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

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Abstract: Composite slab was widely used in construction due to advantages such as easier installation, reduce in usage of concrete and etc. However, the research for composite slab fabricated with self-compacting concrete (SCC) was limited. Therefore, in this study, the structural behaviour of composite slab with 5% of palm oil fuel ash (POFA) and 2.5% of eggshell powder (ESP) was predicted through finite element method (FEM). This present study had successfully created the SCC and green self-compacting concrete (GSCC) composite slab model and analysed the structural behaviour by using ABAQUS software. Next, the convergence study and validation work had been carried out. Parametric studies were carried out with different thickness of composite slab and without mesh reinforcement. The previous study carried out by Bai *et al.* (2020) and Attarde (2014) were referred for validation work. The percentage difference in load was 10.3% for SCC and 1.5% for GSCC meanwhile the percentage difference in deflection was 4.56% for SCC and 6.27% for GSCC. The simulation results were verified since the percentage difference between simulation results and previous research is within 10%. For the parametric study, it showed that the ultimate load had increased from 53.1% to 99.6% when the thickness of composite slab increased from 150 mm to 175 mm and 200 mm. The ultimate load in composite slab had dropped 9.22% and 1.46% when there is no reinforcement for 175 mm and 200 mm. In conclusion, the thickness and reinforcement of composite slab does really affect the structural performance of composite slab.

Keywords: Composite Slab, Self-Compacting Concrete, Finite-Element Method, ABAQUS

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1. Introduction

Composite slab is a slab where the top component of slab is concrete meanwhile the bottom component of slab is steel deck. Composite slab systems were developed in the late of 1930 and the purpose is to save the construction times in tall building. Composite slab is play as an important role to replace the conventional reinforced concrete slab due to many of advantages [1].

Conventional concrete is widely used in construction industry in every country. Nonetheless, the conventional concrete required adequate compaction carried out by skilled labour in order to achieve a durable concrete. Therefore, the self-compacting concrete (SCC) introduced to solve the problem. SCC can flow through the constricted area and fill the formwork homogenously. With the fresh properties of SCC, it is benefitted to use in the structural element that has a large surface area and required more compaction. Composite slab with SCC can reduce the construction duration and has a more simpler construction method.

However, it was found that the research conducted on composite slab with SCC is limited. Besides that, the inconsistent bonding between concrete and steel deck will also affect the performance of composite slab and thus increase the level of difficulties in the process of design. Crisinel & Marimon [2], stated that verification of the structural member is time consuming, complicated and required a large scalar of laboratory test. This result the increasement of manufacturing cost of composite slab. Consequently, the computational modelling was picked to study and analysis the structural behaviour of composite slab in this study. By using FEM, the complex and irregular shape of model can be easily created and analyzed. The finite element model of composite slab using ABAQUS is highly reliable to analysis the behaviour of composite slab [3].

This study focused on computational modelling of GSCC composite slab incorporating partial cement replacement which had used as structural component in building. The objectives of this research were to develop numerical model of green self-compacting concrete composite slab using ABAQUS software and analyze and predict the influence of various composite slab's depth and presence of reinforcement bar on ultimate load, crack pattern and load-deflection profiles of GSCC Composite Slab subjected to flexural load by means of finite element method.

The significances of this study were to provide the detailed prediction information for structural behaviour in terms of ultimate load, load-deflection profile and cracking of composite slab incorporating partial cement replacement. Besides that, it also helped to assist for future research as reference on the composite slab under flexural load study and guide as a baseline for the accuracy of future research on concrete analysis software.

2. Literature review

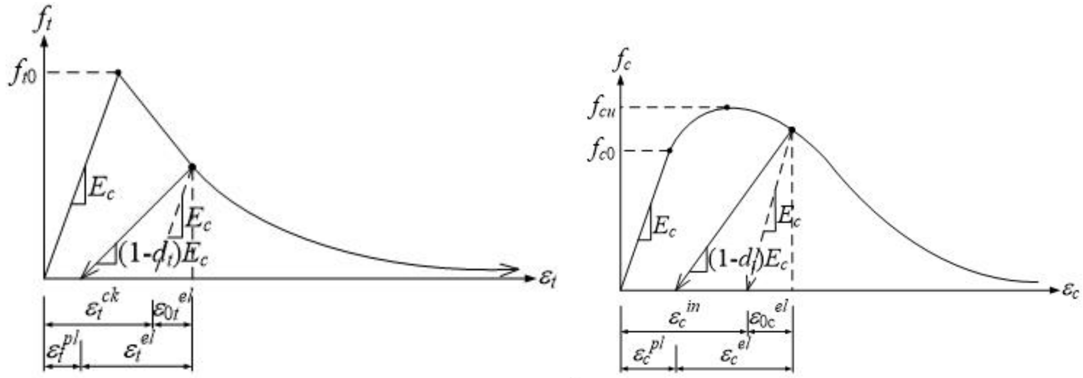
Self-compacting concrete is a concrete where it required a high flowability, passing ability, and resistance to segregation. SCC is made up of cement, aggregate, admixtures, and addition [4]. Kamaruddin [5] carried out an experimental work to study the performance of SCC incorporating with POFA and ESP. It was noticed that the SCC contain 5% of POFA and 2.5% of ESP has the highest compressive strength and tensile strength. The materials of composite slab consist of steel deck, reinforced concrete and reinforcement steel bar. According to the Eurocode 3, the thickness of the steel deck should be more than 0.7mm. The thickness of 0.8mm to 1.2mm are preferred due to the economical reason [1]. For the profiled steel sheet, the yield strength is typically range from 230 MPa to 460 MPa [6]. Steel reinforcement in composite slab is not significant because the steel deck will act as the main component that undertake the tensile force. However, the small amount of steel reinforcement is needed to prevent shrinkage and temperature cracking. According to the Eurocode 4, there are transverse and longitudinal steel reinforcement in composite slab. The reinforcement area for both directions should more than 80mm2/m. The spacing between reinforcement bar should not exceed 2h and 350mm, whichever is lesser [7].

The slab subjected to flexural load have three failure mode which are flexural failure, longitudinal shear failure and vertical shear failure. Longitudinal shear failure is the most common types of failure that will be occur in composite slab. In this type of failure, the diagonal crack is initiated around the concentrated load just before failure and it is followed by end slip between concrete and steel within shear span of composite slab [8].

According to the Eurocode4 [9], the longitudinal shear resistance can be calculated by using partial connection method and m-k method, where m is mechanical interlocking and k is friction occurred in steel-concrete interface. Partial connection method also can used to determine the longitudinal shear strength, τu of composite slab, however, it was limited to use for composite slab with ductile behaviour.

Bai et al. [10] declared that the thickness of steel deck, depth of composite slab and arrangement of shear stud will affect the longitudinal shear resistance and failure mode. The types of concrete in composite slab could affect the performance of composite slab. In the previous research carried out by Attarde [1], the structural behaviour of composite slab was determined through experimental work and then parametric study was carried out by using ABAQUS. It was also found that the deflection of a composite slab with ECC was more than twice of that in SCC slab. This condition occurred is due to the higher ductility and the better longitudinal shear capacity of ECC. Pereira & Simões [11] measured the vertical shear resistance of composite slab in term of geometry. It was noted that the vertical shear resistance of composite slab increased when the overall slab thickness increased.

ABAQUS/Explicit provides three models which are smeared cracking, model, brittle cracking model and concrete damaged plasticity model to simulate the concrete behaviour [12]. Concrete damaged plasticity model is a continuum model used to simulate the concrete behaviour in the damaged and plasticity based. Stress-strain relationship is considered in the analysis of concrete behaviour. Stress-strain curves for concrete under uniaxial loading showed in Figure 1 [13].



(a) Tension behaviour associated with tension stiffening

(b)Compressive behaviour associated with compression hardening

Figure 1: Stress strain curve for concrete under uniaxial loading

In composite slab modelling, the concrete slab was assigned to 8-node linear brick, reduced integration elements (C3D8R) while the steel deck was assigned with 4-node doubly curved purpose shell, elements (S4R). The reinforcing steel was simulated by using T3D2 element [3]. Abdullah *et al*. [14] proposed a connector element to model the interaction between steel-concrete interface. Radial-thrust type connector element (CONN3D2) was used to connect the concrete node to the steel node that are closest to each other. Attarde [1] employed three types of interface contact properties which are penalty contact with friction coefficient of 0.5, kinematic contact with small sliding and kinematic contact with finite sliding. According to the finding, penalty contact provided the maximum accuracy in modelling a load-deflection response that is virtually equal to the experimental one.

3. Methodology

This section explained the procedure of simulation work by using ABAQUS/ Explicit. The methodology of this study was conducted according to the flowchart as showed in Figure 2 below.

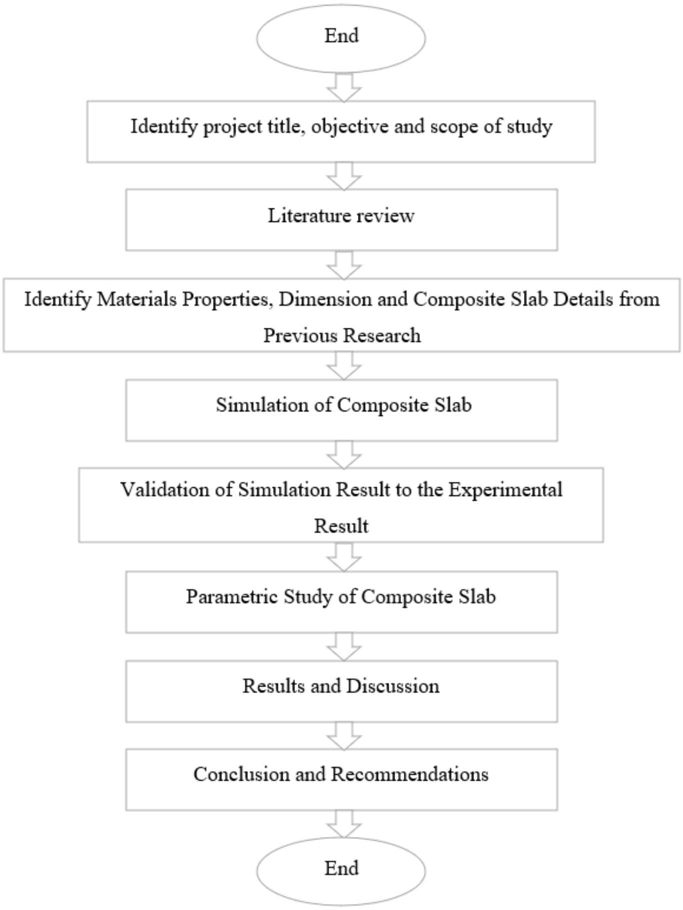


Figure 2: Methodology flowchart

3.1 Material properties and parameters in use

The material properties of SCC and GSCC for the composite slab simulation was referred to the experimental work conducted by Kamaruddin [5] and the details was provided at the Table 1 below.

Table 1: Details of concrete [5]

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

Note: P=POFA and E=ESP

The steel deck used for the composite slab in this research was COMFLOR 60 and the steel deck had dimension of 2500 mm in length and 600 mm in width. Apart from that, the thickness of steel deck is 0.9 mm and the area of steel deck is 1276mm^2/m. However, the detail of steel plasticity and properties for COMFLOR 60 does not provided in previous research, therefore, the steel’s properties and plasticity were referred to the research conducted by Attarde [1]. The properties of steel deck and steel plasticity were showed in Table 2 and Table 3.

Table 2: Properties of steel deck [1]

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 (Residual) Strain	0.2

Table 3: Steel plasticity [1]

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

The composite slab for this research was reinforced by mesh with a bar diameter size of 6 mm. Goh [15] provided the material properties for steel bar with diameter of 6 mm as shown in Table 4.

Table 4: Properties for steel bar with diameter of 6 mm [15]

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

Concrete damaged plasticity was derived from the concrete compression and splitting tensile test which was carried out by Kamaruddin [5]. The concrete damaged plasticity for control specimen and SCC incorporating of 5% of POFA and 2.5% of ESP were listed in Table 5 and Table 6.

Table 5: Concrete damaged plasticity for control specimen [5]

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

Table 5: Concrete damaged plasticity for control specimen (con't) [5]

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
0.13	0.0072	0.99	0.0072

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

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
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, Ls is 850 mm.

3.3 ABAQUS finite element analysis

The finite element analysis is carried out by using ABAQUS/Explicit. The simulation was done by follow the procedure (1) composite slab modelling, (2) assign attributes, (3) analysis of composite slab and (4) data collection.

3.3.1 Composite slab modelling

The structure of composite slab can be divided into three parts during modelling. The three parts consists of concrete, steel deck and reinforcing steel. The dimension given is 2500 mm in length, 600 mm in width and 150 mm in depth. The thickness of the steel deck is 0.9 mm. In ABAQUS, the element of C3D8R was used to model the concrete layer meanwhile the element of S4R was used to model the steel deck. At the same time, the T3D2 element was used to model the reinforcing bar.

3.3.2 Assign attributes

In this stage, the material properties showed in Table 1, 2, 3, 4, and 5 are assigned to the composite slab part by part. In ABAQUS, steel and concrete were assigned as the homogenous material. The roller support and pin support of composite slab were modelled both end of composite slab. Four degrees of displacement (U1, U2, UR1 and UR2) were restrained to indicate the roller support. On the other hand, the pin support is modelled by restrained five degrees of displacement (U1, U2, U3, UR1 and UR2). Besides that, the loading was assigned on top of composite slab in Y direction. Figure 3 showed the assign attribute of composite slab.

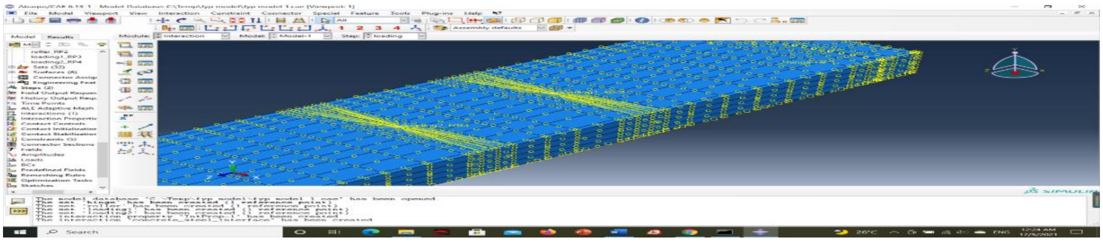


Figure 3: Assign attribute of composite slab

3.3.3 Analysis of composite slab

Each part of the composite slab was assembly together and the mesh were generated. 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. The model was analysed by using ABAQUS/Explicit.

3.3.4 Data collection

This is the post-processing stage where the necessary output parameters were collected for further analysed. The output can be view in the form of graph, table and image. ABAQUS also provide animation to simulate the changes of product in the presence of load.

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 6 and Table 7 presented the details, ultimate load and deflection of previous research for validation work.

Table 6: 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.* [10]	3200	688	150	800	ECC	36.56	4.60
Attarde [1]	1800	960	100	600	SCC	56	4.80

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

Table 7: Experimental results of previous research for validation work

Previous Research	Ultimate Load (kN)	Deflection (mm)
Bai *et al.* [10]	32.93	13.23
Attarde [1]	36.66	3.51

3.5 Parametric study

Parametric study was carried out by varying the depth of verified composite slab model. The parametric study aims to predict the structural behaviour of composite slab with different depth under flexural load. Table 8 shows the dimension of composite slab with different thickness.

Table 8: Dimension of composite slab

Composite slab model	**Length (mm)**	**Width (mm)**	**Depth (mm)**	**Reinforcement bar**
Control- SCC	2500	600	150	Reinforced
Control-GSCC	2500	600	150	Reinforced
CS-1-R	2500	600	175	Reinforced
CS-1-NR	2500	600	175	Not Reinforced
CS-2-R	2500	600	200	Reinforced
CS-2-NR	2500	600	200	Not Reinforced

Note: CS= composite slab, R= reinforced, NR= no reinforced

4. Results and Discussion

Since the scope of this study was to carry out a computational prediction of structural behaviour of composite slab, the result of previous research with almost similar slab dimension, concrete strength and length of shear span was necessary in order to verify the simulation data. The previous research conducted by Bai *et al*. [10] was used to validate the simulation results of this present study. Furthermore, an addition previous research conducted by Attarde [1] was referred as an external evidence to verify the result in study.

4.1 Validation of ultimate load carrying capacity

According to ABAQUS, the ultimate load carrying capacity for control and GSCC specimen was 29.52kN and 33.41kN. In comparison to the composite slab in previous research conducted by Bai *et al*. [10] that had shown in Table 7, the ultimate load obtained was 32.93kN and the difference of load was 10.3% for SCC and 1.5% for GSCC. It was noticed that the ultimate load in GSCC was nearly close to previous research and the difference was 1.5% since they had almost identical concrete strength, shear span and slab thickness.

4.2 Validation of deflection

According to the previous research conducted by Attarde [1] that had shown in Table 7, the type of concrete does not cause a big difference in term of ultimate load but it does have a significant impact in terms of deflection. It showed that the difference in mid span deflection between ECC and SCC is more than 50%. This condition occurred was due to the higher ductility in ECC concrete. In a result, the deflection was compared to that in the previous research conducted by Attarde [1]. According to ABAQUS, the deflection for control and GSCC specimen was 3.637 mm and 3.73 mm. In comparison to the composite slab in previous research conducted by Bai *et al.* [10], the ultimate load obtained was 3.51 and the difference of load was 4.56% for SCC and 6.27% for GSCC.

4.3 Validation of failure mode

The previous research conducted by Bai *et al*. [10] showed the initial crack occurred at the loading point of the composite slab. The crack was initiated at the bottom surface of the composite slab when the load reached 55% of the ultimate load. The crack was then followed by the end slippage when the loading keep increased. A dramatic vertical crack was accompanied with the end slippage. ABAQUS had modelled the crack pattern of the composite slab in this study. The crack pattern of the simulated composite slab showed a nearly similar crack pattern to the previous research.

4.4 Parametric study of POFA and ESP composite slab

The purpose of parametric study was to predict the changes of thickness of composite slab and mesh reinforcement to the structural behaviour in terms of ultimate load carrying capacity, deflection and failure mode of composite slab. The comparison of the results was done and concluded in each section. The parametric study results were listed in Table 9.

Table 9: Results of parametric study

Composite slab model	Depth (mm)	Reinforcement	Ultimate load (kN)	Percentage difference of load to GSCC specimen (%)	Deflection (mm)	Percentage difference of deflection to control specimen (%)
CS-1-R	175	Reinforced	51.16	53.1	1.58	-55.0
CS-1-NR	175	Not Reinforced	46.84	40.2	3.44	-2.0
CS-2-R	200	Reinforced	67.94	103.3	1.72	-51.0
CS-2-NR	200	Not Reinforced	66.69	99.6	1.69	51.9

4.4.1 Effects of various thickness of composite slab in terms of ultimate load carrying capacity and deflection

Based on Table 8, it showed a very obvious increasement in term of ultimate load carrying capacity when the thickness of composite slab increased. The ultimate load increased from 33.41kN to 51.16kN for the first increment of 25 mm in slab thickness. The percentage of load increment was 53%. For the subsequent increment of 25 mm in slab thickness, the ultimate load increased from 51.16kN to 66.69kN. The percentage of load increment was 33%. It was noticed that the increment of ultimate load carrying capacity decreased even the thickness of slab maintain the same increment which is 25 mm.

For deflection, it was discovered that when the thickness of slab increased from 150 mm to 175 mm, the deflection also dropped from 3.73 mm to 1.58 mm. This showed that the slab with a higher thickness can restrained more deflection at the midspan. However, the deflection had slightly increased from 1.58 mm to 1.69 mm when there was another 25 mm increment in thickness of composite slab.

In conclusion, the thickness of composite slab was definitely will affect its structural behaviour. However, the effect will not be significance when the thickness of composite slab reached a limitation.

4.4.2 Effects of mesh reinforcement of composite slab in terms of ultimate load carrying capacity and deflection

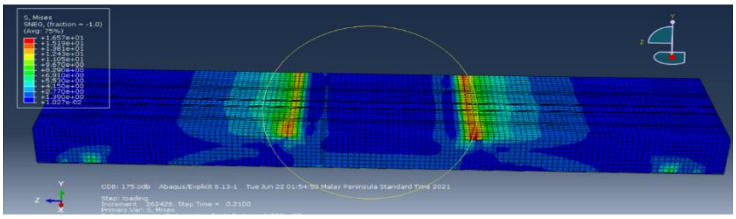
The effect of mesh reinforcement in composite slab had been predicted through the parametric study and the results was recorded in Table 8. For composite slab with 175 mm, the ultimate load carrying capacity with and without reinforcement was 51.16kN and 46.84kN respectively. The outcome revealed that the composite slab with reinforcement can withstand a higher ultimate load. The percentage differences of ultimate load carrying capacity between composite slab with and without reinforcement was 8.4%. However, the percentage differences of ultimate load carrying capacity between composite slab with and without reinforcement reduced when the thickness of composite slab increased from 175 mm to 200 mm. The ultimate load carrying capacity of composite slab with reinforcement was 67.94kN, slightly higher than 66.69kN which achieved by composite slab without reinforcement. The percentage difference in ultimate load carrying capacity was 1.8%.

The presence of mesh reinforcement also helped to reduce deflection in a composite slab with a thickness of 175 mm from 3.44 mm to 1.58 mm and the percentage of differences achieved 54%. The deflection composite slab with 200 mm of thickness in both with and reinforcement was 1.72 mm and 1.69 mm respectively. The difference of deflection in this specimen was very small and the percentage difference was 1.7%.

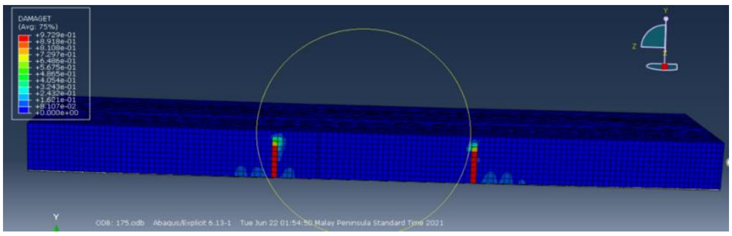
In terms of ultimate load carrying capacity, the composite slab with reinforcement achieved a higher reading than that without reinforcement, however, the difference become smaller when the thickness of composite slab increase from 175 mm to 200 mm. As the thickness of the composite slab increased from 175 mm to 200 mm, the increment in terms of deflection with and without reinforcement decreased.

4.4.3 Failure mode and stress distribution of composite slab

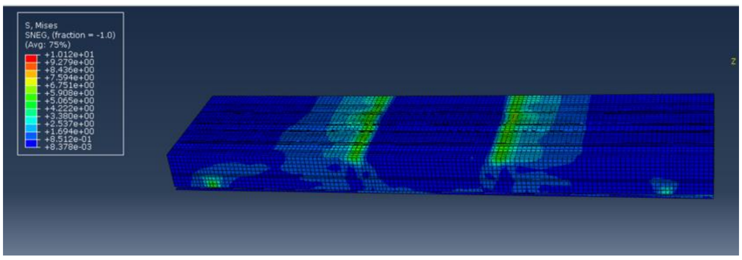
The failure mode and stress distribution of composite slab was studied with the help of ABAQUS. The crack pattern and stress distribution were almost identical to all of the composite slab that studied at parametric study. All of the composite slab showed the crack initiated at the bottom surface of composite slab surrounded the loading point. The end slip occurred when the load remained increased after crack occurred. From the crack pattern obtained from ABAQUS, it was predicted that the composite slab was against longitudinal shear failure, which is commonly occurred in composite slab due to the breaking of the bond between concrete and steel deck interface. The stress distribution and crack pattern of composite slab was showed in Figure 4.



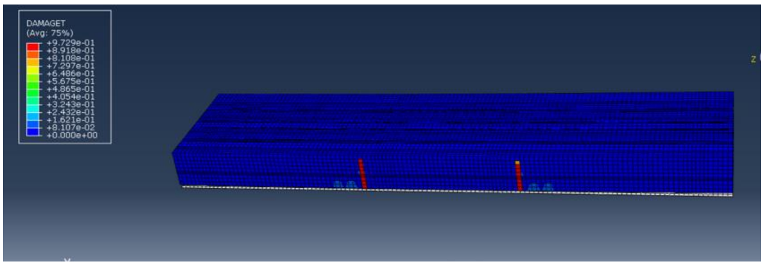
(a) Stress distribution of CS-1-R specimen



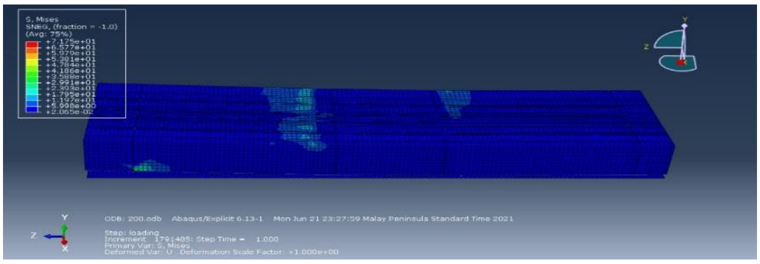
(b) Crack pattern of CS-1-R specimen



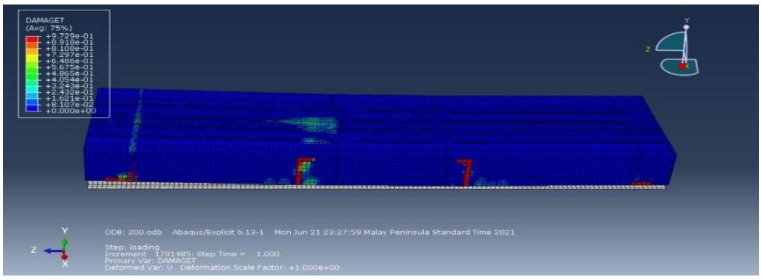
(c) Stress distribution of CS-1-NR specimen



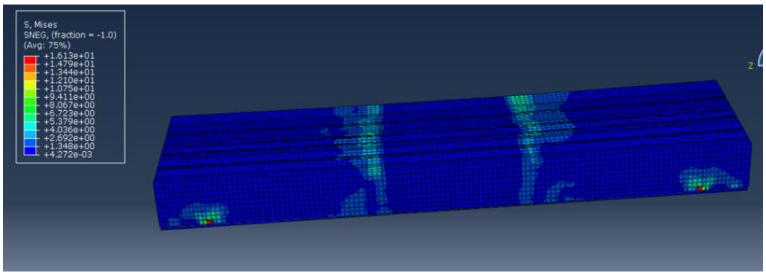
(d) Crack pattern of CS-1-NR specimen



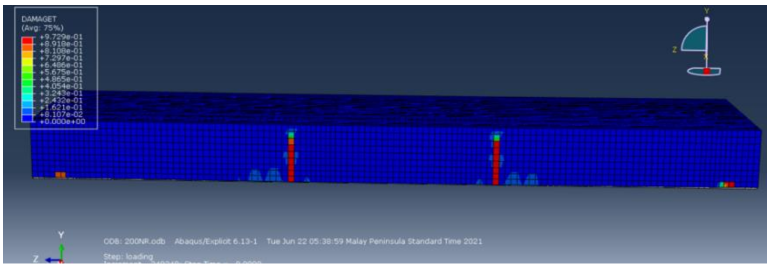
(e) Stress distribution of CS-2-R specimen



(f) crack pattern of CS-2-R specimen



(g) Stress distribution of CS-2-NR specimen



(h) Crack pattern of CS-2-NR specimen

Figure 4: Stress distribution and crack pattern of composite slab in parametric study

5. Conclusion

The conclusion was summarized as below:

i. The ultimate load carrying capacity and deflection of composite slab constructed by GSCC was higher than that in conventional SCC.
ii. The crack pattern was occurred at the bottom surface of composite slab and was surrounded at the loading point for both SCC and GSCCC. The end slip occurred when the load kept increased after crack occurred.
iii. The composite slab was against longitudinal shear failure based on the crack pattern.
iv. The various thickness and mesh reinforcement affected the structural behaviour of composite slab in term of load carrying capacity, deflection and crack pattern, however, the effect decreased when the thickness of slab increased to 200 mm.
v. All the slab was initially crack at the bottom surface of composite slab at the loading point location. The end slip occurred when the load kept increased after the crack occurred.
vi. The crack pattern indicated that the composite slab was against longitudinal shear failure.

Based on the results of the research, the following recommendation was suggested for future research:

i. Previous research with nearly identical concrete strength, slab dimension, shear span should be referred as more as possible in order to improve the accuracy of the FEM prediction study.
ii. The composite slab with other incorporating partial cement replacement should be further study to have a better understanding of composite slab under flexural load.
iii. In present study, the steel deck properties were referred to other type of steel deck but have almost similar dimension of slab. In order to increase the prediction study, further analysis should be done to obtained the properties of the steel deck that used in prediction study.

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