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Computational Prediction Study on Green Self - Compacting Concrete (GSCC) Composite Slab with Different Thickness of Steel Sheet Slab Subjected to Flexural Load

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Abstract: Self-compacting concrete (SCC) is an improved quality of concrete that used less aggregates, but higher cement content than normal concrete. It is able to flow by itself and does not require compaction. Yet, the researches about the structural behavior of SCC composite slab are still lacking. The objectives of this research are to develop a slab model using ABAQUS software and study the influence of various steel sheet slab thicknesses on ultimate load, crack pattern and load-deflection profiles of GSCC composite slab subjected to flexural load by means of finite element method. Convergence study determined the suitable thicknesses of model and validation carried out to check the difference between results from this study and result of previous research. The differences were less than 10% from the previous research results. It was found that the ultimate load compared to previous research had a slightly difference which were 10.3% and 1.5% for control specimen and GSCC composite slab respectively. A series of parametric study was carried out on GSCC composite slab with dimension 150 mm depth by using 0.8 mm, 1.0 mm and 1.2 mm of steel sheet thickness and compared with the GSCC composite slab. The steel sheet thickness of composite slab affected the structural behaviour of composite slab in term of ultimate load, crack pattern and deflection. It was proven that FEA by using ABAQUS was able to predict the structural behaviour of structural elements with a high accuracy level. By partially replacing cement with POFA and ESP, it produces eco-friendly products, reduces cement production and indirectly decreases the emission of carbon dioxide to the atmosphere.

Keywords: Self-Compacting Concrete, Composite slab, ABAQUS, Steel Deck, FEM

1. Introduction

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Malaysia is a developing country and the durability of concrete structure was always a key issue for our country. Self-Compacting Concrete (SCC), also known as self-consolidating concrete, has been developed by Professor Hajime Okamura in late 1980's. It is an improved quality of concrete which can solve many problems faced in construction site. According to Santamaria et al. [1], the mixes can be poured into formwork and it can fill through the rebars due to its special properties. The powder materials such as fly ash and limestone are used in SCC mixtures to achieve optimum workability with high durable and performance [2]. The finite element method (FEM) is a numerical method to solve complex mathematical problems in engineering and physics. It is also known as finite element analysis (FEA). Engineers use it to reduce the number of physical prototypes and experiments and optimize components in their design phase to develop better products, faster while saving on expenses. The common applications for FEM are linear, non-linear, buckling, thermal, dynamic and fatigue analysis.

The aims of this research are to develop numerical model of green self-compacting concrete composite slab using ABAQUS software, to analyze the influence of various steel sheet slab thicknesses on ultimate load, crack pattern and load-deflection profiles of GSCC composite slab subjected to flexural load by means of finite element method and to perform parametric study on GSCC composite slab in term of steel sheet slab thickness. The scopes are to compute a model of GSCC composite slab through FEA by using ABAQUS software, conduct simulations and determine suitable mesh sizes of GSCC composite slab by using FEA and perform a series of parametric study on GSCC composite slab by changing various thickness then compared to its original simulation.

2. Literature Review

Self-compacting concrete is a modified concrete which can be flowed and consolidated under its weight without the vibration. It is a high performance and strength concrete [3]. A study about performance of self-compacting concrete incorporating palm oil fuel ash and egg shell powder as partial cement replacement was conducted by Kamaruddin [4]. This study shows that SCC 5P 2.5E would be the most optimum proportion among 10 different mix proportion of concrete. From the result, SCC 5P 2.5E achieved the maximum compressive strength. Excessive amounts of POFA and ESP in the concrete mix reduces the compressive and splitting tensile strengths. A high amount of POFA and ESP leads to slow down the hydration process and pozzolanic reaction in the concrete.

Composite slabs with steel decking are evolving swiftly with the technology currently. These composite slabs can help in construction sector by improving the quality of building and reducing construction time. and This is due to the expectation imposed on the building construction industry to improve time and structural efficiency. Composite slab can act as a part of composite steel framed building and it satisfy these demands after manipulated different researches' results [5].

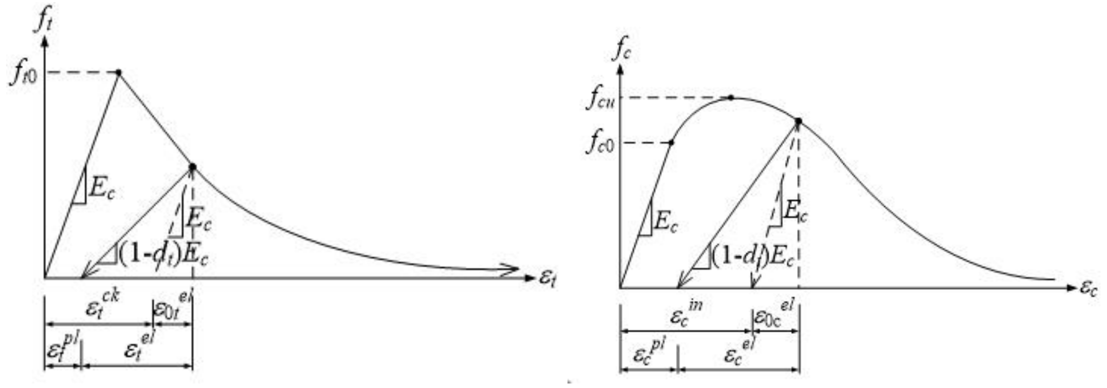
To perform the finite element analysis of steel, true (Cauchy) stress and logarithmic strain are used, which can be derived from the tensile coupon test results. Equation 1 and 2 presented the calculation for true stress (σ_{true}) and logarithmic strain (εlnpl) respectively [6].

$$\sigma_{true} = \sigma_{\mathrm{nom}}(1+ \varepsilon_{\mathrm{nom}}) \text{ Eq1}$$

$$\varepsilon\mathrm{lnpl} = \ln(1+ \varepsilon_{\mathrm{nom}}) \text{ Eq2}$$

where σ_{nom} represents nominal stress, ε_{nom} is nominal strain, and E represents the modulus of elasticity of steel.

The Concrete Damage Plasticity (CDP) was used determine concrete behaviour in FE modelling. CDP model was developed based on concrete failure mechanisms which are compressive crushing and tensile cracking. Stress-strain relationship is considered in the analysis of concrete behaviour. Stress-strain curves for concrete under uniaxial loading showed in below [7]. According to Hossain et al., [6], to determine the inelastic nature of the concrete, the model used isotropic damaged elasticity in correlation with isotropic compressive and tensile plasticity. Figure 1 showed the tension behaviour associated with tension stiffening and the compression stress-strain response of concrete.



(a) Tension behaviour associated with tension stiffening

(b)Compressive behaviour associated with compression hardening

Figure 1: Stress strain curve for concrete under uniaxial loading

Sundararooban & Krishnan [8] used ABAQUS software to create a 3D finite element model to study the behaviour of the composite slab under static load. Materials model, concrete damaged plasticity and elastic-perfectly plastic, are used for concrete and steel. Shell element, SR4 is used to model the steel, which is a 4-nodes doubly curved thin shell element to reduce the integration. C3D8R was an 8-node linear brick 3D solid element used in model of concrete. T3D2 was a 2-node linear 3D truss element used in model of steel rebar. The parameters in this study are the sheet thickness and the grade of concrete. From the results obtained, when the thickness of steel deck sheet and compressive strength of concrete increase, the load and moment carrying capacity of the slab increase.

3. Methodology

A chain of works and procedures were carried out to determine and will analyse the GSCC composite slab model. Before the simulation work begins, the materials properties and dimensions of composite slab were continued from the previous experimental work. To analyse GSCC composite slab, a parametric study was carried out by using 150 mm depth of GSCC composite slab. Model analysis of composite slab was executed by using ABAQUS/Explicit software. The structure behaviour GSCC composite slab subjected to flexural load was determined in terms of ultimate load, crack pattern, and load-deflection profile. After the validation works were done, GSCC composite slab was modelled. Thus, the results obtained were compared.

3.1 Properties of material

The model design's material properties and parameters used in this study is referred to the experiment work by Kamaruddin [4]. The materials used to produce self-compacting concrete are Ordinary Portland Cement (OPC), Palm Oil Fuel Ash (POFA), eggshell powder (ESP), sand, coarse aggregate, water and superplasticizer. The detailed concrete and steel deck properties used in this research are shown in Table 1 and 2.

Table 1: Details of concrete [4]

Concrete Properties	Value
Density	2400 kg/m^3
Young's Modulus for control	26490 MPa
Young's Modulus for 5P 2.5E	31689 MPa
Poisson's Ratio for control	0.17
Poisson's Ratio for 5P 2.5E	0.19

In this research, COMFLOR 60 steel deck was used. Its dimension is 2500 mm in length and 600 mm in width. The thickness of steel deck is 0.9 mm and the area of steel deck is 1276mm^2/m. Since the detailed properties of steel deck was not provided, the steel's properties and plasticity was referred from Attarde's [9] research. The properties of steel deck and steel plasticity were showed in Table 2 and Table 3. The bar diameter used in this research is 6 mm and the reinforcement bar properties were important to ensure the result was accurate. The material properties for reinforcement bar was referred to Goh [10] and it was shown in Table 4.

Table 2: Properties of steel deck [9]

Steel Sheeting Properties	Value
Density	7000 kg/m^3
Young's Modulus	230 GPa (2.30x10^{11} Pa)
Yield Stress	230 MPa (2.30x10^8 Pa)
Poisson's Ratio	0.30
Plastic (Residua) Strain	0.2

Table 3: Steel plasticity [10]

Steel Plasticity	
Yield Stress (MPa)	Plastic Strain (mm/mm)
230	0
251.3	0.000685
232.9	0.008125
313.2	0.093084
251.6	0.21

The bar diameter used in this research is 6 mm and the reinforcement bar properties were important to ensure the result was accurate. The material properties for reinforcement bar was referred to Goh [10] and it was shown in Table 4.

Table 4: Properties for steel bar with diameter of 6 mm [10]

Properties of steel bar	Value
Density	7700 kg/m^3
Young's Modulus	200 GPa
Poisson's Ratio	0.30
Initial Yield Stress	359 MPa
Ultimate Yield Stress	374 MPa
Strain at Failure	0.0049

By using the concrete compression and splitting tensile test which was carried out by Kamaruddin [4], concrete damage plasticity was obtained. The control and 5% POFA and 2.5% ESP SCC specimens' concrete damaged plasticity were shown in Table 5 and 6.

Table 5: Concrete damaged plasticity for control [4]

Concrete Damage Plasticity			
Plasticity			
Ψ	ε	σ_{bo}/σ_{co}	Kc
30	0.1	1.16	0.667
Concrete Compression Behaviour		**Concrete Compression Damage**	

Yield Stress (MPa)	Inelastic Strain (mm/mm)	Damage Parameter	Inelastic Strain (mm/mm)
44.52	0	0	0
46.97	0.0008	0	0.0008
49.04	0.0016	0	0.0016
50.35	0.0024	0	0.0024
50.16	0.0033	0.03	0.0033
46.44	0.0044	0.39	0.0044
36.89	0.0058	0.63	0.0058
31.49	0.0070	0.74	0.0070
26.94	0.0082	0.81	0.0082
Concrete Tensile Behaviour		**Concrete Tension Damage**	
Yield Stress (MPa)	Cracking Strain (mm/mm)	Damage Parameter	Cracking Strain (mm/mm)
3.92	0	0	0
3.66	0.0004	0.27	0.0004
3.39	0.0008	0.36	0.0008
3.13	0.0012	0.43	0.0012
2.87	0.0016	0.50	0.0016
2.62	0.0020	0.57	0.0020
2.38	0.0025	0.62	0.0025
2.11	0.0029	0.68	0.0029
1.89	0.0033	0.72	0.0033
1.65	0.0037	0.77	0.0037
1.43	0.0042	0.80	0.0042
1.21	0.0046	0.84	0.0046
1.00	0.0050	0.87	0.0050
0.81	0.0055	0.90	0.0055
0.63	0.0059	0.93	0.0059
0.45	0.0064	0.95	0.0064
0.28	0.0068	0.97	0.0068
0.13	0.0072	0.99	0.0072

Table 6: Concrete damaged plasticity for concrete with 5% of POFA and 2.5% of ESP [4]

Concrete Damage Plasticity			
Plasticity			
Ψ	ε	σ_{bo}/σ_{co}	Kc
30	0.1	1.16	0.667
Concrete Compression Behaviour		**Concrete Compression Damage**	
Yield Stress (MPa)	Inelastic Strain (mm/mm)	Damage Parameter	Inelastic Strain (mm/mm)

35.35	0	0	0
37.28	0.0008	0	0.0008
38.43	0.0017	0	0.0017
38.84	0.0026	0	0.0026
38.59	0.0035	0.31	0.0035
36.86	0.0046	0.54	0.0046
34.36	0.0058	0.66	0.0058
30.87	0.0070	0.75	0.0070
27.56	0.0083	0.81	0.0083
25.04	0.0095	0.85	0.0095
Concrete Tensile Behaviour		**Concrete Tension Damage**	
Yield Stress (MPa)	Cracking Strain (mm/mm)	Damage Parameter	Cracking Strain (mm/mm)
4.32	0	0	0
4.07	0.0004	0.20	0.0004
3.81	0.0008	0.28	0.0008
3.54	0.0012	0.37	0.0012
3.28	0.0016	0.44	0.0016
3.02	0.0020	0.50	0.0020
2.75	0.0024	0.57	0.0024
2.50	0.0028	0.62	0.0028
2.25	0.0032	0.67	0.0032
1.99	0.0036	0.72	0.0036
1.75	0.0040	0.76	0.0040
1.50	0.0044	0.80	0.0044
1.28	0.0048	0.84	0.0048
1.06	0.0052	0.87	0.0052
0.84	0.0057	0.90	0.0057
0.63	0.0061	0.93	0.0061

3.2 Composite slab design and detailing

The composite slab has different in thickness but constant in length and width. The length and width of the composite slab are 2500 mm and 600 mm respectively. The reinforced steel bars with diameter of 6 mm and spacing of 120 mm were prepared in longitudinal and transverse direction. The hinge and roller supports were placed 150 mm from the both end of composite slab and the length of shear span, L_s is 850 mm.

3.3 Finite Element Analysis of ABAQUS

Finite element method is used to create and analyse the model. By using ABAQUS/Explicit, GSCC composite slab was modelled and simulated under flexural load. This research can help to determine the structural behaviour of composite slab under flexural load accurately after developed model in ABAQUS. Four main procedures area which is important while using ABAQUS are creating slab model, assigning attributes, analysing the model and collecting the data.

3.3.1 Create slab model

A 3D model block wall with eight-node continuum elements (C3D8R) was created based on the correct dimension. The dimension of model is 2500 mm length x 600 mm width and 150 mm thick. The model consists of three parts which are steel deck, SCC and reinforcement. By using C3D8R, a rectangular model was created. Next, the model was edited to the desired dimension.

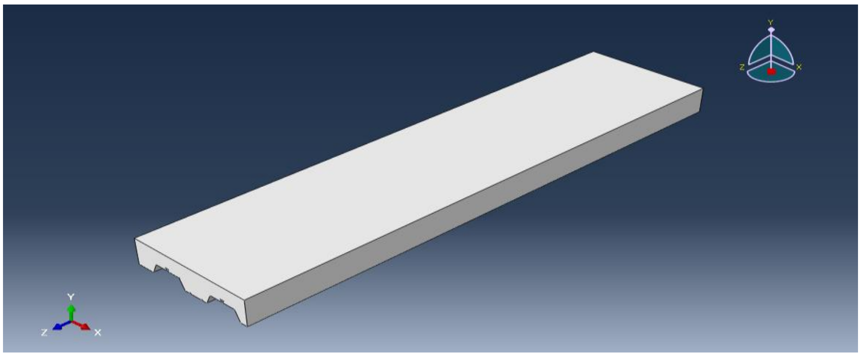


Figure 2: SCC model in ABAQUS

3.3.2 Assign attributes

Steel and concrete were assigned as homogenous material. The concrete damaged plasticity was needed to be chose in this stage. The model assigned the information from Table 1, 2, 3, meshing, loading and boundary condition to the model to proceed analysing the model as in Figure 3.

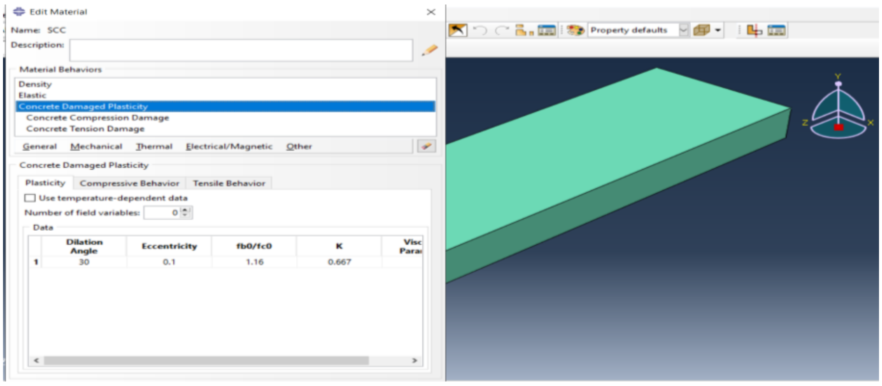


Figure 3: Example of assign attribute of composite slab

3.3.3 Analyse slab model

In this stage, the model was assembled and the meshes were generated with the optimum global size of mesh. The optimum global size of mesh was used to reduce the computational time and maintain the accuracy of the analysis result at the same time.

3.3.4 Data collection

The data was collected once the analysation of model was done. The data can be viewed in animation, graph and table.

3.4 Validation work

Validation work should be carried out in order to verify the simulation results; however, the prediction study was done in this present study. Therefore, the validation work is done by compare the simulation result to the previous research that had nearly similar with composite slab properties in this study. The comparison was done in the aspect of ultimate load, deflection and the crack pattern. Table 7 and Table 8 presented the details, ultimate load and deflection of previous research for validation work.

Table 7: Details of previous research for validation work

Previous research	Length (mm)	Width (mm)	Thickness (mm)	Shear span (mm)	Type of concrete	Concrete Compressive Strength (MPa)	Concrete Tensile Strength (MPa)
Bai *et al.* [11]	3200	688	150	800	ECC	36.56	4.60
Attarde [12]	1800	960	100	600	SCC	56	4.80

Note: ECC= Engineered Cementitious Composite, SCC= Self-Compacting Concrete

Table 8: Results of previous research for validation work

Previous Research	Ultimate Load (kN)	Deflection (mm)
Bai *et al.* [11]	32.93	13.23
Attarde [12]	36.66	3.51

3.5 Parametric study of GSCC composite slab

A series of GSCC composite slab with same material properties and concrete damaged plasticity based on previous research were simulated for parametric study. In this study, the variable parameter is the steel sheet thickness of composite slab. The dimension of the composite slab remains unchanged and it was simulated by FEA. The structural behaviour of the composite slab with different steel sheet composite slab were determined in terms of ultimate load, crack pattern and load-deflection profiles. The dimensions of the steel sheet used for parametric study are listed in Table 9.

Table 9: The difference of composite slab dimensions in term of steel sheet thickness

Composite slab	Thickness of steel sheet (mm)
CS 1	0.8
CS 2	1
CS 3	1.2

4. Result and Discussion

In order to verify the concrete damaged plasticity model in ABAQUS of GSCC composite slab, validation work had been carried out. The simulation results are validated as the slab dimension, concrete strength and length of shear span are similar to previous researches studied by Bai et al. [11] and Attarde [12]. Once the concrete damaged plasticity model was validated, it was used to stimulate the structure behaviour of the composite slab in terms of its ultimate load, load-deflection profile and cracking pattern by finite element analysis. It was also used to conduct the parametric study of GSCC composite slab with different thickness of steel sheet.

4.1 Validation of ultimate load carrying capacity

The most principal result that can be used to validate the simulated data is ultimate load of the model. From the results, it was observed that a slight difference was achieved between the previous research results and simulation results with the estimated error of 10.3% for control specimen slab and 1.5% for GSCC composite slab. The differences were within the acceptable range of ±10 %. Therefore, it was proven that the concrete damaged plasticity model and material properties used were able to model GSCC composite slab under flexural loading.

Table 10: Comparison on ultimate load carrying capacity of control composite slab under flexural load for theoretical and FEA method

Model	L x H x t (mm^3)	Ultimate load, Pu (kN)		Percentage Difference (%) (|Pu(FEM) - Pu(Exp)|/Pu(Exp)) x100
		FEA	Previous research	
Control	2500 x 600 x 150	29.523	32.93	10.3
GSCC with 5%of POFA and 2.5% of ESP	2500 x 600 x 150	33.414	32.93	1.5

4.2 Validation of deflection

Deflection control can be used in the validation work apart from ultimate load. The simulated model showed the largest deflection occur in the midspan of composite slab. The percentage differences between both results were then calculated. Type of concrete does not affect much in term of ultimate load but it affected significant differences in deflection. The difference in mid span deflection between ECC and SCC is more than 50% as ECC has higher ductility. GSCC composite slab sustained larger deflection than that in control specimen.

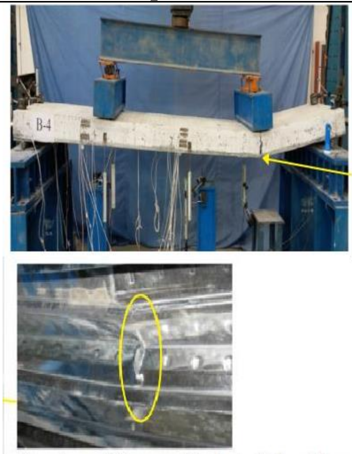
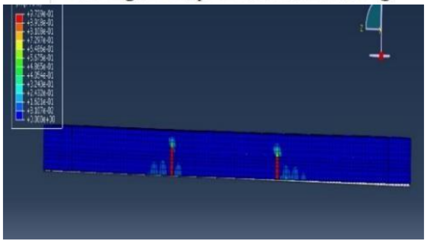
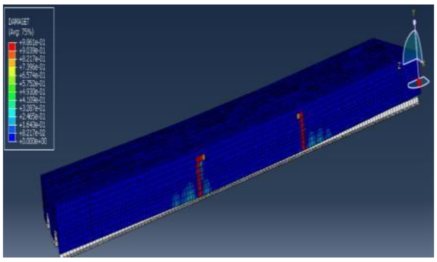
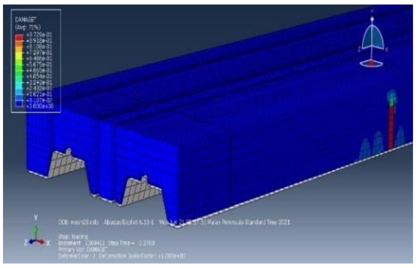
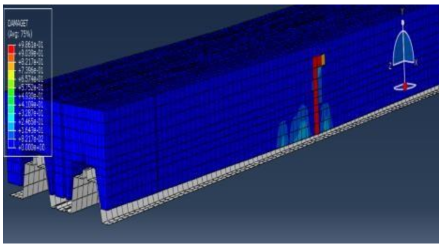
Table 11: Difference of deflection between FEM and previous research

Composite slab	L x H x t (mm)	Deflection (mm)		Percentage Difference (%) (|Deflection(FEM) - Deflection(Research)|/ Deflection(Research)) x100
		FEM	Previous research	
Control	2500 x 600 x 150	3.637	3.51	4.56
GSCC	2500 x 600 x 150	3.73	3.51	6.27

4.3 Validation of failure mode

Failure mode is another way to verify the validation of the results. The crack pattern of the composite slab in ABAQUS is similar with previous research. The crack occurred at the bottom surface of composite slab surrounding the loading point. The end slip was occurred after the crack with the increasing of load. The results were verified as their crack patterns were similar.

Table 12: Failure mode and crack pattern of composite slab

Research	Failure mode	Crack pattern
Bai *et al.* (2020)	The initial crack occurred at the loading point of the composite slab. When the load reached 55% of the ultimate load, the crack started occurred at the bottom surface of composite slab. End slippage was then occurred with the increase of loading.	 Tearing of the profiled steel sheeting
ABAQUS model	The crack pattern of the composite slab is similar with previous research. The crack occurred at the bottom surface of composite slab surrounding the loading point. The end slip was occurred after the crack with the increasing of load. The results were verified as their crackpatterns were similar.	 (a) Crack pattern of SCC specimen  (b) Crack pattern of GSCC specimen  (c) End slip of composite slab for control specimen  (d) End slip of composite slab for GSCC specimen

4.4 Parametric study of GSCC composite slab for parametric study

A series of GSCC composite slab were simulated for parametric study using the same material properties and concrete damaged plasticity from section 3.1 by ABAQUS. The various parameters were the thickness of the steel sheet. The other parameters were kept constant and simulated by FEA. Parametric study had been conducted for three models with different thickness of steel sheet. The full designation and dimension of the composite slab used in the study were listed in Table 10.

Table 13: List of full scaled of composite slab that were analysed by FEA

Composite slab	L x H x t (mm^3)	Thickness of steel sheet (mm)
CS 1	2500 x 600 x 150	0.8
CS 2	2500 x 600 x 150	1
CS 3	2500 x 600 x 150	1.2
GSCC	2500 x 600 x 150	0.9

4.4.1 Effects of different thickness of steel sheet on ultimate load carrying capacity, crack pattern and deflection of composite slab

The ultimate load carrying capacity of the three models which thickness of steel varies from 0.8 mm, 1.0 mm and 1.2 mm were compared with GSCC composite slab. The ultimate load was increasing with the thickness of steel sheet. The thicker the steel sheet of composite slab, the higher the ultimate load of the composite slab.

Table 14: Ultimate load of composite slab with different steel sheet thickness

Composite slab	Steel thickness (mm)	Ultimate load (kN)	Increase in percentage compared to GSCC composite slab (%)
CS1	0.8	32.456	-0.5
CS2	1.0	32.696	0.3
CS3	1.2	32.854	0.8
GSCC	0.9	32.606	0

The flexural load applied had slightly affected the crack pattern on the composite slab. This was due to the effect of the various thickness of steel sheet. Other than failure mode, stress distribution in composite slab can also use to identify the potential failure zone of the composite slab. The composite slab cracked and crushed; this was known as failure mode of composite slab.

The failure mode of composite slab can be further proved by using the load deflection profile obtained from FEA. The deflection of composite slab increase with the ultimate load until it reached maximum ultimate load. It showed the deflection of composite slabs started to decrease once it touched the maximum ultimate load of the composite slab. It can be seen that for most of the composite slab specimens. Each models have similar curves behaviour along the deflection. The longitudinal shear resistance of composite slabs could be improved by increasing the steel sheeting thickness. The increase of steel sheet thickness improved the longitudinal shear capacity and enabled full utilization of the tensile capacity.

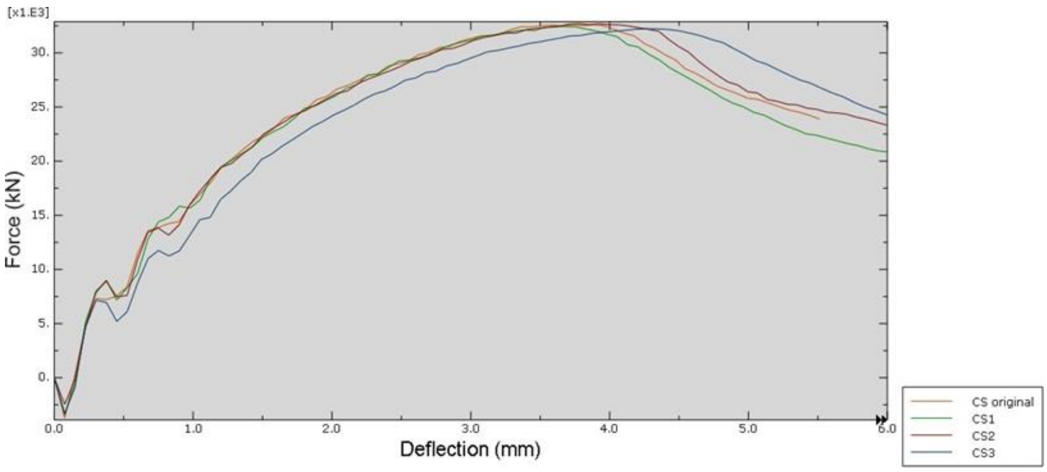


Figure 4: Load deflection profile of composite slab with thickness 0.8 mm, 0.9 mm, 1.0 mm and 1.2 mm

5.0 Conclusion

GSCC composite slab models were successfully developed and created by ABAQUS software to test its structural behaviours under flexural load. It was validated with adequate level of accuracy using previous research results from Bai et al. [11]. From the findings, the ultimate load carrying capacity of composite slab obtained from FEA compared to previous research value had a difference of 10.3% and 1.5% for control specimen and GSCC composite slab respectively. Overall, by using ABAQUS software, FEA method is able to correctly predict the structural behaviour of structural elements.

The structural behaviour of the GSCC composite slab subjected to flexural load was analyzed through finite element analysis. It can be concluded as the ultimate load carrying capacity and deflection of composite slab constructed by GSCC composite slab was higher than that in SCC specimen. The crack pattern occurred at the bottom surface of composite slab and surrounded at the loading point for both SCC and GSCC. The end slip occurred after crack occurred with the increasing of load. Both composite slabs occurred longitudinal shear failure based on the crack pattern.

The increase of steel sheet thickness increased the ultimate load of composite slab. The higher the thickness of steel sheet, the higher the ultimate load of composite slab. The ultimate load of 0.8 mm steel sheet thickness composite slab decreases 0.5% whereas both 1.0 mm and 1.2 mm steel sheet thickness composite slab increase 0.3% and 0.8% compared to GSCC composite slab. Both ultimate load and deflection increase with the increase of steel sheet thickness. The stress distribution of composite slab decreased when the thickness of steel sheet increased. The increase of steel sheet thickness increased with the deflection of composite slab until it reaches the ultimate load. The crack pattern indicated that the composite slab was against longitudinal shear failure.

Based on the results of this research, further experimental research needed in order to improve the results of structural behaviour of GSCC composite slab under flexural load using FEA method. Besides, further study on different concrete replacement should be conducted in order to have better understanding for the structural behaviour of GSCC composite slab. The effect of POFA and ESP to the GSCC composite slab should have further study to be carried out to identify the most suitable percentage used in the GSCC composite slab.

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