

# DETERMINATION OF A 1D ELEMENT STIFFNESS FOR A STEEL-CONCRETE-STEEL STRUCTURE MODELLING VIA PLANE ELEMENT LAYERING

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## ABSTRAKT

Metoda modelování vrstvením je založena na modelování každé materiálové vrstvy jednotlivě pomocí plošných MKP prvků, které jsou propojeny 1D prvky v každém uzlu sítě konečných prvků. Vlastní předchozí studie ukázaly, že výsledky analýzy jsou do jisté míry ovlivněny tuhostí 1D prvků. Z tohoto důvodu by měly být tuhosti stanoveny. První část článku je zaměřena na autorovu motivaci a na stručný popis metody vrstvení. Soubor již provedených zatěžovacích zkoušek je představen pro srovnání výsledků vlastní analýzy se skutečným chováním ocelobetonového sendviče. Tyto zkoušky jsou použity pro srovnání s výsledky vlastní numerické analýzy, přičemž jsou upravovány tuhosti 1D prvků pro dosažení uspokojivé shody. Na základě této analýzy je vedena diskuse ohledně vhodných úprav modelu.

## KLÍČOVÁ SLOVA

1D prvky • Vrstvený model • Tuhost • Ocelobetonový sendvič  
• Klouby

## ABSTRACT

The method of plane element layering is based on modelling of each material layer separately by FEM plane elements, which are connected by 1D elements in each node of a finite element mesh. Previous studies have shown, that results of the analysis are certainly dependent on the stiffness of 1D elements. Therefore, the stiffness must be determined. The first part of the paper is focused on the motivation and a brief description of the considered modelling method. To correlate the results from the own analysis with the real behaviour of the steel-concrete-steel structure, the set of already performed tests is also shown. These tests are used for the comparison with numerical calculation results, while the stiffness of 1D elements is modified for the sufficient compliance. According to this analysis, a discussion is held on appropriate adjustments of the model.

## KEYWORDS

1D elements • Plane layered model • Stiffness • Steel-concrete-steel sandwich • Hinges

## 1. INTRODUCTION

A steel-concrete-steel sandwich (SCS) structure consists of two external steel plates, which are anchored to infill concrete. The composite action is mostly provided by a combination of headed studs and tie bars.

Since the SCS shows a great performance regarding high capacity and resistance, it is considered as one of the construction variants of containment of helium-cooled fast demonstration reactor ALLEGRO. A containment of nuclear reactor is a structure of a very high importance, which requires the detailed structural analysis including nonlinear modelling using volumetric finite elements. However, it must be remembered that it is very demanding to create and calculate such a complex model in terms of the correct setting of input parameters, the time of creation and calculation of the model and finally due to the large volume of data obtained and their complicated evaluation. Since the current goal of project ALLEGRO is a feasibility study analysing several different construction variants, it is more appropriate to analyse the structure with less time-demanding procedure. One of the possible options to simplify the procedure is to model the structure using plane elements and effective stiffness to include materially non-homogeneous cross-section and nonlinear behaviour. Considered alternative is also modelling via plane element layering which is introduced in the following section. The aim of this paper is to perform the sensitivity analysis of input parameters of the discussed model based on plane elements layering method.

## 2. PLANE ELEMENTS LAYERING METHOD

The method is literally based on layering of plane elements while each plane element represents the material layer itself. The offset between plane elements should correspond to the real geometry of the SCS cross-section. A connection between plane elements is provided by 1D elements, which should keep the distance between the planes and create a shear environment. Spacing of 1D elements should be determined for the finite element mesh of plane elements.

To benefit from this method, material models of plane elements should include nonlinear behaviour of each layer (concrete and steel). For layers that represent steel plates, it is appropriate to use von Mises yield criterion, which is typically

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used for ductile materials. For the layer representing the concrete core, both Drucker-Prager and Mohr-Coulomb yield criterion can be used. Both can distinguish different compressive and tensile behaviour, and both are typically used for materials as soil and concrete. The Drucker-Prager yield criterion may be expressed as (Scia Engineer 2019).

$$\left(\frac{m-1}{2}\right)(\sigma_1+\sigma_2+\sigma_3)+\left(\frac{m+1}{2}\right)\sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}}=\sigma_E \quad (1)$$

Where:

$$m=\frac{S_{yc}}{S_{yt}} \quad (2)$$

Where  $S_{yc}$  and  $S_{yt}$  are the uniaxial yield stresses in compression and tension respectively. The Mohr-Coulomb yield criterion may be expressed as [4]:

$$\left(\frac{m+1}{2}\right)\max(|\sigma_1-\sigma_2|+K(\sigma_1+\sigma_2), |\sigma_1-\sigma_3|+K(\sigma_1+\sigma_3), |\sigma_2-\sigma_3|+K(\sigma_2+\sigma_3))=\sigma_E \quad (3)$$

Where:

$$K=\frac{m-1}{m+1} \quad (4)$$

A choice of one or the other is considered as one of the variable parameters of the model.

1D elements contain most of variable parameters that affect results of the analysis. Specifically, it is geometry of a cross-section, material parameters (Young's modulus and shear modulus as the behaviour of 1D elements is considered to be elastic), and possibility of hinge adding. Since the stiffness of 1D elements can be modified by both geometry and material parameters, it makes sense to maintain geometry of the cross-section constant to reduce the number of variables. The dimensions of the cross-section are determined to correspond to the dimensions of the finite element mesh of the plane elements.

### 3. PERFORMED TESTS

As the analysis results significantly vary when the input parameters of the model are changed, the model setup must be calibrated and generalized to correspond to the verified real behaviour of the SCS structure. For this purpose, already performed test is briefly presented below. The out of plane behaviour of the model is calibrated with bending tests on SCS beams (M. Xie, N. Foundoukos, J.C. Chapman. 2007, T.M. Roberts, D.N. Edwards, R. Narayanan. 1996, T.O.S. Oduyemi, H.D. Wright. 1989, McKinley, B. 1999, Peter N. Booth, Amit

H. Varma, Kadir C. Sener, Sanjeev R. Malushte. 2015) while the in-plane behaviour is calibrated with in-plane shear tests on square panels (Masahiko Ozaki, Shodo Akita, Hiroshi Osuga, Tatsuo Nakayama, Naoyuki Adachi. 2004).

#### 3.1. In-plane shear tests

Japanese experimental program (Masahiko Ozaki, Shodo Akita, Hiroshi Osuga, Tatsuo Nakayama, Naoyuki Adachi. 2004) has been chosen for a verification of the out of plane response of the model. The program includes nine SCS panels. All panels were 1200 x 1200 mm in in-plane dimensions and 200 mm thick. The principal variable parameter of panels was different reinforcement ratio. Additionally, four panels were subjected to the combination of the compression and the in-plane shear, while the rest were subjected to the pure in-plane shear. Two panels were also added by a partitioning web plate. However, panels S2-00NN, S3-00NN, and S4-00NN, whose only variable parameter is reinforcement ratio, will be used for the purposes of this paper.

Table 1: Geometry and material parameters of the panels.

Specimen	Geometry						Steel parameters		Concrete parameters	
	Plane dimensions			Width	Steel thickness	Reinforcement ratio	Yield stress	Young's modulus	Compressive strength	Tangential stiffness
	[mm]	[mm]	[mm]	[mm]	[mm]	[%]	[MPa]	[MPa]	[MPa]	[MPa]
S2-00NN	1200	x	1200	200	2.3	2.30%	340	197000	42.2	27200
S3-00NN	1200	x	1200	200	3.2	3.20%	351	199000	41.9	27100
S4-00NN	1200	x	1200	200	4.5	4.50%	346	207000	42.8	27600

#### 3.2. Bending tests

A set of different bending tests from five different experimental programs has been chosen for purposes of calibration of created models. Failure mode of specimens has been the principal selection criteria for inclusion of a specific specimen. A suitable specimen's failure mode is yielding of tensioned steel plate which is followed by crushing of concrete core.

A list of chosen beams is shown below together with all variable parameters of test setup. As can be seen, the principal variables are the bending test type (3-point bending, 4-point bending or 6-point bending), reinforcement ratio (respectively geometry of specimens), composite action elements, and material parameters.

Table 2: Geometry and material parameters of the beams.

Specimen	Ref.	Geometry						Height/ Span	Test	Concrete		Steel			
		Height	Width	Span	Lower steel plate thickness	Upper steel plate thickness	Reinforcement ratio			Bending type	Concrete strength	Tangential stiffness	Yield strength	Ultimate strength	Young's modulus
		[mm]	[mm]	[mm]	[mm]	[mm]	[%]			[-]	[MPa]	[MPa]	[MPa]	[MPa]	[MPa]
BS1	[5]	400	400	1200	6.23	6.23	3.22%	0.333	3 point	by C40/50		384	507	-	
BS4		200	400	1200	6.13	11.95	9.94%	0.167	3 point	by C40/50		384	507	-	
BS7		200	400	1800	6.2	11.93	9.97%	0.111	3 point	by C40/50		384	507	-	
BS10		200	400	2400	6.1	11.95	9.92%	0.083	3 point	by C40/50		384	507	-	
B1	[6]	166	400	1700	8.04	8.04	10.72%	0.098	6 point	27.4	30000	202	-	210000	
B1	[7]	150	150	1450	2	3	3.33%	0.103	4 point	40.5	29600	242 <sup>1)</sup>	339 <sup>1)</sup>	210000 <sup>1)</sup>	
B2		150	150	1450	3	3	4.00%	0.103	4 point	41.3	29600	268 <sup>2)</sup>	389 <sup>2)</sup>	209000 <sup>2)</sup>	
B3		150	150	1450	4	4	5.33%	0.103	4 point	38.9	29600	252 <sup>3)</sup>	379 <sup>3)</sup>	207000 <sup>3)</sup>	
B4		150	150	1450	6	4	6.67%	0.103	4 point	40.5	29600	288 <sup>4)</sup>	475 <sup>4)</sup>	197000 <sup>4)</sup>	
City1	[8]	220	1000	3400	10	10	10.00%	0.065	3 point	43.7	-	452	540	-	
Specimen 4	[9]	1220	610	6705	12.7	12.7	2.08%	0.182	4 point	37.9	-	439.9	-	-	

## 4. MODELLING

The previous section provides important data regarding geometrical and material parameters, yield strength, and ultimate strength. To supplement the data regarding the stress state of specimens, which the references do not include, volumetric nonlinear model of beam specimen 4 and wall specimens S2-00NN, S3-00NN, and S4-00NN have been created.

### 4.1. Modelling via volumetric elements

#### 4.1.1. Wall panels

All parts of the models are modelled using volumetric finite elements. Elements of the concrete core and the external steel plates are fully fixed to each other, which represents the composite action between these layers. The load is applied through the edge reinforcing plates according to test setup.

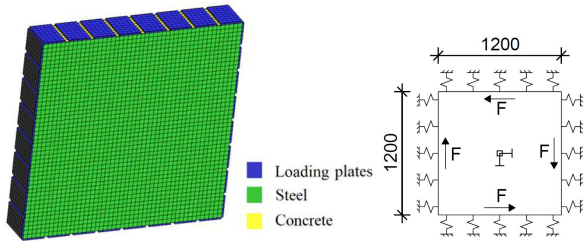


Figure 1: *Volumetric model of the specimen S3-00NN on the left, boundary condition on the right.*

The most basic material parameters of steel (yield stress, Young's modulus) and concrete (compressive strength, tangential stiffness) are taken from experimental measurements see (Tab. 1). The hardening modulus of steel is set up as 700 MPa. The Poisson's constant is considered as 0.3 for steel and 0.2 for concrete. The rest of the parameters, especially for concrete, are chosen to correspond to C40/50 strength class of concrete according to Eurocode 2 (EN 1992-1-1 Eurocode 2 2002). The material of the edge reinforcing plates is considered as linear elastic with elastic modulus of 210 GPa.

The model is loaded by plane forces, which are applied on edge surfaces of the edge reinforcing plates. The increments of the load of 100 kPa are applied on every edge reinforcing plate in the direction of the forces, corresponding to pure shear (Vecchio, and McQuade 2011).

Supports of the models must satisfy these conditions. It must constrain the model enough to avoid instability but has to be released enough to enable extension of the model (i.e., it has to prevent rigid body dominated motion). According to that, every edge reinforcing plate is supported by plane springs with a stiffness of 1000 MN/m<sup>3</sup> in transverse direction of the edge of the model (see figure 1).

#### 4.1.2. Specimen 4

Because specimen 4 is the largest specimen compared to the others, it was selected as the one for volumetric modelling. The composite action is modelled the same way as in case of wall panels. As the elements of the composite action are not physically modelled, model must be supplemented by a measure

that avoids transverse shear failure. It is provided by 1D reinforcement elements, which originally serve for rebars modelling. It only carries normal forces and does not increase the numerical complexity of the model.

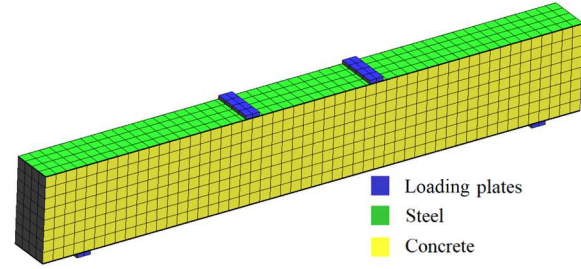


Figure 2: *Volumetric model of the specimen 4.*

Since the only material parameters, which are presented in the experimental program, are the concrete strength 37,8 MPa and yield strength of the steel 439,9 MPa, the rest are defined according to C35/45 strength class of concrete (EN 1992-1-1 Eurocode 2 2002). The Young's modulus of the steel is estimated as 200 GPa, hardening modulus as 700 MPa.

### 4.2. Modelling via plane element layering

#### 4.2.1. Wall panels

In this case, the material model for the concrete has far fewer parameters, because it does not include the failure parameters. Since the considered material model is isotropic elastic-plastic, its only parameters are Young's modulus, shear modulus, and the uniaxial yield stresses in compression  $S_{yc}$  and tension  $S_{yt}$ . The uniaxial yield stress in compression  $S_{yc}$  is considered as compressive strength from experimental measurements see (Tab. 1) and the uniaxial yield stress in tension  $S_{yt}$  is considered as 2.5 MPa, which corresponds to characteristic the tensile strength of the concrete strength class C40/50 (EN 1992-1-1 Eurocode 2 2002). Both Drucker-Prager and Mohr-Coulomb yield criterion has been considered.

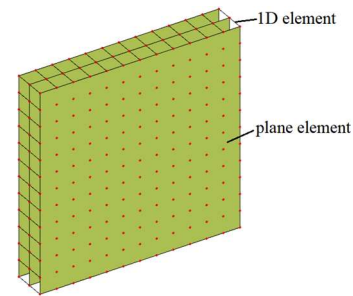


Figure 3: *Plane layered model of the specimen S3-00NN.*

As discussed in the section 2, the dimensions of the cross-section of 1D elements are 120x120 mm, which corresponds to the dimensions of the finite element mesh of the plane elements. 1D elements create a shear environment, which is formed by concrete in a SCS structure. Therefore, the material model of 1D elements is defined with modulus of elasticity that corresponds to the concrete strength class C40/50 (EN 1992-1-1 Eurocode 2 2002). This defines the initial estimate of the stiffness of 1D elements.

Because the plane layered model is much simpler in comparison to the volumetric model, where the problematic singular points can appear, the load is applied directly on the edges of each plane element. All edges are also supported by linear support with a stiffness of 10 MN/m<sup>2</sup> in transverse direction of the edge of the model.

#### 4.2.2. Beams

The width of each set of beams (see Tab. 2) varies, and therefore the size of the finite elements also varies, as they must be adapted to their width. For the set of beams [5], and [6] the finite element size is 100 mm, for [7] 50 mm, for [8] 200 mm, and for specimen 4 it is 150 mm. The finite element size is determined regarding suitable 1D elements placement. At least three 1D elements are designed in the transverse direction of the model. The longitudinal arrangement is controlled by the position of the load and supports.

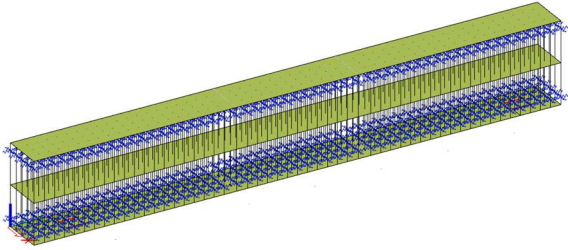


Figure 4: Plane layered model of the specimen 4.

Modulus of elasticity, and the uniaxial yield stress in compression  $S_{yc}$ , are defined according to experimental data measurements. Missing moduli of steel plates are estimated as 200 GPa for [5], [8], and [9]. Missing moduli of concrete cores are determined according to the concrete strength class C45/55 for [8], and C35/45 for [9]. The initial estimate of the uniaxial yield stress in tension  $S_{yt}$  is 2.5 MPa, however as will become apparent later, beam models are quite sensitive on this material parameter. Both Drucker-Prager and Mohr-Coulomb yield criterion has been considered.

Similarly, as in case of wall panel models, the cross-section of the 1D elements corresponds to finite element size and its material is estimated according to material of the concrete core. In case of beam models, transverse shear behaviour must be considered. This includes slip between the concrete core and the steel plates and eventually shear cracking of the concrete core. Reference [6] states an indicative value of the composite action elements shear stiffness as 10 000 N/mm, which is an approximate average determined from push shear tests on 6 mm and 10 mm diameter studs. It can be implemented in the model with elastic hinge that enables the slip between the node of the 1D element and the node of the steel plate plane element. Value 10 000 N/mm is used as initial estimation of shear stiffness of hinges for each model.

### 4.3. Evaluation

#### 4.3.1. Wall panels

To evaluate an accuracy and a suitability of plane layered models, three key moments of the shear response are controlled

(concrete cracking, steel yielding, and concrete crushing). The evaluation of the load-deformation correlation is performed by comparison of tests and model analysis results. Because the volumetric models correlate well with tests results (see figure 5), they can be used for a comparison of stress-strain state of plane layered models.

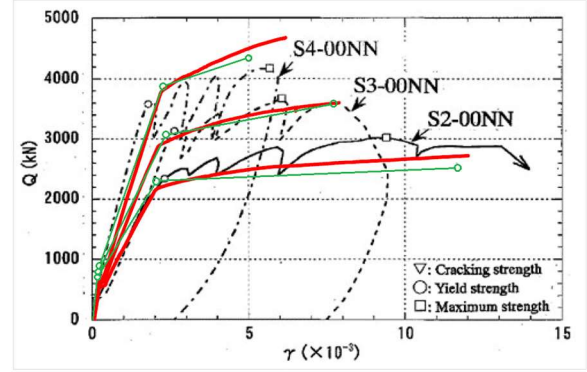


Figure 5: Comparison of the responses of experimental program (black), volumetric model (red), and plane layered model (green).

The figure 5 shows the comparison of the in-plane shear responses of the tested panels (black curves), volumetric model (red curves), and plane layered model (green curves). As can be seen, both models predict the in-plane shear behaviour of the panels very well especially with regard to steel yielding and plastic part of the response. On the other hand, both models underrate the concrete cracking, whereby both models predict the cracking strength approximately twice higher than experimentally measured values.

Table 3: Value comparison of the results of experimental program, volumetric model, and plane layered model.

Specimen	Cracking strength		Yield strength		Ultimate strength	
	$Q_c$ [kN]	$\gamma_c$ [ $\times 10^{-3}$ ]	$Q_y$ [kN]	$\gamma_y$ [ $\times 10^{-3}$ ]	$Q_u$ [kN]	$\gamma_u$ [ $\times 10^{-3}$ ]
Experimental program						
S2-00NN	293	0.115	2290	2.5	2960	9.41 (13.1)
S3-00NN	311	0.134	3070	3.01	3610	6.05 (7.9)
S4-00NN	349	0.103	3510	2.01	4100	5.67 (5.8)
Volumetric model						
S2-00NN	555	0.17	2168	2.08	2726	12.57
S3-00NN	604	0.18	2886	2.17	3596	8.23
S4-00NN	604	0.18	3790	2.28	4670	6.44
Plane layered model						
S2-00NN	702	0.23	2304	2.2	2565	12
S3-00NN	774	0.24	3024	2.29	3384	7.5
S4-00NN	846	0.24	3888	2.26	4356	4.9

The stress state of the model determines the failure of the structure by the concrete crushing. According to (EN 1992-1-1 Eurocode 2 2002), maximum stress  $\sigma_{Rd,max}$  in the compressive diagonal where traverse tension occurs, which is the case of the in-plane shear, is given by the following formula:

$$\sigma_{Rd,max} = 0,6 \cdot v \cdot f_c \quad (5)$$

$$v = 1 - \frac{f_c}{250} \quad (6)$$

As the compressive strength of the panel S3-00NN  $f_c$  is 41.9 MPa, the maximum stress is 20,9 MPa, which approximately corresponds to the stress state of the volumetric model before the collapse. When the plane layered model reaches this stress state, it is considered as failure.

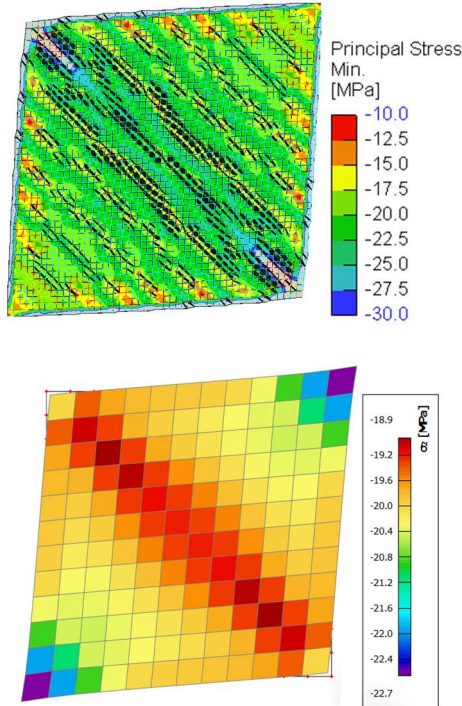


Figure 6: Comparison of the compressive principal stress of the volumetric model, and the plane layered model at the moment of failure.

To achieve the above presented results, it has not been necessary to modify the stiffness of the 1D elements. However, it must be mentioned that the Drucker-Prager yield criterion has been used to achieve this match. When the Mohr-Coulomb yield criterion was used, shear load applied on the model had

to be significantly higher to reach the same deformations as in case of use of the Drucker-Prager yield criterion.

#### 4.3.2. Beams

In the case of beams models, only two key moments of bending response are controlled. As none of the experimental programs include concrete cracking measurements, only steel yielding and concrete crushing are compared.

It is much more complex to calibrate the beam models. The most problematic phenomenon that brings the complexity of out of plane behaviour is the transverse shear. This includes the slip between the concrete core and the steel plates, and the shear cracking of the concrete core, which is problematic especially for higher beams in relation to the span (for example specimen BS1, BS4, and specimen 4).

The author determined three parameters that are able to influence the bending response of the models. The first one is the modification of 1D elements through their moduli of elasticity, which is able to correct deflections. The disadvantage of this procedure is that if the stiffness is modified through moduli of elasticity, the whole stiffness matrix is modified, which could be inappropriate. The other option is more advantageous, because it provides the choice of a degree of freedom that should be released. It is a modification of the hinge which is defined in the node that joins 1D elements and plane elements of the steel plates. This modification of the model can influence the deflection, the distribution of the stress between the steel plates and the concrete core and it also includes the influence of the slip. The last option is to decrease the uniaxial yield stress in tension  $S_{yt}$ , which is the material constant and therefore it should not be principally changed, but it is the only reasonable modification for the specimens with high height-span ratio to match the steel yielding key moment of the bending response. For example, value  $S_{yt}$  has been decreased from 2.2 MPa to 1.2 MPa to get the results of the model of specimen 4 presented above. For specimen BS1, it has been decreased even to 0.1 MPa. Even this modification does not give satisfying results of the model BS1.

Table 4: Comparison of the results of experimental program, volumetric model, and plane layered model.

Specimen	Cracking strength		Yield strength		Ultimate strength	
	$F_c$	$w_c$	$F_y$	$w_y$	$F_u$	$w_u$
	[kN]	[mm]	[kN]	[mm]	[kN]	[mm]
Experimental program						
BS1	-		1096	2.6	1591	18.9
BS4	-		553	6.1	727	14.4
BS7	-		333	7.1	545	45.9
BS10	-		245	8.9	415	70.2
B1	-		550	7	630	16
B1	-		45	1.8	51	13
B2	-		70	1.8	77	9.5
B3	-		90	1	94	7.7
B4	-		120	0.8	124	4
City1	-		1100	30	1375	300
Specimen 4	-		1779.3	22,86	1921.6	95,25
Plane layered model						
BS1	-		1400	2.9	1600	6.5
BS4	-		620	6.9	700	9.9
BS7	-		400	9.7	480	24.9
BS10	-		295	11.3	398	56.3
B1	-		544	8.6	640	23.8
B1	-		48	3.3	57.3	12.7
B2	-		70.5	3.9	81	9.4
B3	-		85.5	4.1	94.5	7.3
B4	-		130.5	5.6		
City1	-		1100	35	1650	320.1
Specimen 4			1780.0	23.2	2074.0	132.7
Volumetric model						
Specimen 4	236	0.7	1713.0	16.2	1965.0	125

The following figure shows the comparison of the bending responses of the specimen 4 (blue curve), volumetric

model (red curve), and plane layered model (green curve). As can be seen, steel yielding is predicted by both models very

well. The plane layered model can be set to closely correspond to the real specimen 4 behaviour. On the other hand, the volumetric model corresponds that well only in relation to the yield load. The yield deflection is a bit smaller. The author explains that himself as aspect of the slip negligence in case of the volumetric model.

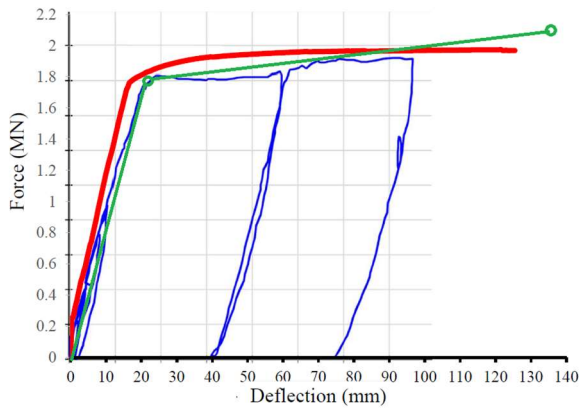


Figure 7: Comparison of the responses of experimental program (blue), volumetric model (red), and plane layered model (green).

The failure of the model is given by achieving of the failure strain of the concrete  $\epsilon_{cu} = 0.0035$ . Both the plane layered model and volumetric model achieve the failure with higher deflection in comparison to the real specimen 4. In this case, the author's opinion is that it could be caused by plasticisation of the composite action elements or compressed steel plate buckling. Neither one of these aspects are implemented in the current model.

## 5. CONCLUSIONS

This paper dealt with in-plane and out of plane behaviour of plane layered models, focusing on the input parameters affecting the accuracy of the analysis results. In the case of the in-plane modelling, the research has shown that the models predict the SCS behaviour well with no need to modify the stiffness of the 1D elements or other input parameters of the models. The investigation leads to a recommendation to use the Drucker-Prager yield criterion for the material model of the concrete core.

In the case of the out of plane modelling, satisfactory results have been obtained for most models, with some modifications to the models being necessary. The most effective way to correct the deformation behaviour of the model is to add the hinges onto the 1D elements and modify their stiffness. The models of the beams with higher height-span ratio had to be modified by decreasing of the uniaxial yield stress in tension  $S_{yt}$  to obtain the best possible match of the yield load.

Suggestions for the further work are as follows. Author would like to improve the models to better predict the transverse shear behaviour, with the following ideas. Hinges could be supplemented with a non-linear function that should consider the plastic behaviour of the composite action elements

and the possibility of the steel plate buckling. Physical model of the concrete core could be layered into more layers, which could better predict the shear cracking.

## ACKNOWLEDGEMENTS

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