selected for the structure. Low ductility class requires only a standard check for seismic load combination but nearly the full seismic load must be taken into account. This approach is rarely economical in high seismic zones. The seismic load may be lowered for middle ductility class because seismic energy is assumed to be dissipated by plastic deformations; see Fig. 1. Cross-sections class 1 or 2 may be used. High ductility class allows for the highest seismic load reduction but places the highest requirements on structural design and detailing. Only class 1 cross-sections must be used.

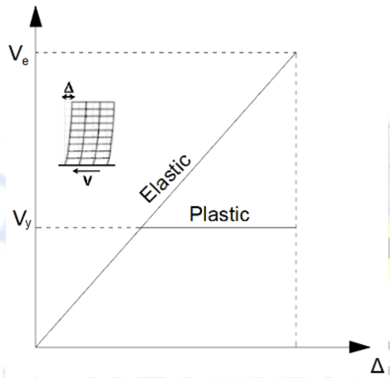

Fig. 1. Elastic (low ductility class) and plastic (middle and high ductility class) design: Decrease in seismic loads due to energy dissipation by plastic hinges

The reliability must be checked by capacity design for middle and high ductility class. Capacity design checks the load resistance of surrounding members and joints during the formation of plastic hinges in selected locations in the structure. It ensures that brittle failure mode is avoided and the structure behaves as intended. Plastic hinges are traditionally designed in beams, rarely in columns of the lowest and the highest floor, or in the joints. Furthermore, proven seismically resistant structural system must be used; that is usually moment resisting frame or frames with concentric or eccentric diagonal bracing.

This paper briefly describes the capacity design of beam-to-column joints in moment resisting frames using Component Based Finite Element Method (CBFEM) [2]. This method is a synthesis of the finite element method and Component method [3].

1.1 Design codes

Steel structures in seismically active zones are regulated by design codes EN 1993 and EN 1998; specifically for joints EN 1993-1-8 [3] and EN 1998-1 [4]. Code EN 1993-1-8 is predominantly focused on static loading and elastic structural analysis. EN 1998-1 provides additional rules for steel structures and unless stated otherwise, rules of EN 1993-1-8 apply also for design in seismically active zones.

2 CAPACITY DESIGN

Capacity design checks the load resistance of joint during the creation of a plastic hinge in the intended location. It is required for middle and high ductility class.
Joint is divided into three macro-components (see Fig. 2):

- Beam
- Connection (e.g. end plate with stiffeners, bolts, and welds)
- Column web panel

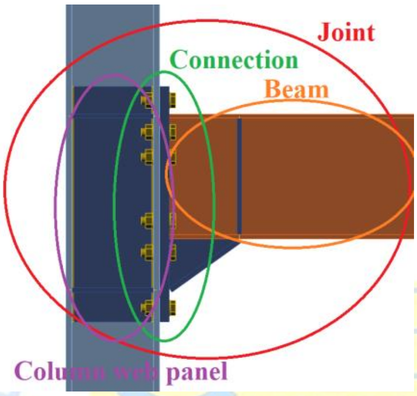

Fig. 2. Macro-components in the joint

Traditionally, the plastic hinge is intended in the beam, which is restrained against buckling. The connection and column web panel must transfer the bending moment that will presumably cause the plastic hinge in the beam and corresponding shear force. According to EN 1998-1: 2005, joints are verified experimentally. In project EQUALJOINTS [5], traditional European joints were thoroughly experimentally and numerically investigated. In some cases, the plastic hinge is intended in end plate, column web panel or in more locations at the same time. The probable instead of design material properties are used for determining the load causing the plastic hinge. The characteristic yield strength is multiplied by two factors – overstrength factor γ_{ov} and strain-hardening factor γ_{sh}. It is recommended to use γ_{ov} = 1.25 and γ_{sh} = 1.2 (EN 1998-1 recommends the value of 1.1 and EN 1993-1-8 the value of 1.2) for most commonly used steel grade for seismic applications S355. Increasing the material properties of the dissipative item, the probable bending moment and the corresponding shear force may be applied. Other elements must safely transfer this load.

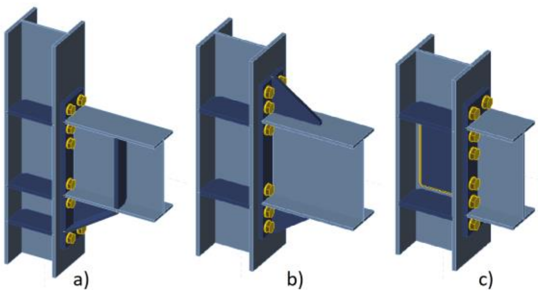

Fig. 3. a) Haunched joint, b) Extended stiffened end plate joint, c) Unstiffened end plate joint

It is absolutely essential to avoid brittle failures, especially welds and bolts must be designed as full-strength. The type and size of governing welds are prescribed – usually full penetration butt welds with added fillet welds at beam flange to end plate or column flange; see Fig. 4.
The connection and column web panel are classified according to bending resistance of the beam to full, equal or partial strength. Until now, the beam was the weakest link and the connection and column web panel were designed as full-strength. Project EQUALJOINTS presents also joints with equal or partial strength. One of the three prequalified bolted joints may be used; see Fig. 3.

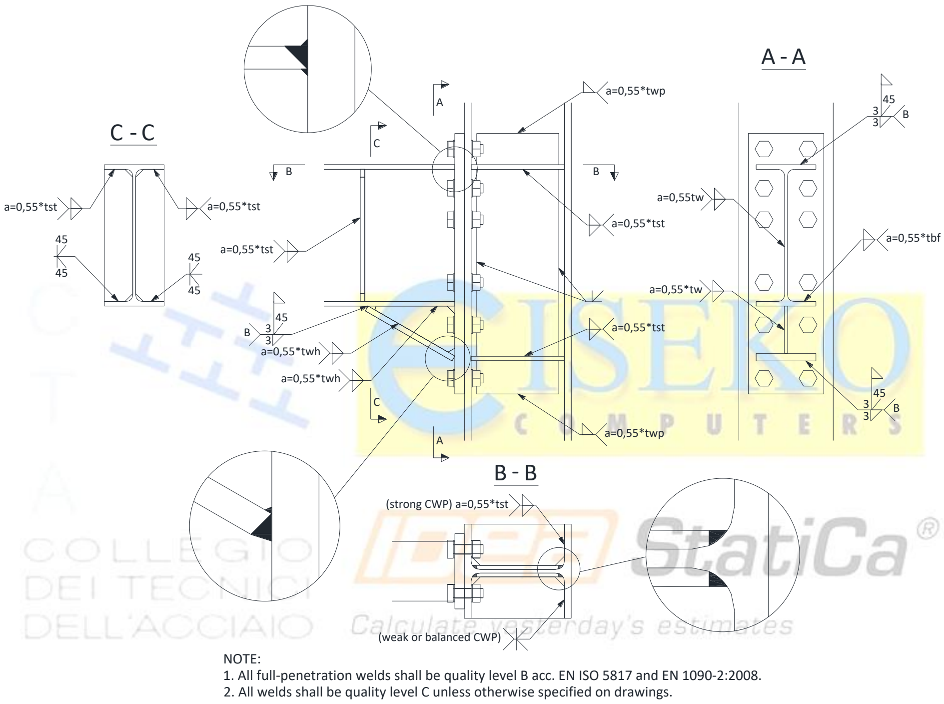

Fig. 4. Prescribed weld types and sizes for a haunched joint with stiffened column web panel [5]

3 PRACTICAL EXAMPLE: HAUNCHED JOINT

3.1 Geometry and loading

The haunched joint was selected for a practical example. It is taken from the ECCS manual [6] – Example 4.2. Its geometry is shown in Fig. 5. The joint is designed as full-strength and plastic hinge is intended to appear behind the haunch. All welds are prescribed in EQUALJOINTS manual, critical welds are full penetration butt welds, single-bevel type welds are reinforced by fillet welds; see Fig. 4. Welds have higher strength than the connected parts. An end plate is connected by 12 bolts M30 grade 10.9. The haunch is with the recommended slope of 35°. The thickness of the haunch flange is 18 mm which is thicker than that of beam flange, 14.6 mm. End plate thickness, 30 mm, is higher than the column flange thickness, 21.5 mm. The column web is reinforced by doublers with a thickness of 10 mm from both sides. The doublers are welded to both column web and flanges.

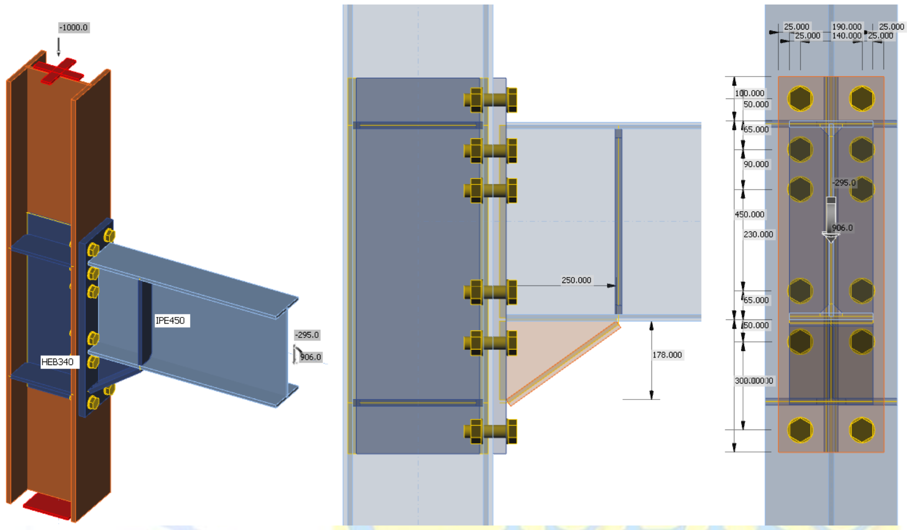

Fig. 5. a) Haunched joint, b) Extended stiffened end plate joint, c) Extended unstiffened end plate

Capacity design checks the joint against the load necessary to create a plastic hinge in the dissipative item – in this example in the beam. Plastic hinges appear gradually in floors – see Fig. 6. All joints and beams should be the same in moment resisting frame against seismic loads so that the plastic hinges appear at similar load.

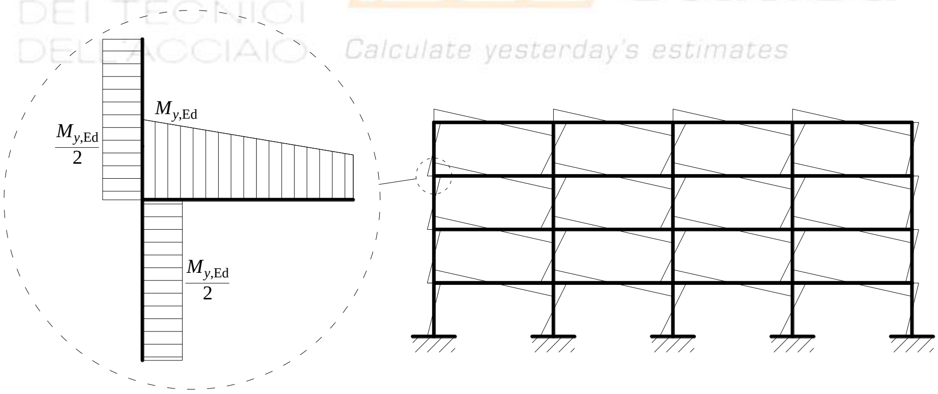

Fig. 6. The course of bending moments at the moment resisting frame at the moment of plastic hinge creation and simplified equivalent load at the segment of the joint

Plastic hinge is expected directly behind the haunch. The bending moment that creates the plastic hinge is $M_{\mathrm{b,pl,Rd}} = \gamma_{\mathrm{ov}}\, \gamma_{\mathrm{sh}}\, f_{\mathrm{yk}}\, W_{y,\mathrm{pl}}$, where f_{yk} is the characteristic yield strength and $W_{y,\mathrm{pl}}$ is the plastic section modulus of the beam around the stronger axis. The bending moment acting on connection and column web panel is increased by the shear load and it is important to correctly set the position of load application. Plastic hinge appears at distance s_h' from the node of the joint. The joint is loaded by corresponding shear load $V_{z,Ed} = -2\ M_{b,pl,Rd}\ /\ L_h$, where L_h is the distance between two plastic hinges on the beam. The bending moment in the node is $M_{y,Ed} = M_{b,pl,Rd} + V_{z,Ed}\ s_h$'; see Fig. 7. Other members are loaded by loads other than seismic from the seismic load combination, usually self-weight, other permanent loads and a portion of imposed loads. In this example, the column is loaded by an axial force N_{Ed} = 1 000 kN. Within the capacity design, two load effects are investigated: a)horizontal movement to the right: $-M_{y,Ed}$ and $+V_{z,Ed}$ and b) horizontal movement to the left: $+M_{y,Ed}$ and $-V_{z,Ed}$.

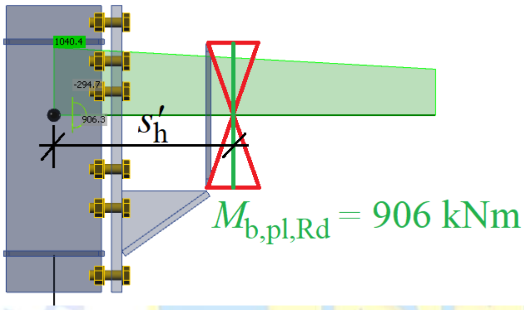

Fig. 7. The course of bending moment; estimation of plastic hinge location

3.2 Results

From the results of software using CBFEM, it can be seen that plastic hinge appears in the intended place just behind the haunch; see Fig. 9. The plastic strain in the hinge is around 5 % so the set load is correct. All checks of connection and column are passing. The biggest plastic strains are in the haunch (1.6 %) and in the column flange (1.3 %) which is below the plastic strain limit of 5 %. Bolts are utilized at 97 %. The most stressed bolts are at the haunch at sagging bending moment. Considering the modification of the material diagram in the dissipative item, i.e. increase in yield strength and assumption of strain-hardening, it is expected that most plastic deformations will occur in the beam in cyclic loading during an earthquake.

The results of CBFEM correspond to the results of the Component method shown in [6] according to EN 1993-1-8 [3]. Neither Component method nor CBFEM can assess the brittle failure, e.g. in heat affected area, or low-cyclic fatigue. Thus, the joint shape and detailing should conform to prequalified joints for seismic applications [5], which are validated by a sufficiently large set of experiments; see Fig. 8.

Fig. 8. Photographs from experiments of haunched joints [5]

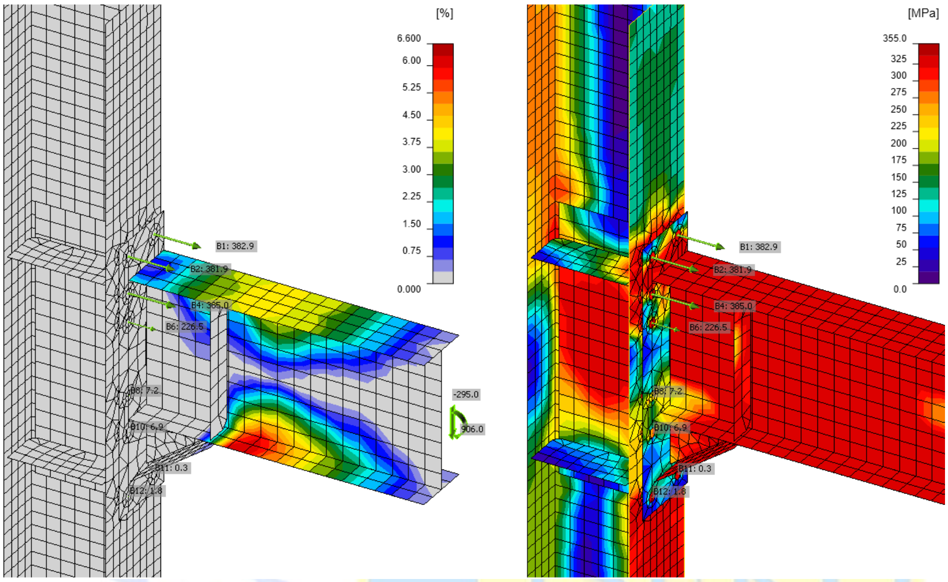

Fig. 9. Plastic strain (on the left) and equivalent stress (on the right)

3.3 Verification and validation

The design of seismic joints follows the guidelines of EN 1993-1-8 [4] so all the verification studies performed for standard joints are valid [2]. The validation of CBFEM method specifically for joints for seismic applications was performed on the set of selected experiments of EQUALJOINTS project [5]. In Fig. 10, it can be seen that all the CBFEM results are conservative and close to the experimental results.

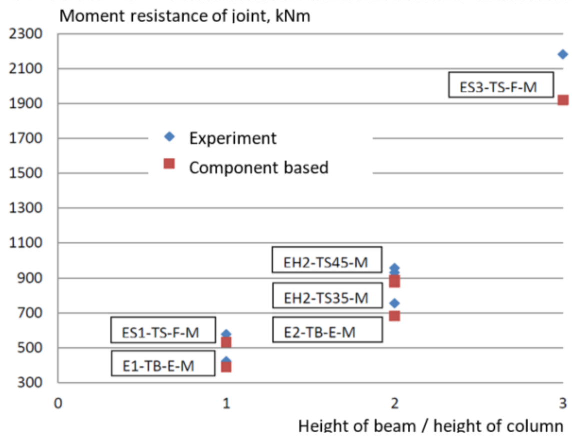

Fig. 10. Comparison of maximum bending resistance by CBFEM with experiments [5]

4 CONCLUSIONS

Load-bearing structure in seismically active zones is designed for load combinations in seismic design situations. If seismic actions are strong, selection of medium or high ductility class is economical, which allows a significant reduction of seismic actions by the assumption of energy dissipation in plastic hinges. Then it is necessary to prove that no brittle failure mode will occur in the structure. The most susceptible are joints which are checked by capacity design.
It is possible to use the Component based finite element method for capacity design. Material properties of the dissipative item are strengthened to allow the transfer of probable bending moment and corresponding shear force that generate a plastic hinge. All the non-dissipative components must pass regular checks.
Capacity design using manual calculations in Component method checks only one particular connection against bending moment and corresponding shear force and does not take into account loads on other members in the joint. On the other hand, CBFEM allows checking of arbitrary load combinations, e.g. with added normal force in the column.

ACKNOWLEDGMENT

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KEYWORDS

Steel joints, seismicity, capacity design, Component based finite element method, Component method