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NUMERICAL MODELLING OF BEAM-COLUMN CONNECTIONS AT MULTI-STOREY COMPOSITE STRUCTURES

NUMERIČKO MODELOVANJE SPOJA GREDA - STUB VIŠESPRATNE KOMPOZITNE KONSTRUKCIJE

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Keywords
- multi-storey structures
- beam-column connection
- frame
- plastic hinge

Abstract

In this paper are presented the theoretical analysis and numerical modelling of the connection between composite beams (steel beams connected with the reinforced concrete slab) and the steel column. Based on analysis by numerical modelling and experimental research of the composite connection model of multi-storey frame structures, corresponding conclusions are obtained and presented.

Ključne reči
- višespratna konstrukcija
- veza greda - stub
- rešetka
- plastični zglob

Izvod

U ovom radu su prikazani teorijska analiza i numeričko modelovanje veze između kompozitne grede (čelična greda spojena sa pločom od armiranog betona) i čeličnog stuba. Na osnovu analize, dobijene numeričkim modelovanjem i eksperimentalnim istraživanjem modela kompozitne veze višespratne rešetke konstrukcije, dobijeni su i prikazani odgovarajući zaključci.

INTRODUCTION

With the beginning of the third Millennium the traffic and population increased, so did the need for buildings and motorway structures. The building space in the centres of the large towns became tight and its price has increased. At the same time the "highest buildings" became an aspiration and prestige of structural designers. The use of multi-storey composite structures (steel columns and beams, and reinforced concrete slabs) became a necessity. The multi-storey composite structure is used for different types of buildings such is office, industrial and public buildings, high-rise parking buildings. These kinds of buildings are built all around the world, mainly in highly developed countries, depicting their financial and technical power.

COMPOSITE STRUCTURES

Composite structures provide a compromise between the tradition and the safety. They are with higher ductility than the concrete structures, and more rigid than "pure" steel structures. Composite structures are fire resistant as well.

The safety and function expressed through the control of the mass, stiffness, strength, and ductility at the structural design of multi-storey composite structures, and mostly of the connections of elements exposed to cyclic-horizontal loads (such is earthquake, wind loads) in combination with other loads is recognized as of high priority for these kinds of structures (buildings). Multi-storey composite structures are shown in Figs. 1–4.

Figure 1. High-rise parking building (under construction).
Slika 1. Višespratno parkiralište (u izgradnji)

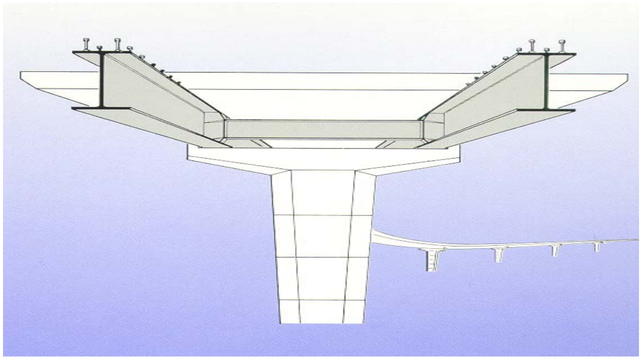

Figure 2. Bridge (steel HE-beams + reinforced concrete slab).
Slika 2. Most (čelične HE-grede + ploča od armiranog betona)

Figure 3. Skyscrapers in Chicago, USA.
Slika 3. Oblakoderi u Čikagu, SAD

DESIGN CRITERIA FOR DAMAGE AND COLLAPSE FOR BEAM-COLUMN CONNECTIONS

The demands of new codes in the numerical modelling of beam-column connection /1/ are incorporated, which is the well-known concept of the seismic resistant structures that proposes development of plastic hinges in the beams, and rarely in the part of the columns. Consequently, the size of the static influence dictating the order of the plastic hinge appearance should be taken into consideration, i.e. column bending strength should be larger then beam bending strength. For each beam-column connection the following equation should be satisfied, /2/:

$$\sum M_{R,c} > \sum M_{R,b} \quad (1)$$

where $\Sigma M_{R,c}$ is a sum of applied bending moments in the column, and $\Sigma M_{R,b}$ is a sum of bending moments in the beams in the connection point. With the alternative of the mechanism of collapse (the order of the element's plastification) and generally the mechanism of energy dissipation, two different approaches exist.

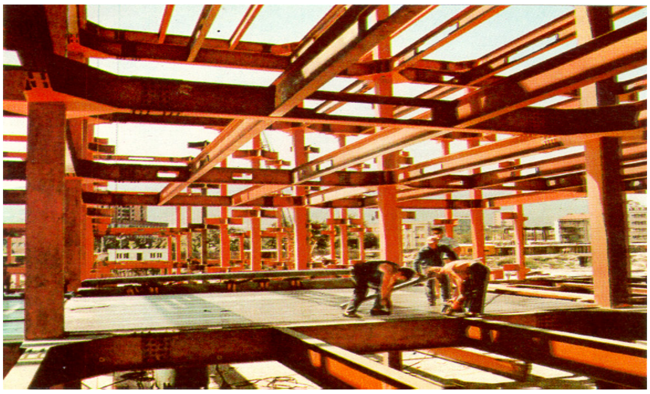

Figure 4. "GTC" in the centre of Skopje (under construction).
Slika 4. „GTC" u centru Skoplja (u izgradnji)

The first is based on the contribution of the panel–zone (Fig. 5) into the energy dissipation with the purpose of its reduction and also accepting a part of plastic deformations, without excluding the contribution of the columns and the beams. The second approach excludes the panel zone into the energy dissipation. As a result, in this case, the end parts of the beam should accept the plastic deformations. Accordingly, the beam–column connection should be specified in detail.

Design of beam-column connection without the contribution of the panel-zone into the energy dissipation

Supposing that the shearing stress is equally distributed in the panel-zone (part of the web of the column between the two beams). Shearing stress developed in the panel-zone is presented as follows:

$$\tau_p = \frac{V_p}{(d_c - 2t_{cf})t_p} \quad (2)$$

where V_p is a shearing force into the panel-zone at the steel beam-column connection (Fig. 5, left),

$$V_p = \frac{\sum M_b}{(d_b - t_{bf})} - V_c \quad (3)$$

In the beam-column composite connection (Fig. 5, right), V_p is a shearing force in the columns designed through the assumption that the zero-moment is located in the middle part of the column section.

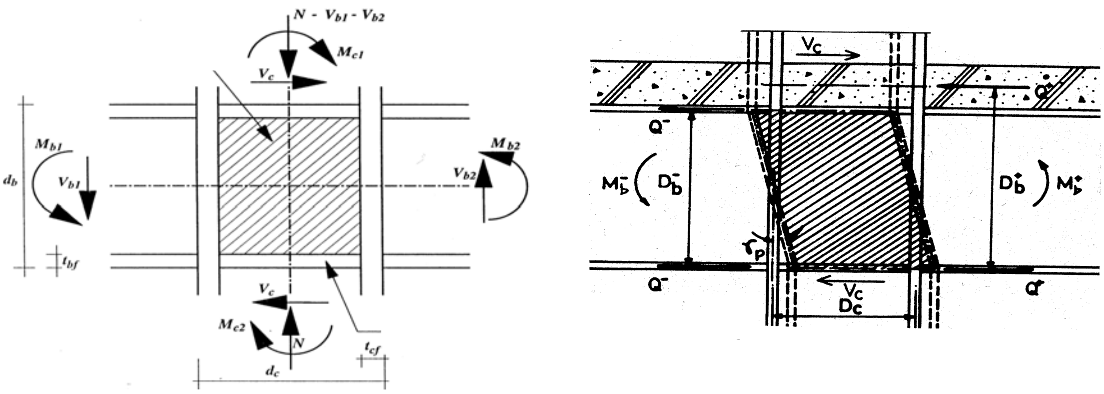

Figure 5. Shearing force in the beam-column connection: in the panel-zone (left) and in the composite connection (right).
Slika 5. Sila smicanja u panel zoni spoja greda-stub: u panel zoni (levo) i u kompozitnom spoju (desno).

$$V_p = \frac{M_b^+}{(d_b - t_{bf})} + \frac{M_b^-}{d_b^{'}} - V_c \tag{4}$$

Consequently, taking into consideration the balance of $\Sigma M_b = \Sigma M_c$, the result is as follows:

$$V_p = \frac{\sum M_b}{(d_b - t_{bf})}\left(1 - \frac{d_b - t_{bf}}{H - d_b}\right) \tag{5}$$

and the average shear stress in the panel-zone is:

$$\tau_p = \frac{\sum M_b}{t_p (d_c - 2t_{cf})(d_b - t_{bf})}\left(1 - \frac{d_b - t_{bf}}{H - d_b}\right) \tag{6}$$

With the main purpose the yielding to occur only in the beam and not in the panel-zone, which is a better solution, according to the Mises-criteria, it follows:

$$\frac{\sum M_{R,b}}{t_p (d_c - 2t_{cf})(d_b - t_{bf})}\left(1 - \frac{d_b - t_{bf}}{H - d_b}\right) \le \tau_y \left(1 - \left(\frac{N}{N_y}\right)^2\right)^{1/2} \tag{7}$$

where $M_{R,b}$ is the sum of the applied bending moments in the beams connected with the column, N – axial force in column, N_y – axial yielding force of pressure.

So, the thickness of the panel zone, t_p, including eventually double slabs, can be calculated.

Beam-column connection should be designed in detail. As an example, the completely welded beam-column connection is relatively rigid, thus in case of small deformation (i.e. deflection) a collapse of the connection will occur. It can be concluded that properly designed connection get together a significant bearing capacity which is in direct correlation with both stiffness and connection ductility. The dependence of the bending moment from rotation at the end of the beam–column connection is one of the most important diagrams for the connection characteristics.

Hysteresis diagrams as a result of the numerical modelling

Three types of elements are used (Type 2, Type 4 and Type 15 from DRAIN-2DX) for numerical modelling of the composite connections, /1/. Modelling of columns is through determination of their geometric and static characteristics using the standard beam-column element – Type2 from DRAIN–2DX, /2/, i.e. designed in the elastic zone. The flexibility of the joint is modelled using the element of the panel–zone. In addition, the panel zone contains rotation spring that connects the beams with the column. With this element so-called "simple connection – element" – Type 4 form DRAIN-2DX /2/, the ductility of the connection through the functional dependence of the bending moment in the joint and the beam-column rotation are controlled, i.e. the stiffness of the connection panel–zone of the beams and the column in the elastic and plastic area, as well as the strain hardening of the material. The steel beam and its end, i.e. defining the length of the plastic hinge (the length of the plastic and elastic part of the beam) is modelled with usage of the element Type 15 from DRAIN 2DX, /3/.

The concrete slab has an influence on the stiffness of the composite beam at positive bending moment, while the reinforcement from the concrete slab has an influence on the stiffness of the connection at a negative bending moment.

As specified in the EC3, /4/, the determination of the designed characteristics of the moment-rotation for the beam-column connection should be in accordance with the theory and supported with experimental research (Figs. 6-8). The importance of experimental research is particularly considerable in the composite connection mostly for the reason of the real characteristic of the moment – rotation of the composite beam (i.e. steel beam + reinforced concrete slab) connected with the steel column.

Figure 6. Specimen SP1, in a system for quasi-static loading.
Slika 6. Uzorak SP1, u sistemu kvazistatičkog opterećenja

Figure 7. Specimen SP2, collapse of reinforced concrete.
Slika 7. Uzorak SP2, kolaps armiranog betona

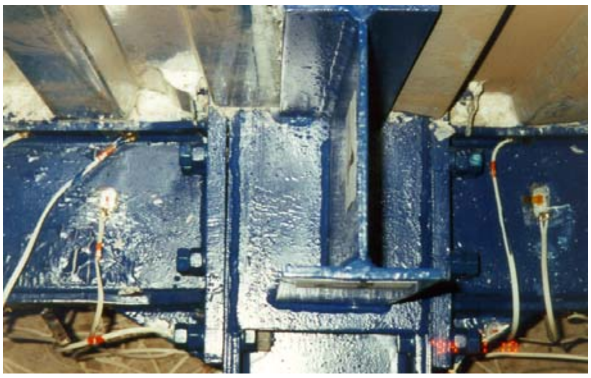

Figure 8. Plastic hinge in web at the end of the beam.
Slika 8. Plastični zglob u rebru na kraju grede

With the moment–rotation diagram (Fig. 9) for the beam-column connection, the following characteristics should be defined: maximal bending moment, rotation stiffness and rotation capacity. Where, K^+ – initial stiffness at M_y^+ (elastic area); K^- – initial stiffness at M_y^- (elastic area); α_1 – coefficient for design stiffness in plastic area at M^+; α_2 – coefficient for design stiffness in plastic area at M^-; M_y^+ – positive yielding moment of bending; M_y^- – negative yielding moment of bending; M^+ – positive moment in plastic area, M^- – negative moment in plastic area.

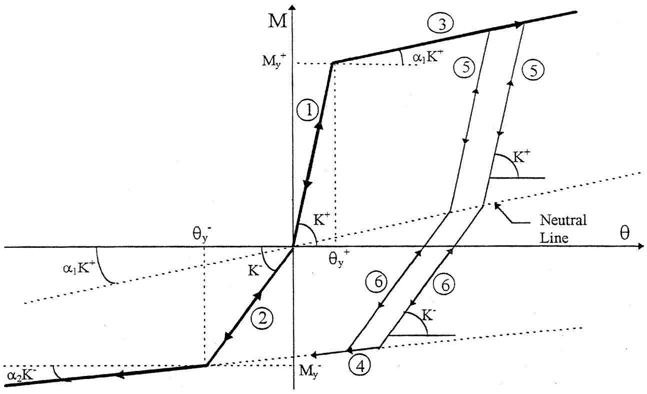

Figure 9. Theoretical *M-Φ* (moment-rotation) diagram for composite beam-column connection.
Slika 9. Teorijski dijagram *M-Φ* (moment-rotacija) za kompozitni spoj greda-stub

Global hysteresis diagrams of the analytical model of the connection between composite beams (IPE 300) and steel column (HEM 260) are given in Figs. 10 and 11. Comparing the global hysteresis diagram with the diagram of experimental quasi-static research (Fig. 11), which is the final step of this numerical design in correlation with the experimental research, i.e. calibration of results, a good agreement between the curves is found.

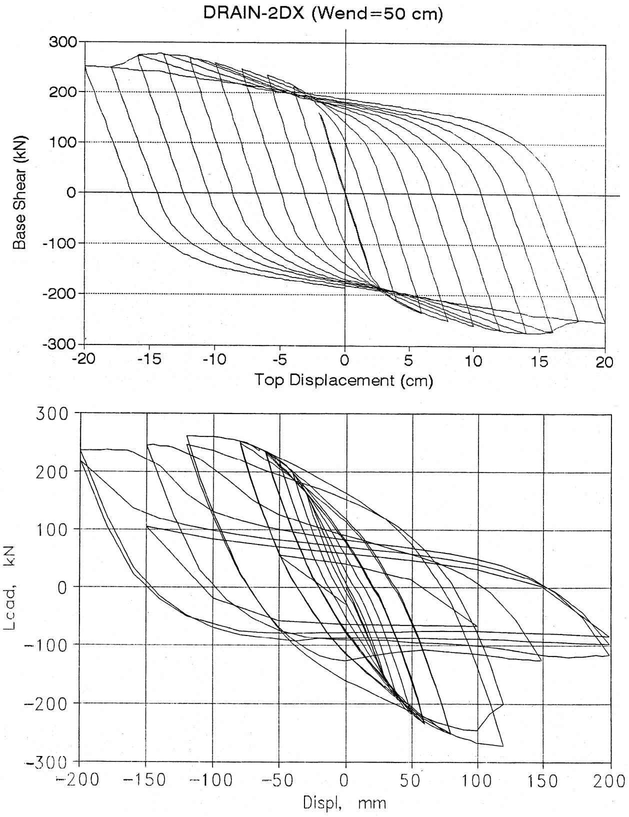

Figure 11. Hysteresis in diagram base shear–top displacement (theoretical – top, experimental – bottom).
Slika 11. Histerezis u dijagramu smicanje osnove–pomeranje vrha (teorijski – gore, eksperimentalno – dole)

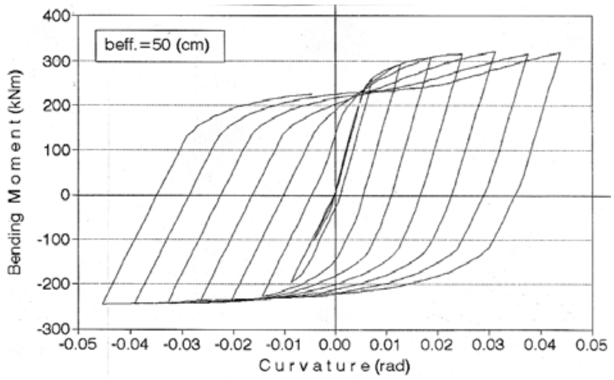

Figure 10. Hysteresis in diagram moment–curvature (theoretical).
Slika 10. Histerezis u dijagramu moment–krivina (teorijski)

CONCLUSIONS

In the numerical modelling of the beam-column connection the existing codes that present the universally recognised concept (i.e., bending strength of columns to be bigger than the bending strength of beams) is incorporated.

Also, with the research presented in /1/, the following design concept of composite frames is accepted: composite frames, their connections (beam-column) are designed so that columns are in elastic area and the energy dissipation is in the ends of the beams, thus the collapse of each one multi storey frame is not a collapse of the whole structure.

With the comparison of theoretical and experimental analysis, /1/, it is concluded that the length of the plastic hinge at the end of the beam is from $d_b/2$ to $d_b/3$ (10–15 cm), where d_b is the height of the beam.

The influence of the effective width of the concrete slab (b_{eff}) on the end of the beam (which is activated under the activity of positive bending moment if the concrete is pressed) on the whole stiffness of the structure and at the activity of lateral loading, is also taken into consideration in this research.

The result is as follows: the width of the concrete slab on the end of the beam is significantly narrower then its value in the middle of the span (determined as of EC4: $b_{eff} = L/4$, where L is a span – the distance between columns) and its value is between b_c and $1.8b_c$, b_c is width of column flange.

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