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Numerical analysis of reinforced concrete earthquake-resistant complex cross sections

Radoslav Markić, Ph.D.
University of Mostar, Faculty of Civil Engineering, Architecture, and Geodesy
radoslav.markic@fgag.sum.ba

Mladen Kustura, Ph.D.
University of Mostar, Faculty of Civil Engineering, Architecture, and Geodesy
mladen.kustura@fgag.sum.ba

Marino Jurišić, Ph.D.
University of Mostar, Faculty of Civil Engineering, Architecture, and Geodesy
marino.jurisic@fgag.sum.ba

Abstract: The European standard EN 1998-1 for the design of earthquake-resistant reinforced concrete structures does not provide direct expressions for the design of reinforced concrete cores as unique complex cross sections in building structures, which consist of two or more walls in both directions of the building, such as hollow rectangular or square cross sections or the even more complex case of multiple connected cores in tall buildings. The standard provides design guidelines with expressions for proving local ductility for individual walls in a plane (rectangular, L, I cross section of the wall). Numerical analysis in the computer program BIAXIAL PRO ver.3.0 has shown the possibility of designing a complex cross section of a reinforced concrete core, thus providing a more realistic insight into the behavior of this type of structures. The bending resistance and ductility were analyzed in accordance with the requirements of EN 1998-1. The advantage of such an approach to design analysis over the traditional method of observing walls in each plane separately was highlighted.

Key words: EN 1998-1, reinforced concrete wall, concrete core, complex cross section, load-bearing capacity, ductility

Numerička analiza armiranobetonskih potresno otpornih složenih poprečnih presjeka

Sažetak: Europska norma EN 1998-1 za proračun potresno otpornih armiranobetonskih konstrukcija ne daje direktne izraze za proračun armiranobetonskih jezgri kao jedinstvenih složenih poprečnih presjeka u konstrukcijama zgrada, a koji se sastoje od dva ili više zidova u oba smjera građevine kao npr. šuplji pravokutni ili kvadratni poprečni presjeci ili još složeniji slučaj višestruko spojenih jezgri u visokim građevinama. Norma daje proračunske smjernice sa izrazima za dokazivanje lokalne duktilnosti za pojedinačne zidove u ravnini (pravokutni, L, I poprečni presjek zida). Numeričkom analizom u računalnom programu BIAXIAL PRO ver.3.0 prikazana je mogućnost proračuna složenog poprečnog presjeka armiranobetonske jezgre čime se omogućava realniji uvid u ponašanje takve vrste konstrukcije. Analizirana je nosivost na savijanje i duktilnost u skladu sa zahtjevima EN 1998-1. Istaknuta je prednost takvog pristupa proračunske analize u odnosu na tradicionalni način promatranja zidova u svakoj ravnini zasebno.

Ključne riječi: EN1998-1, armiranobetonski zid, betonska jezgra, složeni poprečni presjek, nosivost, duktilnost

1. INTRODUCTION

The behavior of reinforced concrete structures subjected to earthquakes is a current topic in modern scientific research. In today's civil engineering profession, designing earthquake-resistant load-bearing structures in areas of potential seismic activity has become mandatory in terms of controlling the resistance and deformability of the load-bearing structure. The development of modern computers has enabled the use of computer programs for static and dynamic analysis of complex spatial concrete structures made of linear (columns, beams) and planar (slabs, walls) elements, which also allowed for the inclusion of nonlinear material properties. It can be said with a high degree of certainty that today's civil engineers, designers of load-bearing structures, in most cases design buildings three-dimensionally (3D computational model) using all the available capabilities of the commercial computer programs at their disposal. In a simplified manner, methods for seismic analysis of load-bearing structures can be divided into linear and nonlinear. Linear methods include the lateral force method ("force-based approach") and modal analysis using the response spectrum ("response spectrum method"). Non-linear methods include non-linear static calculation by gradual pushing ("push-over analysis") and non-linear dynamic calculation using a time record ("response-history analysis"). All these analyses are basically linear analyses, although some of them are called non-linear and are implemented in most of the mentioned commercial computer programs. It is generally considered that the most reliable approach for designing earthquake-resistant structures is based on an incremental-iterative displacement calculation, where deformations in the materials are controlled in each increment. In modern regulations and scientific papers, such an approach is called "performance-based design", which is presented in more detail in [1] and [2]. In addition to controlling the load-bearing capacity and serviceability of the structure, it also enables the calculation of ductility.
The concept of ductility as an essential property for reinforced concrete earthquake-resistant structures is a parameter that is not easy to determine. This concept that can also be translated as resilience is often defined in terms of deformations or displacements. It is also generally related to the stiffness of the overall structure, which is very difficult to determine in the case of reinforced concrete structures.
The EN 1998-1 standard [3] provides guidelines for the calculation of local ductility, which also specify recommendations for detailing the reinforcement in individual structural elements. The intention is to program specific locations in the structure so that the energy introduced by an earthquake is dissipated at those very locations, leaving the rest of the structure more or less undamaged.
Reinforced concrete cores (staircase cores, elevator cores or combined) consisting of connected concrete walls are the most common form of ensuring earthquake resistance in building construction. Due to their load-bearing capacity and stiffness (flexural, torsional), they are often elements for ensuring earthquake resistance in tall structures.
In engineering practice, the calculation and analysis of such cores is reduced to 3D modeling in a computer program, where the walls are modeled with 2D finite elements and for the proof of load-bearing capacity and assurance of ductility, they are treated separately as a separate rectangular wall for each direction of the structure. In doing so, it is allowed to take into account the contribution of the marginal parts of the transverse walls.
For known internal forces (M,N,V), the wall is dimensioned so that the required reinforcement is determined and adopted according to the requirements of the standard regarding local ductility and the principles of minimum required reinforcement in accordance with standard provisions.
Such an approach is not wrong, however, it does not provide a realistic picture of the behavior of such a structure because, for example, concrete cores are complex cross sections where

the application of numerical methods is necessary to determine the stiffness, load-bearing capacity, and stress state in the concrete and reinforcement.
Analyzing a complex cross section with a numerical model that allows for the analysis of the stress-strain state of the section, determination of load-bearing capacity, and ductility for a known geometry and reinforcement layout is an approach that provides the engineer with a higher-quality insight into such a structure and enables him to make a better distribution of reinforcement in the walls, which ultimately leads to seismically more resistant and safer structures.

2. DUCTILITY

Ductility can be expressed as a measure of a structure's nonlinear behavior or the ability of a structure to withstand nonlinear deformations before failure. Pronounced nonlinearity, according to [4], in load-bearing structures causes yielding and impending failure, which is the opposite of brittle (non-ductile) structures, as shown in Figure 1. The property of ductility is highly desirable in earthquake-resistant structures because it dissipates the seismic energy that is imparted to the structure by ground motion. Reinforced concrete structures have proven to be very reliable in earthquake resistance because they can be designed and constructed as ductile structures. The dissipation of seismic energy in reinforced concrete structures takes place through the softening of the structure, controlled cracking and deformation of concrete and reinforcement, where the kinetic energy is converted into mechanical energy. Therefore, ductility is one of the priorities when designing reinforced concrete and other structures and is the subject of many scientific papers.

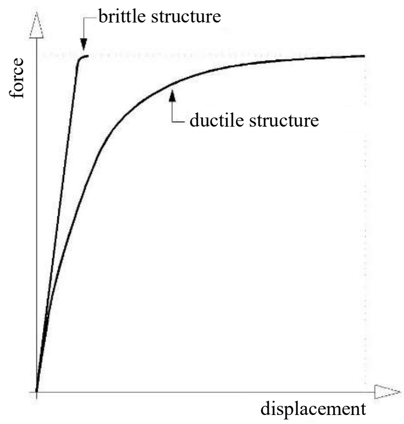
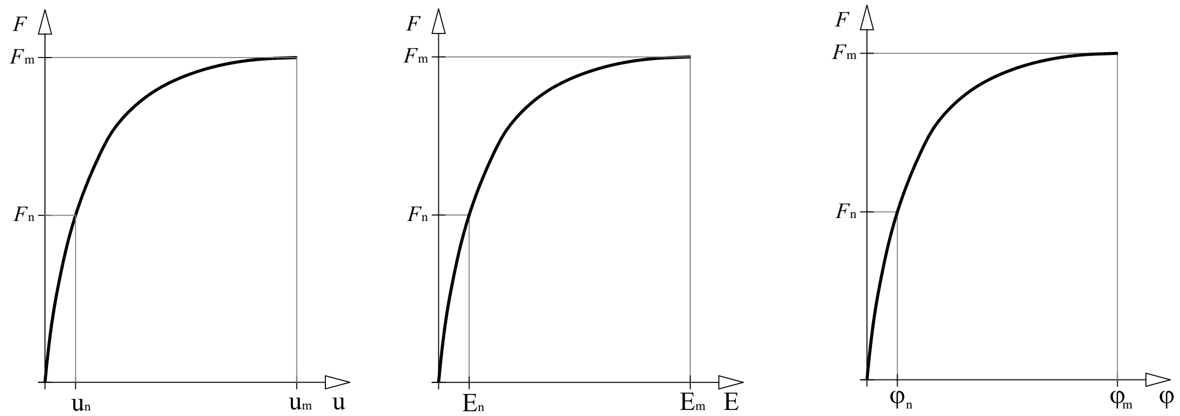


Figure 1. Brittle and ductile structure according to [4]

No universal mathematical expression for defining ductility has yet been adopted. Ductility is usually expressed in terms of displacement (u), dissipated energy (E) and curvature (φ). The dimensionless value of the ductility factor is usually defined as the ratio of the maximum load F_m that causes u_m, E_m, φ_m, to the load F_n at the moment of a certain nonlinearity u_n, E_n, φ_n shown in Figure 2.



In terms of displacement – displacement ductility | In terms of dissipated energy – energy ductility | In terms of curvature – curvature ductility

Figure 2. Most common approaches to ductility calculation [4]

The detailed calculation of structural ductility is complex because it depends on many parameters. There are many papers and studies on this topic. Some of them are presented in papers [5,6,7,8]. Abdelrahman et al. [5] introduced the ductility index as the ratio of the displacement at failure and the equivalent displacement of an uncracked section at a load equal to the ultimate load. Tann et al. [6] defined the ductility coefficient as the ratio of the displacement at 95% of the failure load to the displacement at 67% of the failure load. Park and Paulay [7] proposed a ductility index in terms of curvature as the ratio of the curvature at failure to the curvature at yield of tensile reinforcement. Park [8] analyzed the ductility of reinforced concrete structures in the context of their application in seismic areas.
Standard EN 1998-1 [3] does not provide direct expressions for controlling the ductility of reinforced concrete walls with complex cross sections. This greatly complicates their design and dimensioning and requires more detailed numerical analyses.
In EN 1998-1 [3], Section 5.2.3.4 Local ductility condition defines the conditions that must be met for structural parts to be considered ductile. It introduces the concept of curvature ductility factor μ_φ. It is defined as the ratio of the post-ultimate strength curvature at 85% of the moment of resistance, to the curvature at yield, provided that the limiting strains of concrete, ε_{cu}, and steel $\varepsilon_{su,k}$ are not exceeded, according to Figure 3.

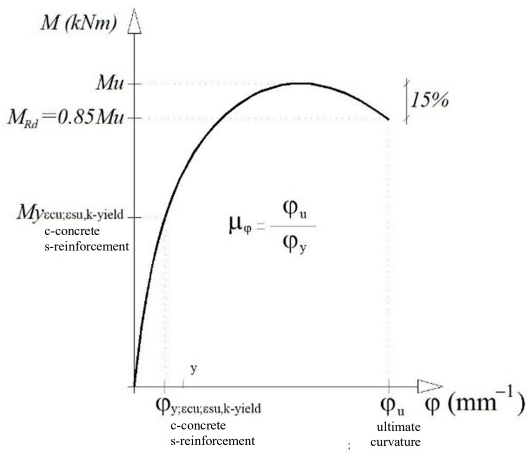


Figure 3. Definition of the curvature ductility factor according to [3]

A structure is considered ductile if the curvature ductility factor μ_φ of these areas is at least equal to one of the following values:

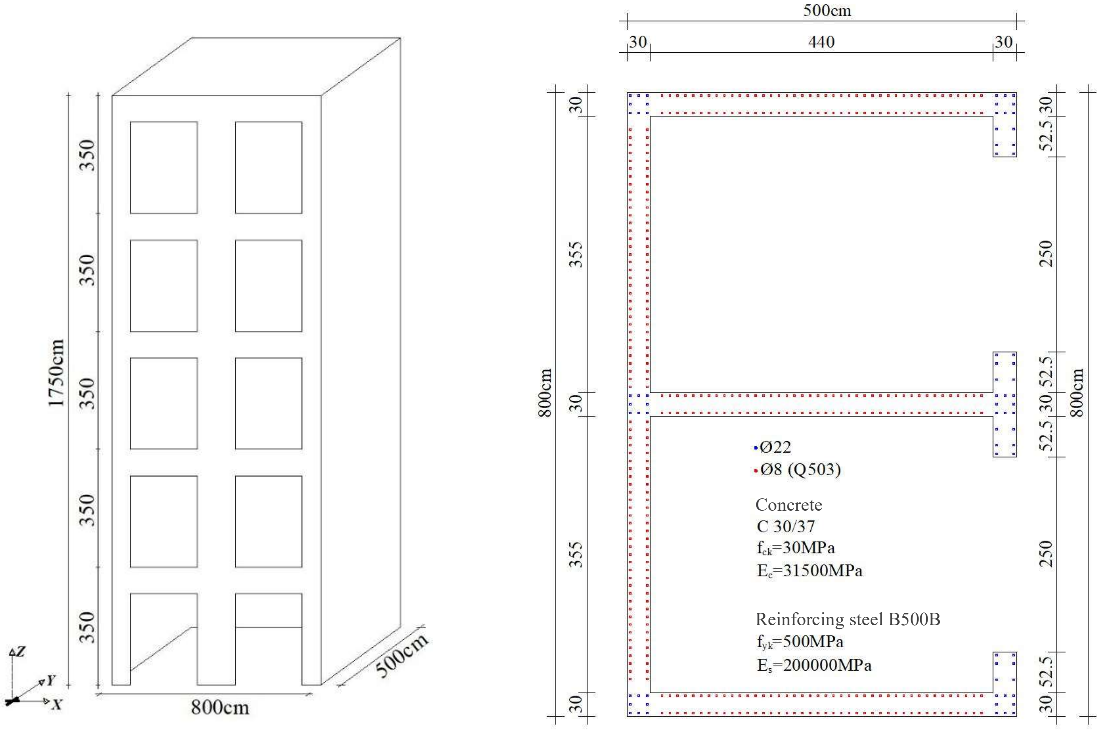
$$\mu_\varphi = 2q_0 - 1 \qquad \text{if } T_1 \geq T_c \qquad (1)$$

$$\mu_\varphi = 1 + (2q_0 - 1)\, T_c/T_1 \qquad \text{if } T_1 < T_c \qquad (2)$$

where q_0 is the corresponding basic value of the behavior factor from Table 5.1 of standard EN 1998-1 [3], T_1 is the fundamental period of the building, both taken within the vertical plane in which bending takes place, and T_C is the period at the upper limit of the constant acceleration region of the spectrum, according to 3.2.2.2(2)P of standard EN 1998-1 [3]. The standard also specifies that in critical regions of primary seismic elements with longitudinal reinforcement of steel class B in EN 1992-1-1:2004 [9] (Table C.1), the curvature ductility factor μ_φ should be at least equal to 1.5 times the value given by expression (1) or (2), whichever applies.

3. CALCULATION EXAMPLE

Figure 4 shows a calculation example of a reinforced concrete core. The internal forces acting on the core are determined within a 3D calculation model using one of the seismic analysis methods.
The computational analysis of the seismic core in the BiaxialPro 3.0 [10] program is carried out by treating the entire core as a single, complex cross section, rather than observing each wall as a separate wall for each direction of the building.
For a pre-defined cross section and layout of the reinforcing steel, a computational verification is performed in accordance with EN 1992-1-1:2004 [9] and EN 1998-1 [3].
The calculation in BiaxialPro 3.0 [10] is performed using the finite element method, which allows for the calculation of the bearing capacity and stress-strain state of any cross-section shape with an arbitrary reinforcement layout.
For the example in this paper, the calculation diagram for concrete in compression was adopted in the form of a parabola and a straight line according to Figure 5, while the tensile strength of the concrete was neglected. For the calculation diagram of steel in compression and tension, a bilinear diagram was adopted according to Figure 5. Concrete class C30/37 was specified for the concrete, and steel class B500B for the reinforcement, with a maximum deformation of 10‰ adopted.
The calculation shows the stresses in the concrete and steel for SLS combinations. The M-N bearing capacity diagrams and the M-φ diagrams, which also show the stiffness of the core section for the installed reinforcement, are presented. For a given ULS combination of actions, the curvature ductility factor μ_φ of the cross section was calculated in accordance with EN 1998-1 [3], Section 5.2.3.4. Local ductility condition of the section for the design of structures in seismic areas.

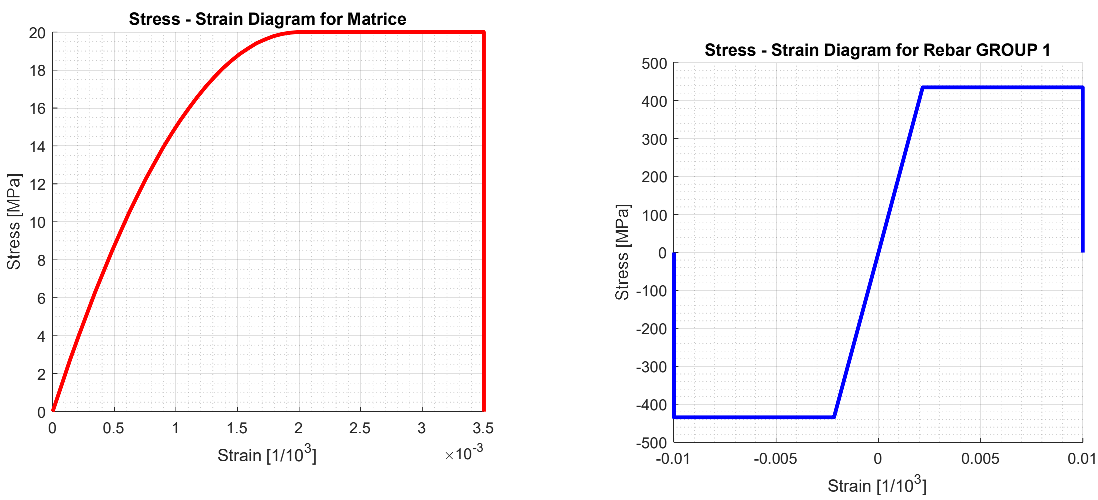


3D view of the concrete core

Cross section and installed reinforcement

Figure 4. Reinforced concrete core

Figure 5 shows the adopted calculation models for concrete and steel materials.

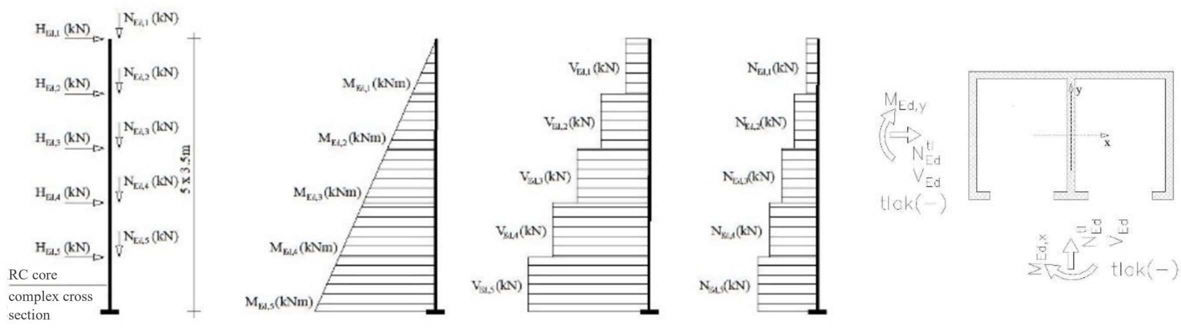


Calculation diagram stress–strain for concrete class C 30/37

Calculation diagram stress–strain for reinforcing steel B500B

Figure 5. Calculation diagrams of materials in Biaxial Pro 3.0 [10] according to EN 1992-1-1:2004 [9]

Figure 6 shows the calculation model of the core and the internal forces, while Table 1 provides the values of the design internal forces for which the cross section will be analyzed.



Simplified member model with representation of internal forces (M, N, V)

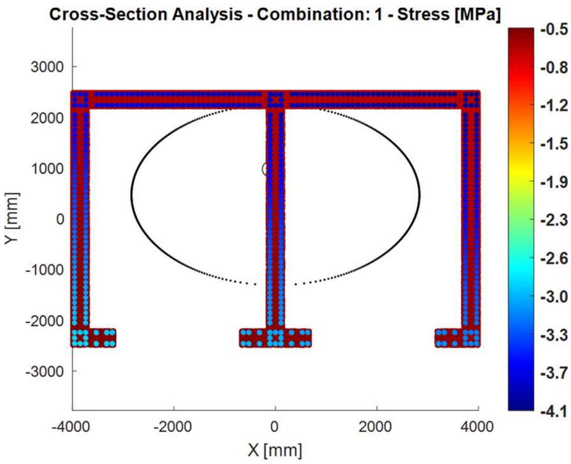
Cross section and forces

Figure 6. Calculation model of the core

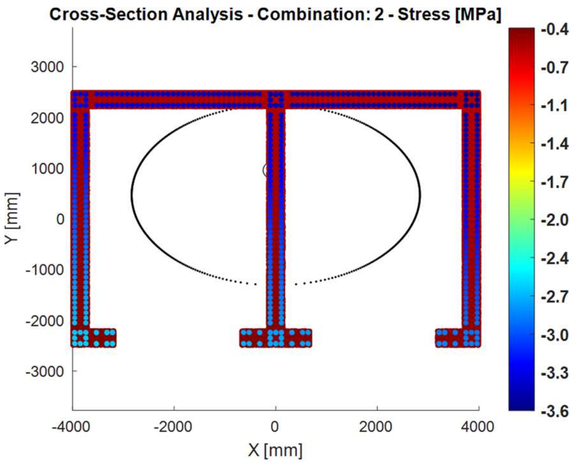
Table 1. Design combinations of actions for ULS / SLS

Design combinations of actions	N_{Ed} [kN]	$M_{x,Ed}$ [kNm]	$M_{y,Ed}$ [kNm]
SLS-1	-5000	2300	1200
SLS-2	-4500	2000	1000
SLS-3	-4000	1500	900
ULS-1	-6000	4000	0
ULS-2	-6000	0	6000
ULS-3	-5000	2500	6000

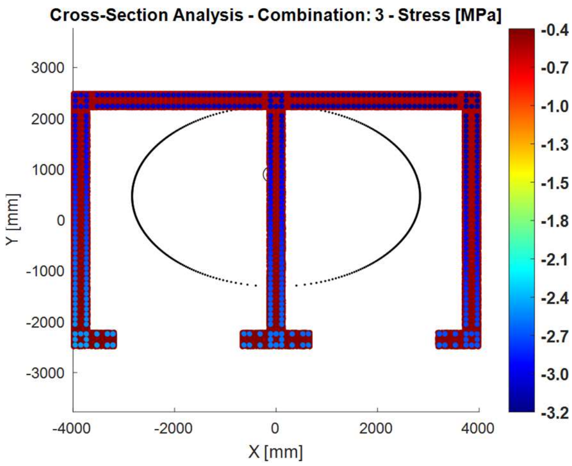
For the serviceability limit state, SLS, the combinations of actions are marked with numbers according to the following order:
1 – Characteristic SLS combination
2 – Frequent SLS combination
3 – Quasi-permanent SLS combination
For the ultimate limit state, ULS, the action combinations are marked with the numbers 1 to 3 and represent the internal forces obtained from the design combinations of seismic actions.
The axial force N_{Ed} is compressive (negative sign “–”).
The bending moment $M_{x,Ed}$ is about the X axis. A positive value represents compressive stress on the upper side of the cross-section.
The bending moment $M_{y,Ed}$ is about the Y axis. A positive value represents compressive stress on the right side of the cross-section.
The following section presents the calculation results obtained from the BiaxialPro 3.0 computer program [10].
Figure 7 shows the normal stresses in concrete and steel for the SLS combinations.



Design stresses in concrete and reinforcement for the SLS combination of actions SLS-1



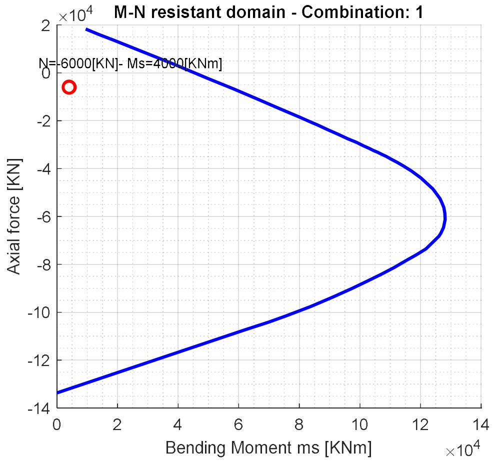
Design stresses in concrete and reinforcement for the SLS combination of actions SLS-2



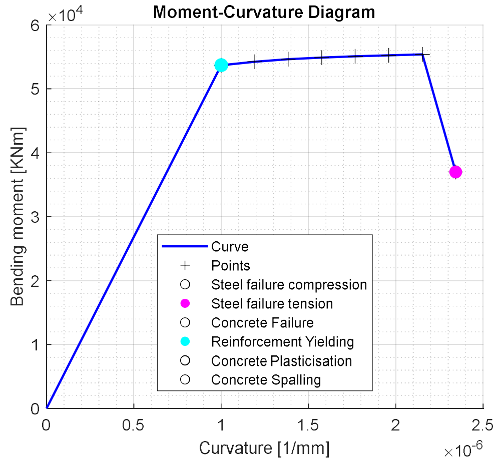
Design stresses in concrete and reinforcement for the SLS combination of actions SLS-3

Figure 7. Design stresses in concrete and reinforcement for the SLS combinations of actions from BiaxialPro 3.0 [10]

Figures 8, 9 and 10 show bearing capacity diagrams M-N and diagrams M-φ for given ULS combinations.
The curvature ductility factor μ_{φ} was calculated for each ULS combination.



M-N diagram for the combination of actions ULS-1



M-φ diagram for the combination of actions ULS-1

$\varepsilon_{c,min.} = -0.000733$ minimum value of concrete strain
$\varepsilon_{s,min.} = -0.0006653$ minimum value of reinforcing steel strain
$\varepsilon_{s,max.} = -0.0108925$ maximum value of reinforcing steel strain
$\varphi_{(s-yield)} = 0.0000010 \ \ mm^{-1}$ cross-section curvature at the yielding point of the reinforcing steel
$M_{(s-yield)} = 53710.1 \ \ kNm$ bending moment at the yielding point of the reinforcing steel
$\varphi_{(c-pla \ \ )} = 0.0000123 \ \ mm^{-1}$ cross-section curvature at the yielding point of concrete in compression
$M_{(c-plast)} = 59605.8 \ \ kNm$ bending moment at the yielding point of concrete in compression
$\varphi_{(Ult)} = 0.0000023 \ \ mm^{-1}$ ultimate curvature of the cross section
$M_{(Ult)} = 37015.8 \ \ kNm$ ultimate bending moment of the cross section
$\varphi_y = 0.0000010 \ \ mm^{-1}$ min. curvature at the yielding point (s-yield) / plasticization point (c-plast)
$M_y = 53710.1 \ \ kNm$ min. bend. moment at yielding (s-yield) / plasticization point (c-plast)
$N_{Ed} = -6000.0 \ \ kNm$ design axial force from ULS-1 combination (- compression)
$M_{Rd} = 56828.4 \ \ kNm$ ultimate bending moment at the corresponding value of axial force N_{Ed}
$\varphi_{y'} = 0.0000010 \ \ mm^{-1}$ equivalent cross-section curvature at yield (in this example corresponds to the steel yield value)

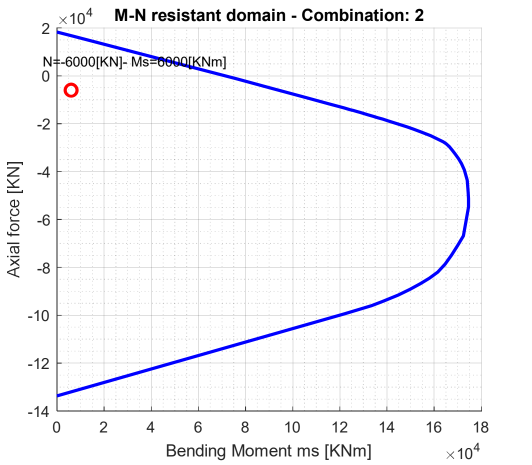
The curvature ductility factor μ_φ of the cross section is calculated using the expression

$$\mu_\varphi = \frac{\varphi_{ult.}}{\varphi_y}$$

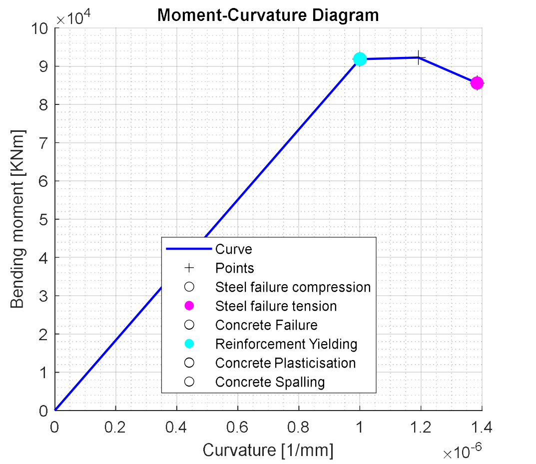
φ_{ult} = min. ($\varphi_{15\%}$; $\varphi_{u,c}$; $\varphi_{u,s}$); $\varphi_{ult.}$ = 0.0000023 mm^{-1} ; $\varphi_{y'}$ = 0.0000010 mm^{-1}
$\varphi_y = M_{Rd}/M_y \times \varphi_{y'}$
for the combination of actions ULS-1 it is
$\mu_\varphi = \varphi_{ult} / (M_{Rd}/M_y \times \varphi_{y'})$ = 0.0000023 / (56828.4 / 53710.1 x 0.0000010)
μ_φ = 2.174

Cross-section ductility factor for the combination of actions ULS-1

Figure 8. Results of core cross-section ductility calculation from BiaxialPro 3.0 [10] for the combination of actions ULS-1



M-N diagram for the combination of actions ULS-2



M-φ diagram for the combination of actions ULS-2

$\varepsilon_{c,min.} = -0.0008858$ minimum value of concrete strain
$\varepsilon_{s,min.} = -0.0008434$ minimum value of reinforcing steel strain
$\varepsilon_{s,max.} = -0.0101332$ maximum value of reinforcing steel strain
$\varphi_{(s-yield)} = 0.0000010 \quad mm^{-1}$ cross-section curvature at the yielding point of the reinforcing steel
$M_{(s-yield)} = 91852 \quad kNm$ bending moment at the yielding point of the reinforcing steel
$\varphi_{(c-plast)} = 0.0000123 \quad mm^{-1}$ cross-section curvature at the yielding point of concrete in compression
$M_{(c-plast)} = 59605.8 \quad kNm$ bending moment at the yielding point of concrete in compression
$\varphi_{(Ult)} = 0.0000014 \quad mm^{-1}$ ultimate curvature of the cross section
$M_{(Ult)} = 85599 \quad kNm$ ultimate bending moment of the cross section
$\varphi_y = 0.0000010 \quad mm^{-1}$ min. curvature at the yielding point (s-yield) / plasticization point (c-plast)
$M_y = 91852 \quad kNm$ min. bend. moment at yielding (s-yield) / plasticization point (c-plast)
$N_{Ed} = -6000.0 \quad kNm$ design axial force from ULS-2 combination (- compression)
$M_{Rd} = 94013.8 \quad kNm$ ultimate bending moment at the corresponding value of axial force N_{Ed}
$\varphi_{y'} = 0.0000010 \quad mm^{-1}$ equivalent cross-section curvature at yield (in this example corresponds to the steel yield value)

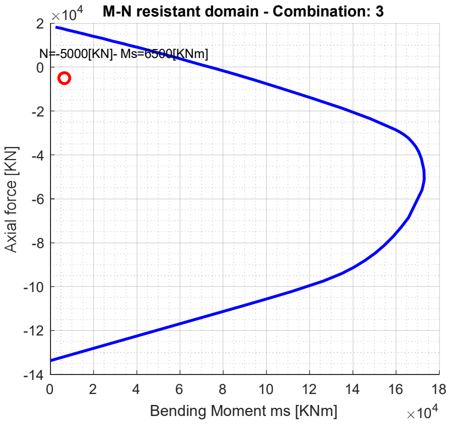
The curvature ductility factor μ_φ of the cross section is calculated using the expression

$$\mu_\varphi = \frac{\varphi_{ult.}}{\varphi_y}$$

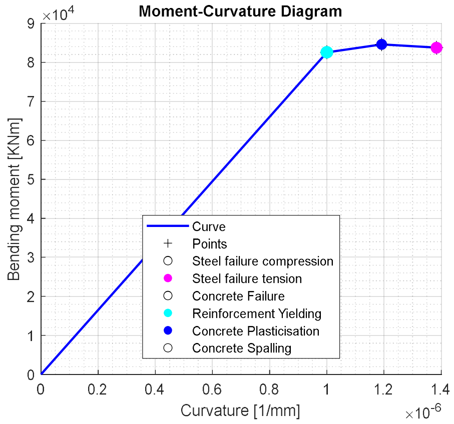
φ_{ult} = min. ($\varphi_{15\%}$; $\varphi_{u,c}$; $\varphi_{u,s}$); $\varphi_{ult.}$ = 0.0000014 mm^{-1}; $\varphi_{y'}$ = 0.0000010 mm^{-1}
$\varphi_y = M_{Rd}/M_y \times \varphi_{y'}$
for the combination of actions ULS-2 it is
$\mu_\varphi = \varphi_{ult} / (M_{Rd}/M_y \times \varphi_{y'})$ = 0.0000014 / (94013.8 / 91852 x 0.0000010)
μ_φ = 1.367

Cross-section ductility factor for the combination of actions ULS-2

Figure 9. Results of core cross-section ductility calculation from BiaxialPro 3.0 [10] for the combination of actions ULS-2



M-N diagram for the combination of actions ULS-3



M-φ diagram for the combination of actions ULS-3

$\varepsilon_{c,min.} = -0.0023784$ minimum value of concrete strain
$\varepsilon_{s,min.} = -0.0023248$ minimum value of reinforcing steel strain
$\varepsilon_{s,max.} = -0.0101793$ maximum value of reinforcing steel strain
$\varphi_{(s-yie\ \ )} = 0.0000010\ \ mm^{-1}$ cross-section curvature at the yielding point of the reinforcing steel
$M_{(s-yie\ \ )} = 82567.9\ \ kNm$ bending moment at the yielding point of the reinforcing steel
$\varphi_{(c-plast)} = 0.0000012\ \ mm^{-1}$ cross-section curvature at the yielding point of concrete in compression
$M_{(c-plast)} = 84574.8\ \ kNm$ bending moment at the yielding point of concrete in compression
$\varphi_{(Ult)} = 0.0000014\ \ mm^{-1}$ ultimate curvature of the cross section
$M_{(Ult)} = 83718.1\ \ kNm$ ultimate bending moment of the cross section
$\varphi_y = 0.0000010\ \ mm^{-1}$ min. curvature at the yielding point (s-yield) / plasticization point (c-plast)
$M_y = 82567.9\ \ kNm$ min. bend. moment at yielding (s-yield) / plasticization point (c-plast)
$N_{Ed} = -5000.0\ \ kNm$ design axial force from ULS-3 combination (- compression)
$M_{Rd} = 91334.6\ \ kNm$ ultimate bending moment at the corresponding value of axial force N_{Ed}
$\varphi_{y'} = 0.0000010\ \ mm^{-1}$ equivalent cross-section curvature at yield (in this example corresponds to the steel yield value)

The curvature ductility factor μ_φ of the cross section is calculated using the expression

$\mu_\varphi = \frac{\varphi_{ult.}}{\varphi_y}$

φ_{ult} = min. ($\varphi_{15\%}$; $\varphi_{u,c}$; $\varphi_{u,s}$); $\varphi_{ult.}$ = 0.0000014 mm^{-1} ; $\varphi_{y'}$ = 0.0000010 mm^{-1}
$\varphi_y = M_{Rd}/M_y \times \varphi_{y'}$
for the combination of actions ULS-3 it is
$\mu_\varphi = \mu_\varphi = \varphi_{ult} / (M_{Rd}/M_y \times \varphi_{y'})$ = 0.0000014 / (91334.6 / 82567.9 x 0.0000010)
μ_φ = 1.265

Cross-section ductility factor for the combination of actions ULS-3

Figure 10. Results of core cross-section ductility calculation from BiaxialPro 3.0 [10] for the combination of actions ULS-3

3. CONCLUSION

The design of reinforced concrete cores in buildings is recommended to be analyzed as a single complex cross section. This requires the use adequate numerical models (computer programs) that allow monitoring of the behavior of such a complex cross section under the simultaneous action of axial force and bending moments in both directions. The computational

analysis must include the calculation of bearing capacity and the calculation of the stress-strain state for an arbitrary cross-section strain plane. The curvature ductility factor μ_φ of the cross section, calculated in accordance with EN 1998-1 [3], Section 5.2.3.4, is one of the most important indicators of whether a reinforced concrete structure is constructed with the required safety against seismic actions.
It is recommended that local ductility checks for complex reinforced concrete cross sections with arbitrary reinforcement layouts be performed using one of the software solutions such as BiaxialPro 3.0 [10].
The calculation example demonstrated the applicability of the computer program BiaxialPro 3.0 [10] for the calculation of a complex concrete core with a known reinforcement layout.
Some authors have also recommended the computer program SAP2000 v24.0.0, module Section Designer [11], for calculating the cross-section ductility factor, where they analyzed and calculated the ductility of the complex section.
When selecting the dimensions of walls of complex cross sections, local and global instability issues must be taken into account. More on this can be found in the paper [12].
It is recommended to follow the guidelines of standard EN 1998-1 [3] for selecting the wall thickness dimensions. Section 5.4.1.2.3 of standard EN 1998-1 [3] gives requirements for ductile walls stating that the thickness of the web, b_{w0} (in meters), should satisfy the expression: $b_{w0} \geq \max \{0.15;\ h_s / 20\}$, where h_s is the clear story height in meters. It is recommended to limit compressive stresses in the concrete according to standard provisions. The quantity and layout of reinforcement in the cross section, the method of confinement with hoops, and the selection of the concrete class largely affect the load-bearing capacity and ductility.

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