1st Croatian Conference on Earthquake Engineering
1CroCEE
22-24 March 2021 Zagreb, Croatia

DOI: https://doi.org/10.5592/CO/1CroCEE.2021.116

Experimental and numerical assessment of reinforced concrete column under cyclic loading

Eldin Kaloper[1], Edhem Živalj[2], Senad Medić[3]
[1] *Mag.ing.aedif.*, GEOKONZALTING Ltd, *kaloper27@hotmail.com*
[2] *Mag.ing.aedif.*, FABING Ltd, *edhemzivalj@gmail.com*
[3] *Assistant Professor*, Faculty of Civil Engineering, University of Sarajevo, *senad_medic@yahoo.com*

Abstract

In this paper a nonlinear finite element analysis of reinforced concrete frame elements exposed to monotonic and cyclic loading is presented. The analysis was executed using 3D solid elements in DIANA FEA and frame elements with localized nonlinearities in SAP 2000. The results were verified against the experimental testing conducted at the Institute for Materials and Structures of the Faculty of Civil Engineering University of Sarajevo. The static cyclic tests include nine cantilever beams (20/20/200 cm) reinforced with the same longitudinal reinforcement and different transverse confining reinforcement. Occurrence and development of cracks on the beams were monitored and mapped during the experiments. Major cracks localize in the plastic hinge whose length is roughly equal to cross-sectional height. This observation matches well with the recommendations given in EC 8. The influence of the normal force according to the first and second order theory, the percentage of longitudinal reinforcement, the arrangement of stirrups on the load bearing capacity and ductility of the elements were analysed. Maekawa - Fukuura constitutive model was assumed for concrete while embedded reinforcement was simulated using von Mises, Menegotto - Pinto, Monti - Nuti and JSCE 2012 material models depending on monotonic or cyclic loading protocol. The effect of simple and specially dedicated reinforcement models capable of reproducing buckling or Bauschinger effect on the column behaviour is significant. The influence of mesh density and iterative approach on crack localization and crack width was investigated. The performance of smeared cracking approach and localized nonlinearity concept was critically assessed.

Key words: Experimental testing, nonlinear FEA, RC column, smeared cracking, 3D solid, DIANA FEA, SAP2000

1 Introduction

In earthquake design it is often required to carefully shape the potential plastic hinge zone in order to avoid brittle failure of load-bearing elements or collapse of entire building. Therefore, it is necessary to ensure the redistribution of bending moments from more stressed to less stressed elements.

Generally, the ductile behaviour of a cross-section (local ductility) causes a ductile response of the entire structure (global ductility). Sections tend to behave in a ductile manner if tensile reinforcement yields before concrete starts to crush. The combination of high compressive stress and large reinforcement area (over reinforced section) reduces cross-sectional curvature capacity and leads to brittle or unannounced failure. In order to achieve the desired ductility of a plastic hinge where major cracks localize, it is important to provide sufficient transverse reinforcement. The role of transverse reinforcement is not only to resist shear forces but also to confine concrete, i.e., to prevent transverse deformation and introduce triaxial compression stress state in concrete. Theoretical M-N-κ curve can be obtained if constitutive laws of concrete and reinforcing steel are given. The concrete cover is unconfined and it is assumed to be ineffective upon reaching the ultimate compressive stress of concrete. On the other hand, the triaxially compressed (confined) area of concrete cross-section provides resistance even for very large strains. The effect of compressive normal force is twofold: it increases the load bearing capacity and reduces the ductility.

The aim of this research is to experimentally and numerically analyse the effects of different transverse reinforcement layouts on the behaviour of concrete beams subjected to cyclic loading without axial force. A total number of tested beams is nine and experimental research was conducted using specially designed auxiliary steel structure in the laboratory of the Institute for Materials and Structures, Faculty of Civil Engineering, University of Sarajevo. Dimensions of a typical beam are 20x20x200 cm and in terms of the static system the beam can be assumed as a cantilever. All beams have the same longitudinal reinforcement. The difference between the groups lies in the form and arrangement of transverse reinforcement. The first group was reinforced according to EC 2 [1] where low ductility is assumed. The second and the third group of beams were reinforced according to the rules of EC 8 [2] for DCM (medium class ductility).

2 Experiments

Beams were divided into three groups as follows: S1, S2 and S3 (Fig.1). Typical cracking pattern is displayed in Fig.2 with localization of damage in the plastic hinge zone. Crushing of concrete cover was observed, however, concrete confined by stirrups retained its integrity. Details of experimental campaign are explained in [3].

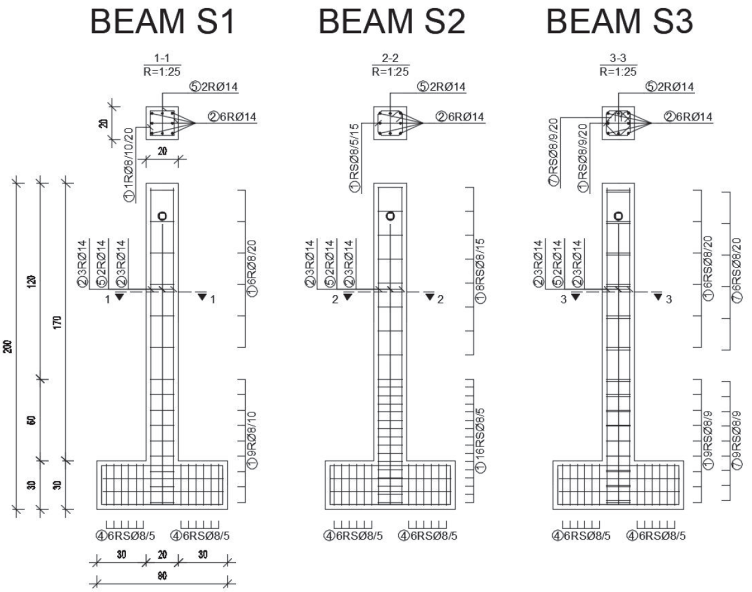

Figure 1. Reinforcement plan of the tested beams

Figure 2. Localization of cracks in the plastic hinge zone of S3-A beam (front and side view)

3 Numerical modelling

The establishment of an appropriate mathematical model for the analysis of an engineering problem is to a large degree based on sufficient understanding of the problem under consideration and a reasonable knowledge of the finite element procedures available for solutions. This observation is particularly applicable in nonlinear analysis because the appropriate nonlinear kinematic formulations, material models and solution strategies need to be selected.

3.1 SAP 2000

Beams consist of three different materials: confined concrete, unconfined concrete (cover) and reinforcement. Nonlinear behaviour within the cross-section affects the nonlinear behaviour of the entire load bearing structure. This is especially true for structural elements such as frames, where extreme internal forces are often concentrated on the element ends. Hence, one can assume that the nonlinear behaviour can be concentrated in a single cross-section (plastic hinge). Integration of normal stresses in fibers along the height of cross-section with respect to deformations yields a moment-curvature (M-κ) diagram [4]. However, if analysis with localized nonlinearity in a plastic hinge is applied, M-Ø (moment-rotation) relation must be defined instead of M-κ relation by multiplying the curvature with the assumed length of the plastic hinge. This length can only be estimated. According to [2], the length of the critical area l_{cr} (plastic hinge) is equal to the beam depth h_w.

Linear σ-ε diagrams for concrete are largely used to obtain cross-sectional forces in reinforced concrete structures while the reinforcement is ignored. However, the actual behaviour of materials (concrete, reinforcement) described by σ-ε diagrams is nonlinear and adequate constitutive relations should be used for accurate determination of cross-sectional forces. Mander's model for concrete [5] and Simple model [6] for reinforcing steel were used in this paper. According to Mander, confined and unconfined concrete have different compressive stress and strain limits due to the presence of confining reinforcement. The cross-section is divided in the corresponding materials as shown in Fig. 3a.

Nonlinear properties of the plastic hinge placed at the beam fixed end were assigned using a link element. Time record of imposed displacements on the beam top was used for Time-History analysis. Takeda model was selected for modelling hysteretic behaviour of reinforced concrete (Fig. 3a). It is a sophisticated model that takes into account the stiffness degradation and makes a distinction between big and small cycles of hysteretic curve [7].

When maximum forces (reaction at the fixed end) obtained using numerical model are compared against the experiment, there are no significant differences as it is shown in Fig. 3b. The maximum force of 31.76 kN was obtained using the numerical model while the maximum force of 35.36 kN was obtained in the experiment.

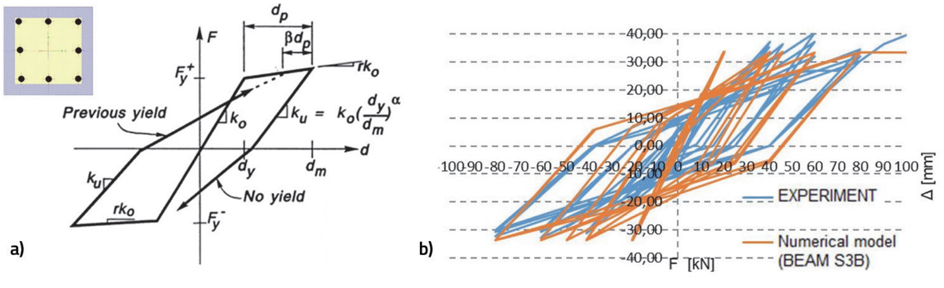

Figure 3. a) Definition of the cross-section: confined concrete, unconfined concrete (cover) and reinforcement and Takeda hysteretic model, b) Comparison of hysteresis loops for S3-B beam

3.2 DIANA FEA

Modelling of the beam was performed using solid elements with Maekawa – Fukuura constitutive model for concrete in DIANA FEA [8] (Fig. 4). The Maekawa-Fukuura concrete model in DIANA is a combination of the Total Strain crack model combined with the Maekawa Cracked Concrete curves, and the Elasto-Plastic Fracture model. In contrary to the Total Strain crack model the Maekawa-Fukuura concrete model makes use of a non-orthogonal crack definition [9].

The Maekawa Cracked Concrete curves are uniaxial stress-strain relations for loading, unloading and reloading conditions in respectively the tensile and compressive strain domains. In the main directions of the coordinate system related to the active crack the stresses are calculated with these equations using the equivalent uniaxial strain [10]. Typical stress distribution in reinforcement and crack localization are shown in Fig. 5. Constitutive laws for reinforcement include Menegotto-Pinto and Monti-Nuti models [11, 12]. However, buckling of reinforcement was not detected and both models yield the same response (hysteretic behaviour in Fig. 6). Influence of compressive force and geometric nonlinearity is shown in Fig. 7 and Fig. 8 using JSCE model [13] where reduction of load bearing capacity can be noticed.

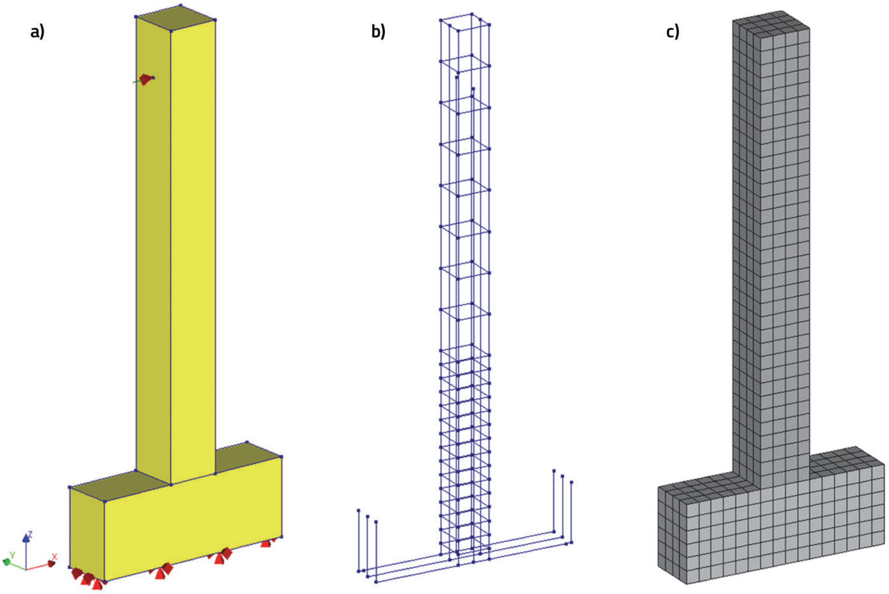

Figure 4. a) Geometry of the beam, b) reinforcement truss elements, c) FE mesh with CHX60 h = 5 cm

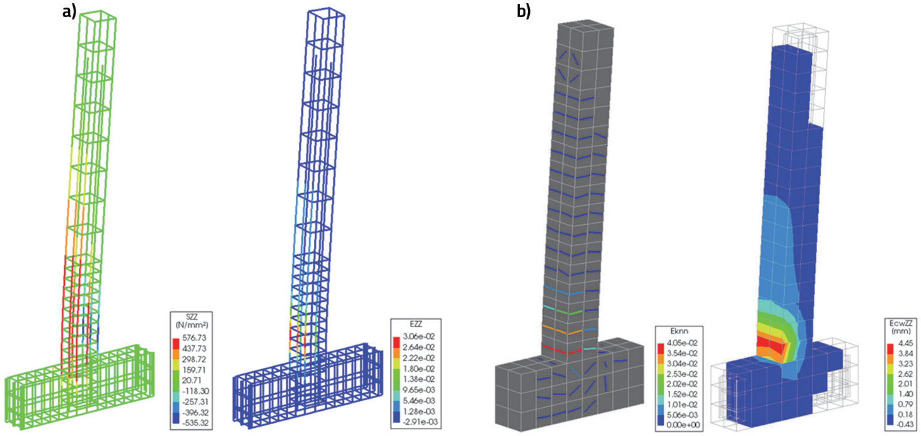

Figure 5. a) Stresses and deformations in reinforcement, b) crack strains and crack widths in concrete

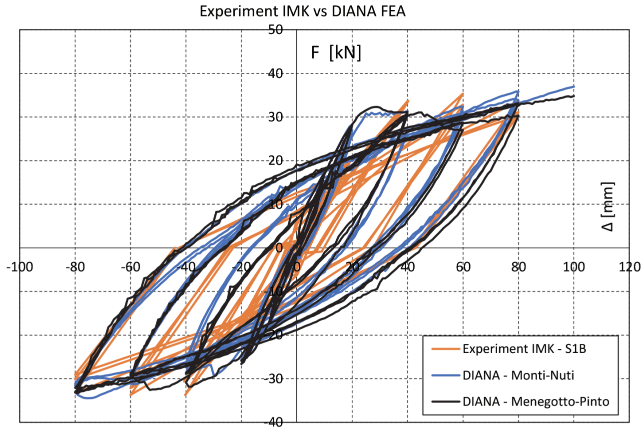

Figure 6. Comparison of test results and numerical modelling

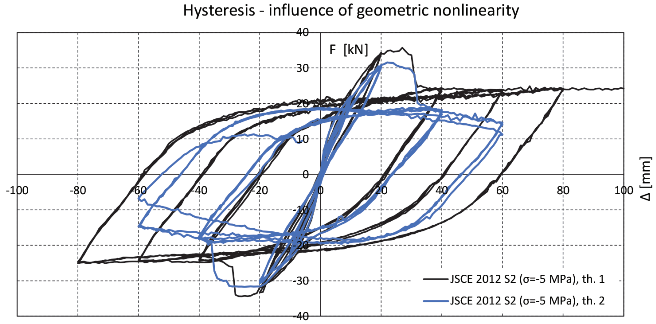

Figure 7. Influence of geometric nonlinearity

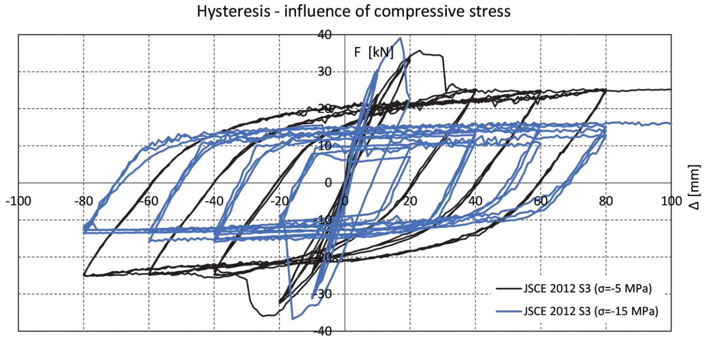

Figure 8. Influence of compressive stress

5 Conclusion

During stronger earthquakes structures can be shifted well in the nonlinear range of behaviour which is mostly characterized by cracking. Damages should occur in carefully shaped zones (plastic hinges) so that adequate load-bearing capacity and ductility are provided. The total load-bearing capacity of a cross-section or an element cannot always be accurately estimated from the allowable stress or the coefficient of safety. Namely, not only the load bearing capacity but also the ductility is of crucial importance for dissipation of energy released by ground motion. The main result of the cyclic testing is represented through a force-displacement diagram. The difference between the hysteresis curves of beams reinforced with different transverse reinforcement is almost non-existent. It was concluded that the additional confinement reinforcement does not provide larger load bearing capacity and ductility in comparison to the beams reinforced for low ductility when the beams are exposed to bending without axial force. Occurrence and development of cracks on the beams were also monitored and mapped during the experiments. Typical cracking due to bending was observed. Major cracks localize in the plastic hinge whose length is roughly equal to cross-sectional height. This observation matches well with the recommendations given in EC 8. Models with localized nonlinearity within link element are quite good for practical engineering analysis. Refined models using DIANA FEA provide deeper insight into structural response. Sophisticated models employing nonlinear concrete and reinforcement constitutive laws provide information on cracking and local stresses. However, they require experience and one should apply complex modelling with due care, paying attention to discretization, iterative procedures and convergence criteria which can be serious source of error.

References

[1] Eurocode 2 (2004): Design of concrete structures – Part 1-1: General rules and rules for buildings, European Committee for Standardization, Brussels, EU.

[2] Eurocode 8 (2005): Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings, European Committee for Standardization, Brussels, EU.

[3] Medić, S., Živalj, E., Biberkić, F., Zlatar, M., Hrasnica, M. (2018): Experimental study on behavior of reinforced concrete beam subjected to cyclic loading, 16th European Conference on Earthquake Engineering, Thessaloniki 18-21 June, 2018, The European Association for Earthquake Engineering/Hellenic Society of Earthquake Engineering, 10 pages.

[4] Kwak, H-G., Kim, S-P. (2002): Nonlinear analysis of RC beams based on moment-curvature relation, Computers and Structures, 80 (7): 615-628.

[5] Mander, J.B., Priestley, M.J.N., Park, R. (1988): Theoretical Stress - Strain Model for Confined Concrete, Journal of Structural Engineering, 114(3): 1804-1826.

[6] CSI (2008): CSI Technical note. Material Stress-Strain Curves. Computers and Structures Inc.

[7] Takeda, T., Sozen, M.A., Nielsen, N.N. (1970): Reinforced Concrete Response to Simulated Earthquakes, Journal of Structural Engineering Division, 96 (12): 2557-2573.

[8] DIANA (2016): DIANA - User´s Manual. TNO DIANA BV, Delft, the Netherlands.

[9] Schreppers, G. (2016): Validation report Maekawa-Fukuura model and Cracked Concrete curves in Total Strain Crack model in DIANA. Report 2016-DIANA-R1602, DIANAFEA BV.

[10] Maekawa, K., Okamura, H., Pimanmas, A. (2003): Non-linear mechanics of reinforced concrete. Spon Press, 1st edition, UK.

[11] Menegotto, M., Pinto, P.E. (1973): Method of analysis of cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under normal force and bending. Preliminary Report IABSE, 13, 15-22.

[12] Monti, G., Nuti, C. (1992): Nonlinear cyclic behavior of reinforcing bars including buckling. Journal of Structural Engineering, 118(12), 3268-3284.

[13] JSCE Standard Specifications for Concrete Structures (2012): Design. Technical Report Japan Society of Civil Engineers.