Buckling of Concrete Panels under Biaxial Compression According to Rheological-Dynamical Theory

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Abstract:

This paper is concerned with experimental verification of inelastic buckling and failure analysis of concrete panels according to rheological dynamical theory (RDT). Iterative modulus calculation of buckling stress is presented and verified for concrete panels under biaxial and axial compression. For biaxial compression, three different concrete mixtures with two stress ratios are considered. Some experimental results from literature are also used to verify RDT calculation for concrete panels under axial compression as well as analytical expressions for concrete wall panel in two-way action. Besides normal concrete strength, this calculation can be used for fibre-reinforced ultra-high performance concrete UHPC. The calculation according to RDT had shown that the values of material parameters of such modulus of elasticity and Poisson’s ratio have a significant influence on the structural material constant as well as buckling stress results. The calculation of buckling stress which is necessary for RDT calculation was carried out using the corresponding model in Abaqus software.

Keywords:

Rheological-Dynamical theory, Concrete Panels, Buckling Analysis, Biaxial Compression of Concrete, Stability of Concrete Panels

1 Introduction

Compression members such as walls and columns have a very important role for the stability of buildings, industrial objects etc. There are many scientists and engineers, who have studied the structural stability problems. Leonhard Euler developed mathematical solution for columns under compression. With Euler's equations the critical buckling load of elastic material columns under various end conditions can be calculated. [1] have studied the theory of elastic stability of thin panels. They derive the mathematical solutions for plates under axial and biaxial compression.

Biaxial concrete strength has been topic of interest of many researchers. The results by [2] have shown that the compressive strength under biaxial compression is only 16 % larger than under uniaxial compression. [3] have studied the normal and high strength concrete panels specimens with dimensions 150 x 150 x 40 mm under biaxial loading. Their results show that the ultimate strength of concrete under biaxial compression was higher than under uniaxial compression. The maximum biaxial strength occurred at a biaxial stress ratio of 0.5 for all specimens tested. Load bearing behavior and stability of concrete wall panels have been investigated by several researchers, where some of the basic mathematical variations of different parameters were

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researched. This includes the variation of panel dimension (slenderness, thickness), steel reinforcement, eccentricities, concrete strength, and support condition. Many studies have investigated the behavior of concrete wall panel in one or two-way action. Two-way action considers the buckling of concrete walls, with side supports and axial compression. An overview of researches can be found in [4]. [5] carried out experimental studies on reinforced concrete panels with and without fibres to biaxial compression-tension loading. The panels were 1000 mm long in the tensile direction, 500 mm high in the compression direction and 100 mm thick. The results have shown the reduction of the compression strength of the cracked reinforced concrete with and without steel fibres. A material model for cracked reinforced concrete with and without fibres is derived. Methods for design concrete walls are also a part of many codes and standards. Most of the mathematical equations are based on experimental investigations or some empirical solutions. [6] refers to reinforced concrete walls with a length to thickness ratio of 4 or more and in which the reinforcement is taken into account in the strength analysis. For walls subjected predominantly to out-of-plane bending, the rules for slabs apply. Second order effects may be ignored, if they are less than 10 % of the corresponding first order effects. [7] proposed a new simpler formula of the Euler buckling stress of isotropic rectangular panels under axial compression loading in one and two orthogonal directions. This formula takes into account the transverse shear effect in a uniform manner across the thickness of the panel. The numerical verification was made on steel panels using the finite element method.
This paper shows the calculation and experimental verification of biaxial buckling load using the RDT. RDT is a mathematical-physical analogy proposed by Milašinović D. D. and it describes inelastic and time-dependent problems. This theory describes the critical mechanical behavior of viscoelastoplastic (VEP) materials under the cyclic stress variation. The scheme of the RDA modulus iterative method is already presented by [8]. This method was numerically verified for stability problems of steel panels. The experimental verification of this method on concrete panels is presented in this paper. Chapter 2 contains a short overview of the theory and RDA modulus iterative method. In chapter 3 is presented the experiment and in chapter 4 the verification on examples from literature.

2 Buckling according rheological-dynamical theory

2.1 RDA-a short overview

Since 2000 Milašinović D. D. developed a mathematical-physical analogy called rheological-dynamical analogy (RDA) which describes inelastic problems related to the load-bearing capacity of structural members (such as buckling and VEP deformation, fatigue of metals etc.). Mathematical analogy is given between rheological and dynamical model. The rheological body is shown in Figure 1 using the following symbols: N for the Newtonian dashpot, StV for Saint-Venant's body, H for the Hookean spring, "|" for a parallel connection and "—" for a connection in a series.

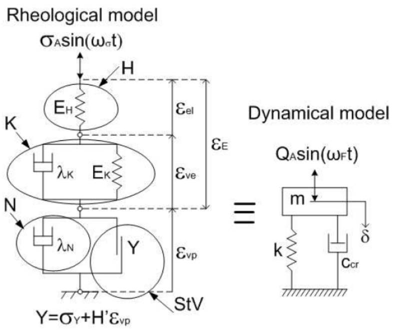

Figure 1: Analogy between rheological and dynamical model - [9]

Since the Hookean spring, Kelvin's body (K = H|N) and viscoplastic body (StV |N) are connected in a series, the stress loads in all the bodies are equal. The total axial strain is the sum of three components: elastic (instantaneous), viscoelastic and viscoplastic. Milašinović D. D. (1996) [10] gives differential equation for this model,

$$\ddot{\varepsilon}(t) + \dot{\varepsilon}(t) \cdot \left(\frac{E_K}{\lambda_K} + \frac{H'}{\lambda_N}\right) + \varepsilon(t) \cdot E_K \cdot \frac{H'}{(\lambda_K \cdot \lambda_N)} =$$

$$\ddot{\sigma}(t) \cdot \frac{1}{E_H} + \dot{\sigma}(t) \cdot \left[\frac{E_K}{(\lambda_K \cdot E_H)} + \frac{H'}{(\lambda_N \cdot E_H)} + \frac{1}{\lambda_K} + \frac{1}{\lambda_N}\right] +$$

$$+\sigma(t) \cdot \left[\frac{(E_K + H')}{(\lambda_K \cdot \lambda_N)} + E_K \cdot \frac{H'}{(\lambda_K \cdot \lambda_N \cdot E_H)}\right] - \sigma\gamma \cdot \frac{E_K}{(\lambda_K \cdot \lambda_N)} \tag{1}$$

where E_H is Young's modulus and σ_Y is the uniaxial yield stress. The four material constants in fixed steps of time are: coefficient of viscoelastic viscosity λ_K and viscoplastic viscosity λ_N, and moduli E_K (viscoelastic) and H´ (viscoplastic). Milašinović D. D. (2000) [11] derived the solution of the differential equation and presented the inelastic response of viscoelastic and viscoplastic material under cyclic stresses with constant amplitude. The solution of the differential equation is also presented in [12] and [13]. Additionally to these solutions the RDA modulus for homogeneous isotropic inelastic material was derived in RDT, which is shown in the Equation (2),

$$E_R = E_H \cdot \frac{1+\delta^2+\varphi}{(1+\varphi)^2+\delta^2} \tag{2}$$

where E_H is Young's modulus, δ is the ratio of the load or the stress frequency to the frequency of natural vibrations and φ is the creep coefficient. The RDA modulus is used in different inelastic problems for mechanic as well as for stability issues.

[9] derived relation between Poisson's ratio and creep coefficient which is based on the Bernoulli energy theorem. This relation is given by (3),

$$\varphi = \frac{2\cdot\mu}{1-2\cdot\mu} \tag{3}$$

where μ is Poisson's ratio.

2.2 RDA modulus iterative method

[8] derived RDA equations for isotropic 3D continua. The RDA modulus for homogeneous isotropic inelastic material is presented in other form, which is given by (4),

$$E_R = \frac{3\cdot E_H}{(5-4\cdot\mu)+2\cdot(1+\mu)\cdot\varphi} \tag{4}$$

The second relation, given by Eq. (5) assumes the linear relationship between the stress σ and the creep coefficient. [9] has introduced this assumption and named it the law of flow,

$$\sigma(t) = \frac{\sigma_E}{\varphi^*} \cdot \varphi(t); \quad \sigma_E = \frac{1}{K_E} \cdot \varphi^* \tag{5}$$

where K_E is the structural material constant and φ^* the creep coefficient at the limit of elasticity. This coefficient K_E can be defined on concrete cylinders and is presented in [9] with (6) and (7):

$$\lambda_E = \pi^2 \cdot \frac{i^3}{I} \cdot \frac{1}{\gamma\varphi} \tag{6}$$

$$K_E = \lambda_E \cdot \frac{i^3}{I} \cdot \frac{1}{E_H\gamma} \tag{7}$$

where γ is the specific weight of the material, i is the minimum radius of gyration, λ_E is the slenderness ratio at the limit of elasticity and I is the minimum moment of inertia of the cross section. Taking into account (4) and (5) a mathematical function between RDA modulus and critical stress is made. The RDA modulus in first iteration can be calculated using the equation:

$$E_R^{(1)} = \frac{3 \cdot E_H}{(5-4\cdot\mu)+2\cdot(1+\mu)\cdot\sigma_{cr}\cdot K_E} \tag{8}$$

The buckling stress σ_{cr} causes the decrease of stiffness and is the input parameter for the next iteration. The corresponding modulus after (n) iterations is given by the following equation:

$$E_R^{(n)} = \frac{3 \cdot E_H}{(5-4\cdot\mu)+2(1+\mu)\cdot{\sigma_{cr}}^{(n-1)}\cdot K_E} \tag{9}$$

(9) is used to calculate the buckling stress of concrete panels under biaxial compression. The buckling stress is calculated using the finite element method in the Abaqus software. The RDA modulus changes in each iteration from the buckling stress and for each iteration a buckling calculation in Abaqus is required. This iterative procedure can be simplified by using a linear numerical function between modulus and buckling stress. This numerical function was found using several buckling stress calculations for different E-modulus and is used in (9). This procedure is described in Chapter 3.

3 Experimental verification

3.1 Materials and test specimen

The concrete panel specimens used in this study were 500 x 500 x 50 mm in dimension. The panels are reinforced with a Q84 reinforcing mesh on both sides that has a bar thickness of 4 mm. Concrete cover is 10 mm. The edges of the panel are additionally reinforced with stirrups of 4 mm, that are welded on reinforcement mesh. All reinforcement is constructive and in theoretical consideration is not taken into account. Reinforcement should exclude early failure of the corners. Self-compacting concrete with 8 mm aggregate size was used. Normal weight concrete mixtures with three different concrete strengths are tested. The reinforcement as well as formwork of panels are presented in Figure 2. The care and storage of all concrete samples until the test was carried out within the company Binis Beton in Banja Luka (Bosnia and Herzegovina), where the concrete strength on cubes 150 mm are tested. Concrete cylinders *d/h* = 150 mm/300 mm are tested at the University of Novi Sad - Serbia (Laboratory of Civil Engineering Subotica). The elastic modulus, Poisson's ratio and density are tested on cylinders. The results are shown in Table 1.

Figure 2: Reinforcement and formwork of concrete panels

3.2 Experimental set-up

The experiments were performed in the company Selena d.o.o. in Banja Luka (Bosnia and Herzegovina) with a hydraulic machine (No. 000100). The machine was upgraded for the biaxial compression tests. Horizontal compression was realized by two parallel-bonded hydraulic cylinders (Product Lukas with 100 tons per cylinder) which are placed in the same steel frame with concrete panels. The steel frame is coated with fat on the inside to reduce the friction allocation between the panel and the steel frame. Eccentricity of load was zero. The experimental set-up is shown in Figure 3.

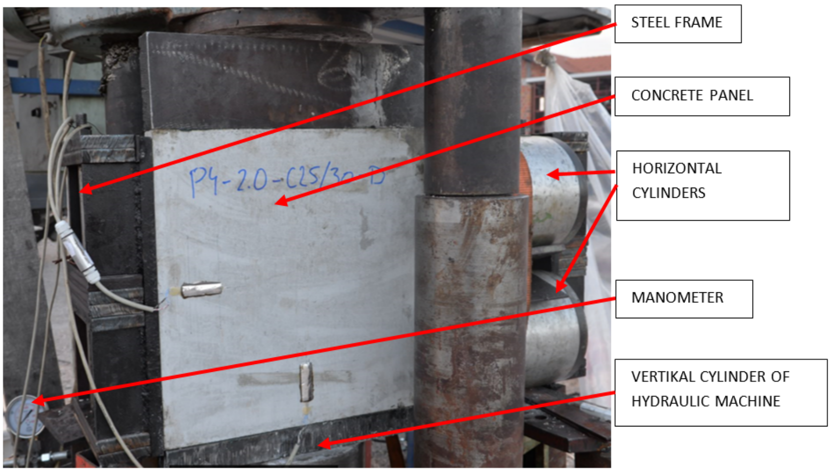

Figure 3: Experimental set-up

Two different biaxial stress ratios for compression were considered. For tests with stress ratio 1.0 it was necessary to use a pressure booster because the horizontal and vertical cylinders deliver different forces. A pressure booster is a cylinder with different surfaces of the front and dorsal sides whose surfaces throughout the mechanism are obtained by applying Pascal's law. These surfaces are approximately aligned with the surfaces of the horizontal cylinders and the vertical cylinder of the press. The vertical cylinder has the following dimensions D_1 = 320 mm (A_1 = 804 cm^2), while two horizontal cylinders with a diameter of D_2 = 171,5 mm together give the area A_2 = 462 cm^2 and the ratio of their surfaces is 0,57. To obtain a ratio of 1,0, a pressure booster is used, which has a cylinder diameter of 62 mm and a piston rod of 45 mm. The ratio of the dorsal and front surfaces is 2,11; thus, the pressure in the horizontal cylinders will be many times greater than the pressure in the vertical cylinder. Without considering the influence of friction forces in cylinders the ratio of the horizontal and vertical forces would be

0,57 x 2,11 = 1,2. This ratio was corrected by measuring the friction of the cylinder. The influence of the friction in the cylinder was determined using one horizontal cylinder which was placed in the ram press. The separate measurement was carried out by first suppressing the upper cylinder with the lower cylinder and at the same time reading pressures. The measurement was also made in the opposite direction by pumping with a manual pump and moving the cylinders down. Loss due to friction in the cylinder was determined to be about 10%. Taking into account the loss due to friction in the pressure booster the stress ratio was corrected to 1,08. For the stress ratio 0,57 the pressure booster was not necessary. Figure 4 shows the entire tying scheme.
In this experiment the stress ratios of horizontal and vertical force 1,08 and 0,57 were applied. Pressure readings on the manometer are converted into pressure on the concrete surface 50 x 5 cm and a coefficient of 0,9 is used due to the influence of friction in the cylinders. The approximate load rate range was about 0,2 – 0,6 MPa/s. This was made using a force increment regulator. The measuring of the concrete strain in two directions was carried out on a few samples using a strain gauge (HBM-1-LY41-50/120) and the corresponding Catman software, which is owned by the Institute for Testing Materials and Structures in Banja Luka (Bosnia and Herzegovina). The strain measurements in the edge area (distance from edge 7,5 cm) was used only to control the real stress ratios during the experiment. All pressure measurements were recorded with a camera until concrete panel failure.

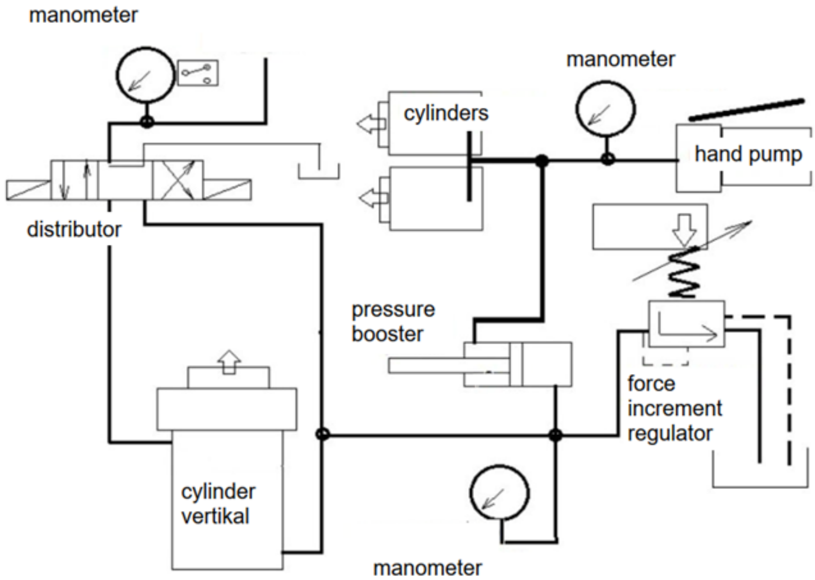

Figure 4: Experimental tying scheme

3.3 Test results

The test results on cubes and cylinders are shown in Table 1 and the measurement on concrete panels under biaxial compression with stress ratios 1,08 and 0,57 is shown in Table 2. Failure of concrete panels is shown in Figure 5.

Figure 5: Failure of concrete panel (stress ratio 1.08 left) / (stress ratio 0,57 right)

Table 1: Material parameters for three different concrete mixtures

No.	Mixture	Age (days)	Density γ (kg/m3)	Modulus of Elasticity E (MPa)	Poisson's ratio μ	Compressive strength $f_{c,cylinder}$ (MPa)	Compressive strength $f_{c,cube}$ (MPa)
1	A	119	2416,33	36602,62	0,110	41,64	47,29
2		179	2405,01	36200,00	0,120	38,25	44,01
3		179	2397,46	38320,39	0,110	39,61	46,11
average values			**2406,26**	**37041,00**	**0,113**	**39,83**	**45,80**
4	B	179	2463,48	38800,00	0,100	45,04	57,51
5		179	2444,62	37722,22	0,125	59,30	58,89
6		116	2471,03	39180,61	0,120	48,66	58,88
average values			**2459,71**	**38567,61**	**0,115**	**51,00**	**58,42**
7	C	157	2442,73	38175,52	0,104	58,17	72,27
8		111	2476,69	38985,85	0,090	58,17	72,91
9		179	2450,28	39357,14	0,103	48,67	73,43
average values			**2456,57**	**38839,50**	**0,099**	**55,00**	**72,87**

3.4 Verification of test results according to RDT

The calculation method according to the RDA modulus iterative method is shown in this chapter for concrete panels (stress ratio 0,57 and mixture A); other results can be found in Table 4. The first iteration for the calculation of the buckling stress is made using the finite element method in Abaqus (with finite element type S3), where the linear elastic model with modulus elasticity and Poisson's ratio from Table 1 are considered. To avoid a repeated calculation in Abaqus, a linear function between modulus of elasticity and buckling stress is used and thus the iterative method is accelerated. The Abaqus model and the linear function for the stress ratio of 0,57 are shown in Figure 6. The coefficient K_E was calculated using Eq. (6) and (7). The values for mixtures A, B, and C were 0,07, 0,06, and 0,08, respectively. The iterative method was performed using Eq. (9) and is shown in Table 3.

Table 2: Vertical buckling stress on concrete panels under biaxial compression - test results

Concrete panel	Vertikal buckling stress σ_v (MPa)	
P1-1.08-A	**20,3**	**Stress ratio σ_h/σ_v = 1,08**
P7-1.08-B	20,3	
P8-1.08-B	18,8	
average value	**19,6**	
P9-1.08-C	24,6	
P10-1.08-C	26,0	
average value	**25,3**	
P1-0.57-A	27,5	**Stress ratio σ_h/σ_v = 0,57**
P2-0.57-A	26,1	
P3-0.57-A	31,8	
P4-0.57-A	28,9	
average value	**28,6**	
P5-0.57-B	34,7	
P6-0.57-B	28,9	
P7-0.57-B	30,4	
P8-0.57-B	31,3	
average value	**31,3**	
P9-0.57-C	35,3	
P10-0.57-C	43,4	
P11-0.57-C	37,6	
P12-0.57-C	32,4	
average value	**37,2**	

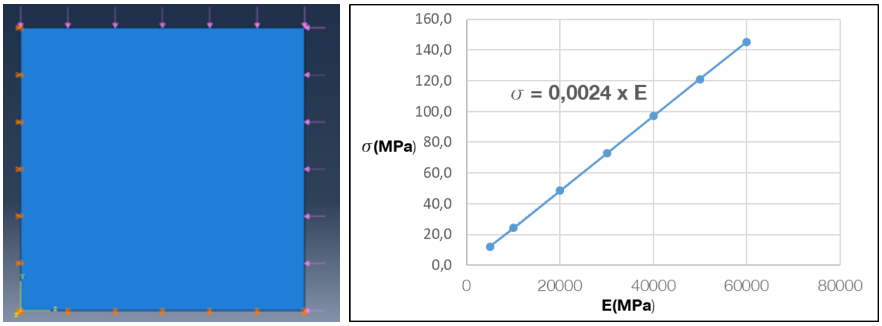

Figure 6: Abaqus model (left) / Linear function between modulus of elasticity and buckling stress (right)

The buckling stress on concrete panels according to RDT is 29,14 MPa, which was very well matching with the experimental value of 28,60 MPa. A comparison between the RDT calculation and the experiment values are shown in Table 4. The buckling mode 1 of concrete panels in Abaqus in first iteration is presented in Figure 7.

Table 3: RDA modulus iterative calculation for mixture A and stress ratio 0.57

Modulus of Elasticity E (MPa)	Poisson's ratio μ	K_E	RDA modulus E_R (MPa)	Vertikal buckling stress σ_v (Mpa)
37041	0,113	0,07	37041,00	88,90
37041	0,113	0,07	5976,82	14,34
37041	0,113	0,07	16307,68	39,14
37041	0,113	0,07	10355,17	24,85
37041	0,113	0,07	13113,05	31,47
37041	0,113	0,07	11672,71	28,01
37041	0,113	0,07	12383,07	29,72
37041	0,113	0,07	12022,24	28,85
37041	0,113	0,07	12202,86	29,29
37041	0,113	0,07	12111,77	29,07
37041	0,113	0,07	12157,53	29,18
37041	0,113	0,07	12134,50	29,12
37041	0,113	0,07	12146,08	29,15
37041	0,113	0,07	12140,25	29,14
37041	0,113	0,07	12143,19	29,14

Table 4: Comparison between RDT calculation results and experiment values

Stress ratio / Mixture	Vertikal buckling stress σ_v (Mpa) - Test	Vertikal buckling stress σ_v (Mpa) - RDA	η (-)
1,08 / A	20,3	23,9	0,85
1,08 / B	19,6	24,7	0,79
1,08 / C	25,3	24,2	1,05
0,57 / A	28,6	29,1	0,98
0,57 / B	31,3	29,9	1,05
0,57 / C	37,2	29,3	1,27

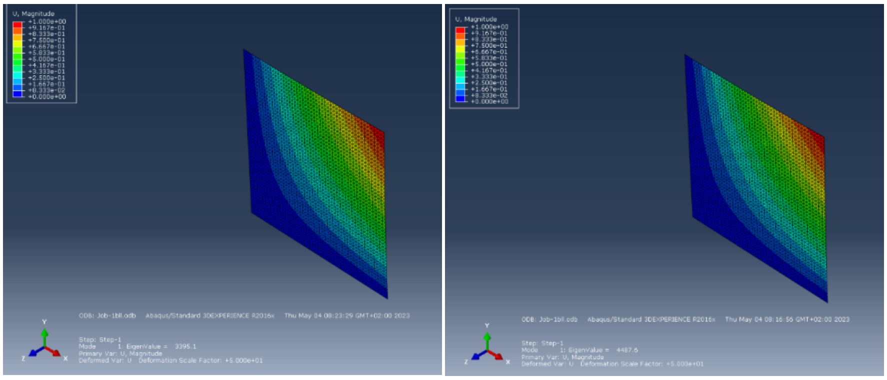

Figure 7: Buckling mode 1 of concrete panels in Abaqus in first iteration (stress ratio 1.08 left) / (stress ratio 0.57 right)

4 Verification against results from literature

4.1 Example 1

In addition to the experiment from chapter 3 in this example the verification of the RDA iterative method for stability of concrete panels under axial compression is shown. The experimental results from Lechner T. and Fischer O. (2015) [14] are used. They researched the load bearing behavior and stability of slender wall panels made of normal strength plain concrete and fibre-reinforced ultra-high performance concrete UHPC under axial compression. They considered different eccentricity values as well as the panel thickness. For this example, only concrete panels with dimensions $b \times h \times t = 1200 \times \mathrm{mm}\ 400 \times \mathrm{mm}\ 60\ \mathrm{mm}$ with an eccentricity of 10 mm are considered. Material parameters were measured on cubes 100 mm and cylinders 150 mm x 300 mm. Since for the calculation of the structural material constant K_E the measured values of modulus of elasticity and Poisson's ratio are necessary, this was partially taken into account. For normal concrete mixture (with the name C50/60) and for mixture of UHPC (with the name B5Q) modulus of elasticity 37000 MPa and 51000 MPa are used respectively. Poisson's ratio 0,15 and density 2400 kg/m^3 was used for both mixtures. The structural material constant K_E for C50/60 and B5Q were calculated 0,05 and 0,04, respectively. The experimental set up and Abaqus model used for this example are shown in the Figure 8.

Analogous to calculation in Section 3.4. the same calculation method was used. For every mixture are used two concrete panels. The test results of buckling forces for two concrete panels with mixtures C50/60 and B5Q are (510,0 kN, 483,0 kN) and (836,0 kN, 941,0 kN), respectively. The RDT calculation results for C50/60 and B5Q are 694,4 kN and 933,6 kN, respectively.

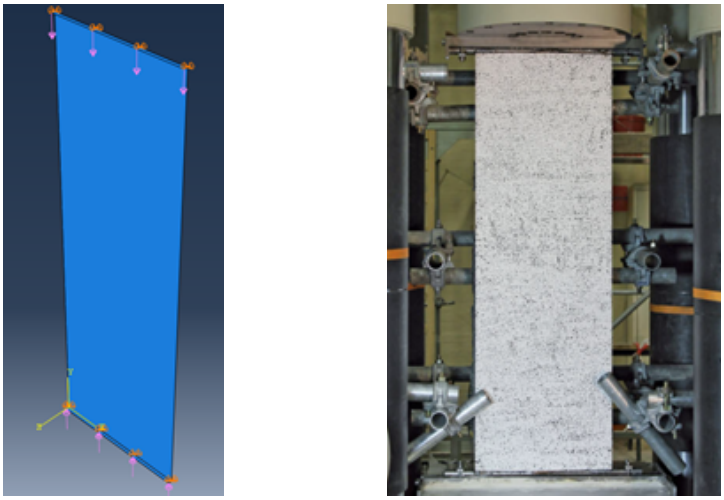

Figure 8: Abaqus model (left) and experimental set up from Lechner T. and Fischer O. (2015) [14] (right)

4.2 Example 2

For further verification of the RDA iterative method in this example analytical expressions from literature on two-way action concrete panel were used. [15] tested 24 rectangular, reinforced concrete panels. The analytical expression as well as the results can be found in [4]. This expression is given by (10),

$$f_{cr} = 0.425 \cdot f_c' \cdot B \cdot [-B + (4 + B^2)^{0.5}]; \quad B = \frac{\pi^2 \cdot (\frac{1}{L} + L)^2 \cdot (h/b)^2}{6 \cdot \varepsilon_0 \cdot (1-\rho)} \tag{10}$$

where $L = a/b$, if $a/b < 1$ and *L*=1 if $a/b > 1$. *a*, *b*, and *h* are panel length, width and thickness, respectively. Average ultimate strain of concrete after 28 days was assumed for this example ε_0=0,0035 and the total reinforcement ratio ρ for this example was zero.
For the calculation of this example a concrete panel with length *a* = 4 m, width *b* = 2 m and thickness *h* = 0.05 m was used because [15] tested the concrete panels with aspect ratio *a*/*b* = 2,,0. slenderness b/t = 75 to 128,51 and concrete strength f_c' = 16,65 to 27 MPa. For the calculation concrete with strength of f_c' =25 MPa was used. The modulus of elasticity of 28960,4 MPa was calculated with [6]. Poisson's ratio 0,20 and density 2400 kg/m^3 was used for the calculation on this example. The structural material constant K_E = 0.04 was calculated. The calculation results of buckling stress according to (10) and RDT calculation are 17,1 MPa and 17,7 MPa, respectively.

5 Conclusions

In this paper was presented and experimentally verified the RDA iterative modulus method for the calculation of biaxial buckling stress of concrete panels. The experimental results from Chapter 3 showed a very well matching with RDT calculation for both compression stress ratios. The measured values of modulus of elasticity, Poisson's ratio, and density have a significant influence on the structural material constant K_E as well as buckling stress results according to RDT. The first iteration of buckling stress was calculated using a model in Abaqus where the end conditions as well as the finite element mesh have influence on results. For further iterations (without Abaqus), a linear function between buckling stress and modulus of elasticity was used in this paper and has enabled faster calculations. In the Section 4.1 the RDA iterative modulus method used for calculation of buckling stress of concrete panels under axial compression is discussed. It was shown that this method can be used on normal strength plain concrete and fibre-reinforced ultra-high performance concrete UHPC. In the Section 4.2 the RDT calculation was compared with the analytical expression from literature on two-way action concrete panel. This results also show a very good matching.
As presented in this paper the RDA iterative modulus method in combination with finite element method can be used for the calculations of axial and biaxial buckling stress for different concrete mixtures, where it is necessary to have the material parameters values.

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