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Numerical Modelling of Impact Loads on RC Beams Utilizing Spent Garnet as a Replacement for Fine Aggregate

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ABSTRACT

Spent Garnet (SG) is one of the waste materials that attracts the interest of researchers to use it as a replacement for fine aggregate in concrete materials. As experimental investigation was carried out to assess the performance of a reinforced concrete (RC) beam incorporating SG as a substitute for fine aggregate. The study involved subjecting the beam to low-velocity impact loads within a controlled testing configuration. The primary objective of this study was to determine the optimal proportion of spent garnet (SG) to replace fine aggregates in reinforced concrete (RC) beams subjected to impact loads with a 100 kg impact weight dropped from a height of 1.5m, equivalent to a velocity of 5.4 m/s. To evaluate the effectiveness of SG as a replacement for fine aggregates, RC beams with varying percentages of SG (0%, 10%, 20%, 30%, and 40%) were numerically modelled using the Finite Element Method (FEM) incorporating the Concrete Damage Plasticity (CDP) constitutive model to simulate their behaviour under low-velocity impact loads. The study aimed to comprehensively examine the failure mode of the RC beams. The findings through FEM showed that the inclusion of SG in the concrete mix enhanced the material's behaviour and decreased the failure and damage of the beams as the percentage of SG in the mix increased, indicating its effectiveness as a replacement for fine aggregates, which is consistent with the experimental results.

1. Introduction

In recent years, the depletion of natural resources such as coarse and fine aggregate has resulted in numerous environmental issues. To address this problem, some previous researchers such as [1-10], have explored the use of waste materials to create sustainable concrete. It is worth noting that river sand has been used as a material in concrete and masonry work for a long time. River sand has a smoother texture and better shape of grains requiring very little water. The moisture trapped

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between particles is very suitable for any concrete purposes in construction. Additionally, spent garnets (SG) have been discovered as a viable option in its own right. The term "garnet" refers to a group of multifaceted minerals made up of silicate compounds containing Calcium (Ca), Magnesium (Mg), Ferrous iron (Fe) or Manganese (Mn), Aluminium (Al), Chromium (Cr), Ferric Iron (Fe), or even Titanium (Ti), which have similar crystal lattice structures and chemical formulas [11]. One such waste material is SG, which has unique properties that make it suitable as a replacement for sand in concrete. Garnets, which make up SG, have high density, low compressibility, and are more stable under pressure. However, it should be noted that SG can only be used for a limited period of time before it must be discarded as mentioned by [12]. When garnet that has been recycled becomes so worn out that it can no longer be used for abrasive blasting, it is taken out of shipyards and called "spent garnet. "Garnets are used in a variety of applications in industry [13]. Despite this, there has been little research conducted to study the characteristics, of SG as a replacement for sand in mortar.

Garnets are valued in abrasive applications for their hardness and recyclability. In the year 2013, Malaysia brought in 2000 tonnes of garnet from Australia to employ as a sandblasting substance to prepare surfaces for painting by eliminating rust and paint. The SG waste can be repurposed as a raw material in the concrete industry without any negative impact on quality [14]. Figure 1 depicts the SG obtained from Boustead Naval Shipyard Sdn. Bhd. This study incorporated SG into the concrete mix as a replacement for fine aggregate, given its similar properties to typical sand. The objective was to produce structural elements with SG as a substitute for fine aggregate.

Fig. 1. Spent Garnet

Concrete is a vital material in building construction, and the impact resistance of concrete plays a crucial role in determining the sturdiness of certain structure under impact loading. The way a building's structure cracks and fails is influenced by the characteristics of the reinforced concrete (RC) utilized, and there are established guidelines for reinforcement that need to be adhered to in order to create a concrete structural component. RC beams are crucial structural elements whose failure can lead to severe structural damage. While the shear strength of steel is similar to its tensile strength, concrete is considerably stronger in compression than in shear or tension. This is why the phenomenon of shear failure dominance was observed in reinforced concrete (RC) beams exposed to impact loads, as noted in previous experimental research [9]. The resistance of a building or structure to impact loading is a key factor in determining its overall strength. Impact load refers to the sudden application of force on a structural member, rather than a continuous and prolonged force. After an impact load is applied to a structural element, changes in the shape of the structure are often visible. As stated in the text, the behaviour of a concrete structure under impact loads is significantly different from that under static loads, as the structural component undergoes tensile or compressive stresses or strains during the impact [15]. Considering the abrasive properties of SG highlighted in the previous paragraph, it is intriguing to explore its potential as a substitute for fine aggregate in RC beams. The objective is to evaluate its impact response under low-velocity impact loads.

Conducting experimental tests on RC beams under impact loads is both time-consuming and expensive. Moreover, the testing setup requires a skilled person to ensure the accuracy of the laboratory work. As a result, numerical simulation can be an alternative approach to investigating their impact response. Finite Element Method (FEM) is a numerical technique that involves dividing reinforced concrete structures into smaller, simpler elements and solving the equations governing each element. Several studies, including [16-24] have successfully used FEM to model and analyse various composite materials or reinforced concrete structures such as slabs, beams, columns, and walls. This paper aimed to develop a numerical procedure using FEM combined with Concrete Damage Plasticity (CDP) constitutive model to simulate the behaviour of RC beams containing SG under low-velocity impact loads. RC beams with varying percentages of SG, ranging from 0% to 40%, were modelled numerically based on the experimental test. The aim of this research is to develop the numerical procedure using Finite Element Method (FEM) for effectively simulating RC beam consisting of SG under low-velocity impact loads. RC beams with different percentages (0%, 10%, 20%, 30% and 40%) of SG were successfully modelled. In recent years, many simulation software programs have been developed to help users save time and energy while obtaining a result. A complicated problem can be solved such as impact or crush simulations using a much simpler solver based on the fundamental principle of FEM. The study also focused on the material descriptions of CDP and highlighted the benefits of using SG to decrease failure and damage in RC beams subjected to impact loads. The study concludes by emphasizing the importance of utilizing concrete elements that can minimize failure and damage to prevent structural collapse or damage after impact loads.

2. Numerical Simulation

This section provides an overview of the numerical simulation techniques used to simulate the impact response of RC beams that contain SG as a substitute for fine aggregates. There are three stages involved in the Finite Element Method (FEM), which are pre-processing, processing, and post-processing. The pre-processing stage is the most crucial, where modelling inputs were carried out in four steps, including modelling idealization, element discretization, defining appropriate steps, and generating material and geometry properties, as well as loading and boundary conditions. These steps are further discussed in the following subsections. Figure 2 depicts the FEM analysis flow chart.

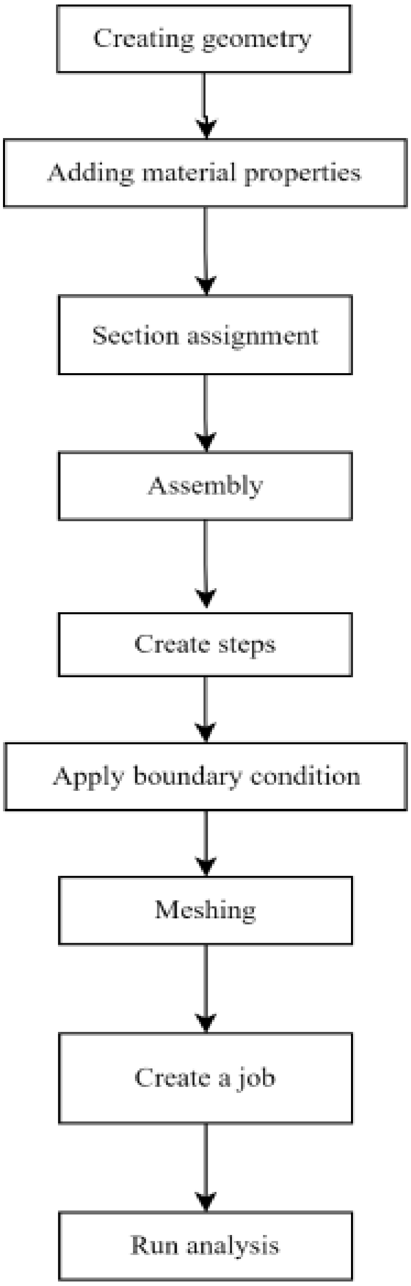


Fig. 2. Methodology flow chart

2.1 Modelling Idealization and Geometry

This stage involved the emulation of the beam and impactor in accordance with the experimental study. Although 2-D modelling offers faster computational times, it is less accurate than 3-D modelling. The modelling process comprised two primary components: the RC beam and impactor. The simulation utilized an RC beam with dimensions of 120 mm in width, 150 mm in height, and 800 mm in length, consistent with the experimental work (refer Figure 3).

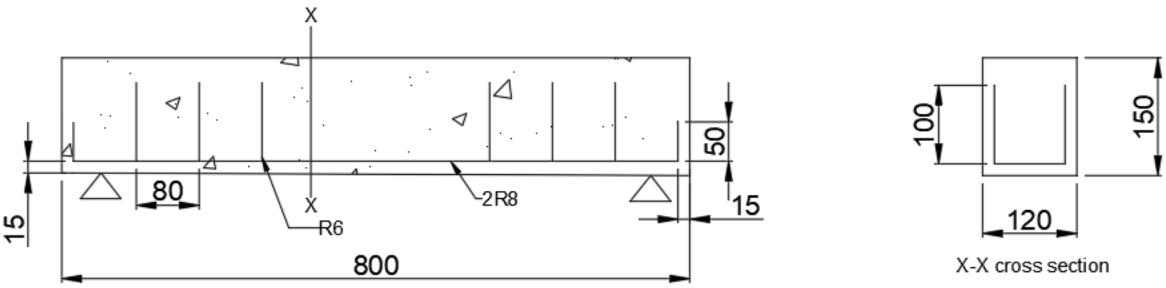


Fig. 3. Dimension of RC beam containing SG

The drop load of 100 kg was applied to the RC beam to simulate the experimental conditions. The geometry of steel impactor, steel reinforcement and beam were modelled based on experimental test setup as shown in Figure 4.

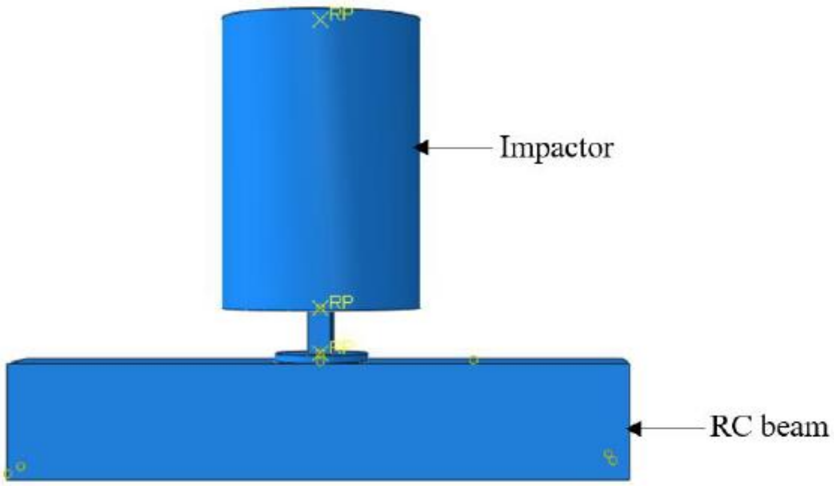


Fig. 4. The model of impactor and RC beam based on experimental setup

2.2 Material Property of Model

This section utilizes the materials obtained from laboratory work conducted at JRC, UTHM. The data set was input into the ABAQUS software to evaluate the model's characteristics that govern damage formation. Essential properties, such as compression strength and flexural strength, were provided by an experimental study and are showed in Table 1.

Table 1
Material properties of RC beam consisting SG

SG (%)	Compression Strength (N/mm^2)	Flexural Strength (N/mm^2)
0	35.6	17.48
10	29.5	17.30
20	34.6	17.38
30	24.3	16.34
40	22.3	15.64

Other parameter data for CDP constitutive model, such as dilating angle, flow stress ratio, and others, were obtained from a previous study conducted by Mokhatar *et al.,* [24], as presented in Table 2.

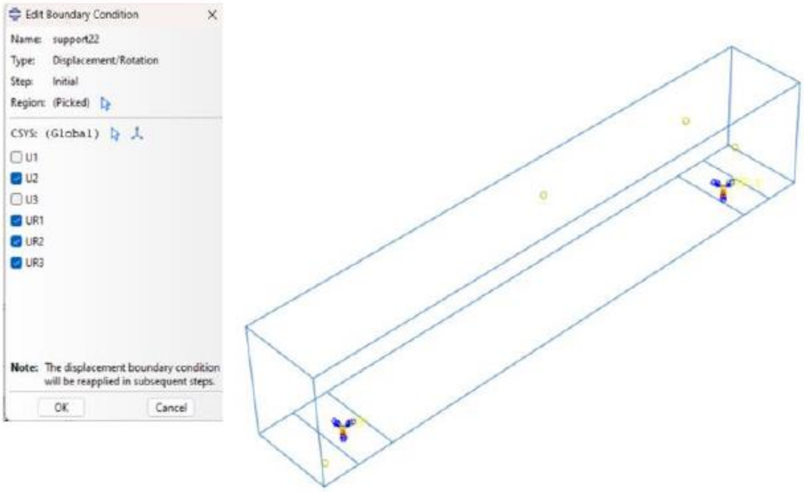
Table 2
Parameter of CDP taken from [24]

CDP model parameters				
Dilation angle	Eccentricity, ε	σ_{bo}/σ_{co}	Kc	Viscosity parameter, μ
38°	1	1.12	1	0.666

2.3 Boundary Condition

The impact load test was conducted at the middle span of the RC beam, based on the experimental work. The loading that was put on was simulated by a force that was applied at the centre point of the beam. In the simulation, the horizontal direction was set as free, as the beam was in roller support in the actual experiment.

Figure 5 illustrates the simulation's attempt to replicate the actual experimental setup for the beam component. To ensure the simulation accurately captured the experimental conditions, the initial and boundary conditions must include the velocity of the drop-weight during the impact loading test. Hence, the experiment's setup was used to create the loading and boundary conditions for the impactor, with a velocity of 5.4m/s employed in this study. The impact load test was carried out by launching the drop-weight vertically, similar to the experimental test.


Edit Boundary Condition

Name: support22
Type: Displacement/Rotation
Step: Initial
Region: (Picked)

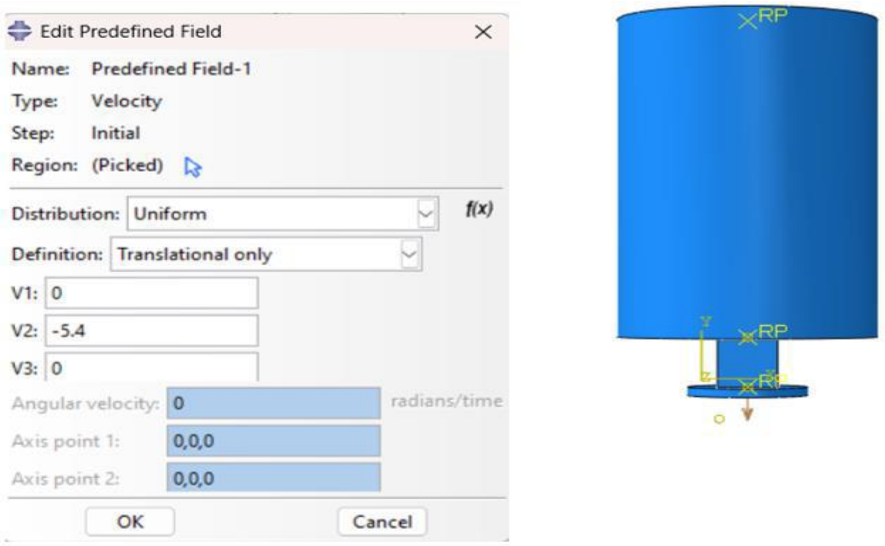
CSYS: (Global)

☐ U1
☑ U2
☐ U3
☑ UR1
☑ UR2
☑ UR3

Note: The displacement boundary condition will be reapplied in subsequent steps.

Fig. 5. Boundary condition location for support region

Figure 6 illustrates the impactor's loading and boundary condition.

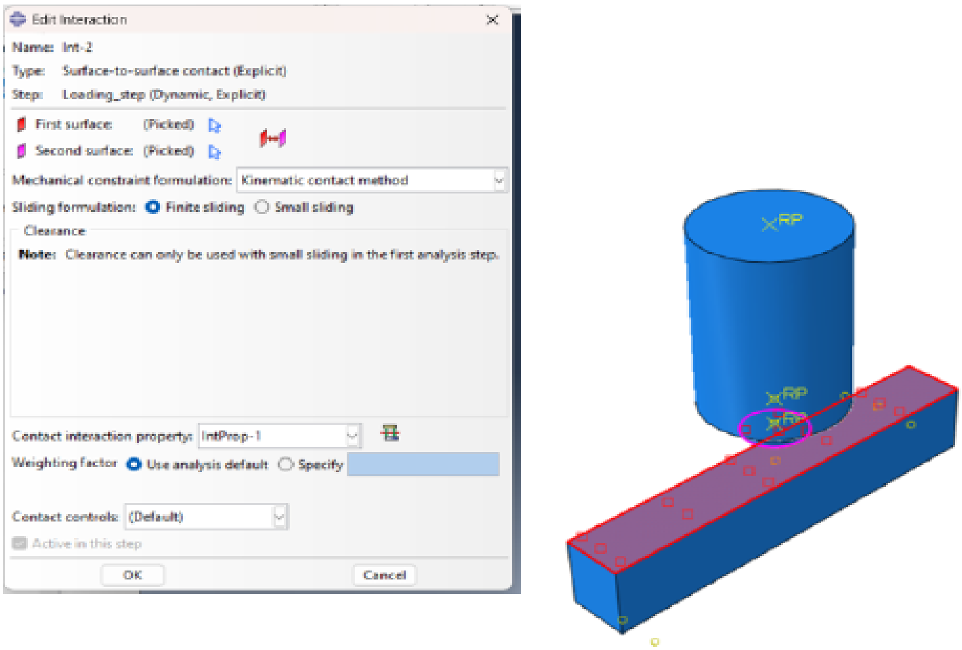


Edit Predefined Field

Name: Predefined Field-1
Type: Velocity
Step: Initial
Region: (Picked)
Distribution: Uniform
Definition: Translational only
V1: 0
V2: -5.4
V3: 0
Angular velocity: 0 radians/time
Axis point 1: 0,0,0
Axis point 2: 0,0,0

Fig. 6. Boundary condition and loading for impactor

While Figure 7 portrays the surface interaction characteristics between the beam and impactor, which must be accurately modelled to ensure precision. Proper interaction between the concrete and steel reinforcement is also crucial in this simulation.

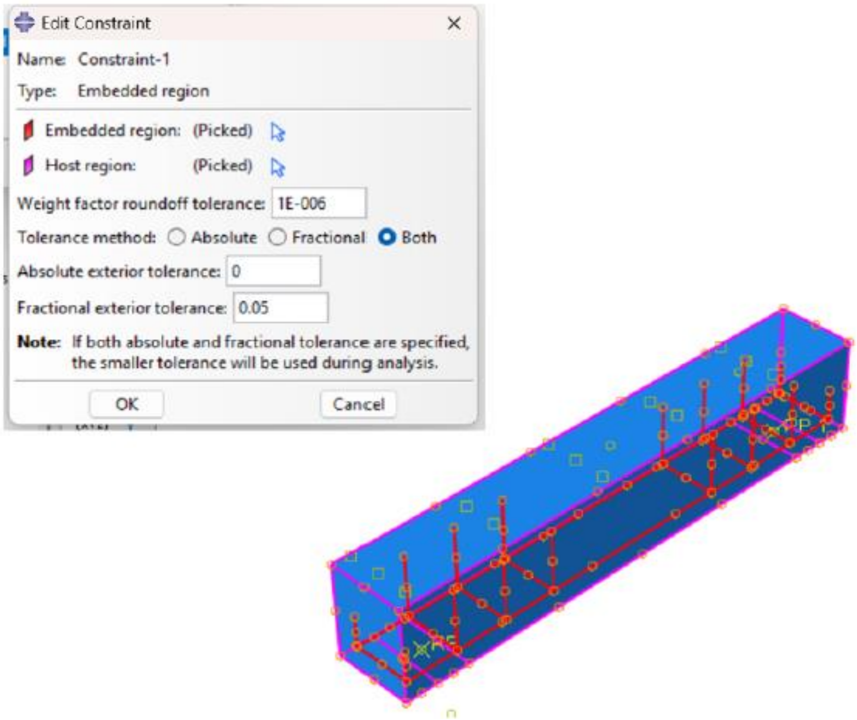


Edit Interaction

Name: Int-2
Type: Surface-to-surface contact (Explicit)
Step: Loading_step (Dynamic, Explicit)
First surface: (Picked)
Second surface: (Picked)
Mechanical constraint formulation: Kinematic contact method
Sliding formulation: ● Finite sliding ○ Small sliding
Clearance
Note: Clearance can only be used with small sliding in the first analysis step.
Contact interaction property: IntProp-1
Weighting factor ● Use analysis default ○ Specify
Contact controls: (Default)
☑ Active in this step

Fig. 7. Surface interaction properties between the beam and impactor

Therefore, the embedded technique was utilized to model the interaction between steel and concrete, as depicted in Figure 8.



Edit Constraint

Name: Constraint-1

Type: Embedded region

Embedded region: (Picked)

Host region: (Picked)

Weight factor roundoff tolerance: 1E-006

Tolerance method: ○ Absolute ○ Fractional ● Both

Absolute exterior tolerance: 0

Fractional exterior tolerance: 0.05

Note: If both absolute and fractional tolerance are specified, the smaller tolerance will be used during analysis.

Fig. 8. Embedded technique for steel reinforcement and concrete

3. Results and Discussion

3.1 Mesh sensitivity

In this method, achieving convergence through mesh sensitivity is crucial in order to determine the most suitable mesh size. While a smaller mesh size can produce more accurate results, it requires a longer computation time. For this particular study, the global mesh seed for the beam began at 35mm as shown in Figure 9 and gradually decreased until the result was close to the experimental outcome. In order to achieve numerical results with greater precision, it may be beneficial to conduct a mesh sensitivity study, utilizing appropriate boundaries for mesh segments and allocating a finer mesh within the region of interest. This region is typically one where stress concentration and the development of damage are more prominent.

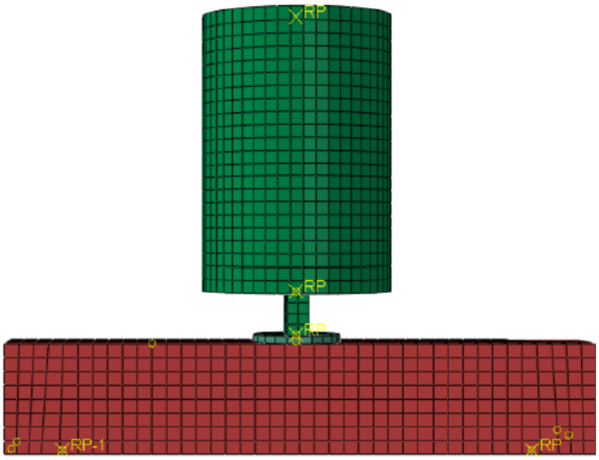


Fig. 9. Meshing of 3-D modelling

Beginning at 35mm and concluding at 15mm, the investigation into mesh sensitivity revealed that stress concentration beneath the impactor region produced comparable results for sizes of 20mm and 15mm, as indicated by Table 3 and Figure 10.

Table 3
Result of mesh refinement

Mesh size (mm)	Total element	Stress value under impact region (MPa)
35	370	1.52
30	394	1.78
25	556	2.13
20	868	2.26
15	1668	2.30

As a result, a mesh size of 20 was deemed suitable for all models utilized in this study.

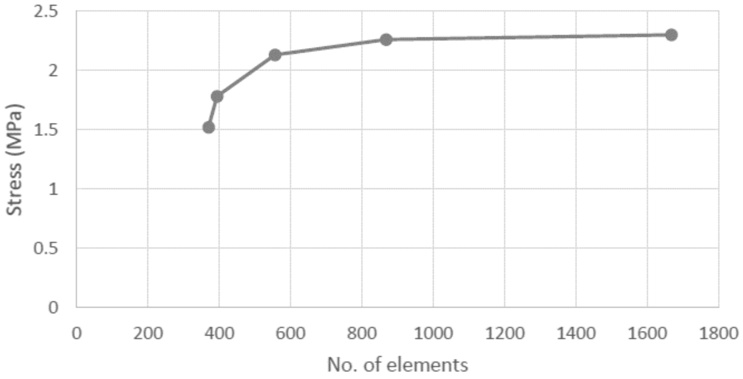


Fig. 10. Stress pattern for mesh refinement study

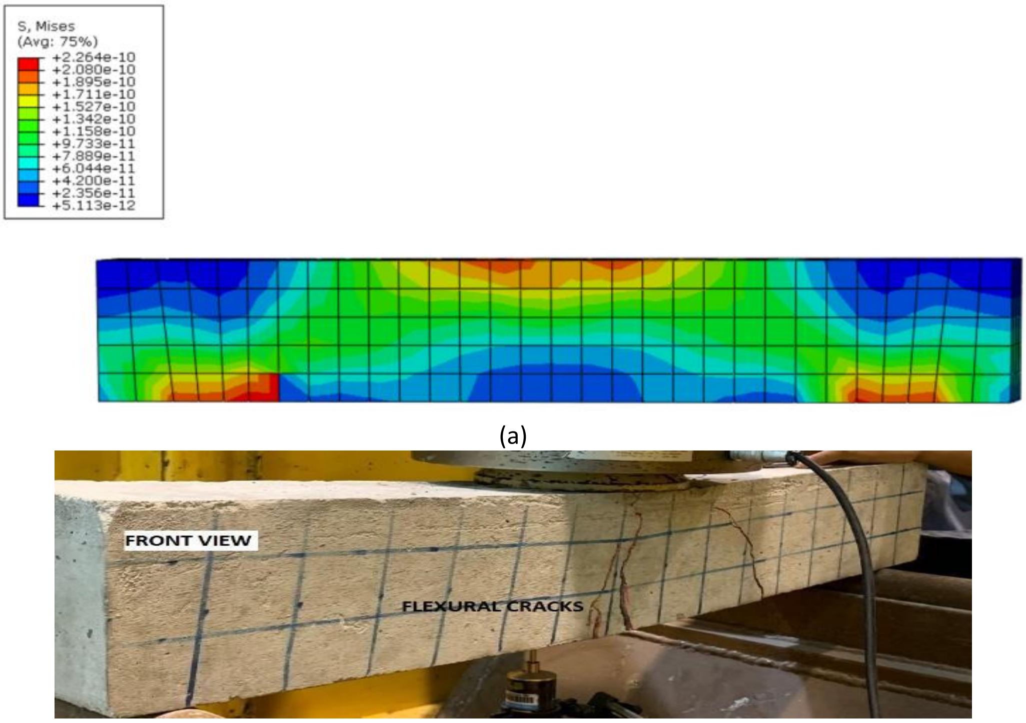
3.2 Failure of RC Beam

At the Jamilus Research Centre, FKAAB, an experiment was carried out to evaluate five specimens under the same 1.5 m drop height with a constant velocity in this study. The total failure modes of the specimens were successfully recorded for the impact at a moderate drop height. The impact load used in the test was 100 kg. In flexural failure, the beam bends excessively due to the moment caused by the impact loading, resulting in cracks on the tension side of the beam and eventual failure. On the other hand, shear failure can occur when diagonal cracks form at an angle of approximately 45 degrees to the longitudinal axis of the beam due to the impact loading. This can lead to the concrete separating from the reinforcing steel, resulting in a sudden and catastrophic failure [25].

This analysis involved running five models of RC beam using FEM at a velocity of 5.4m/s, which was consistent with the experiment. The results were compared to show the various failure patterns based on the percentage of spent garnet (SG) replacement in RC Beam. Simulation works were conducted for the impact load test, and these were compared with the experimental study. Figure 11 to Figure 15 illustrate the failure mode of SG in both simulation works utilizing the CDP model and experimental study.

The reaction force's overall response pattern exhibited a slight deviation from the experiment's findings, and the defect present in each beam that contained SG was measured and compared to the results of the trial and the control beam. Figure 11(a) to Figure 15(b) demonstrate the different results obtained from the simulation and experiment studies, depending on the percentage of SG in the RC beam.

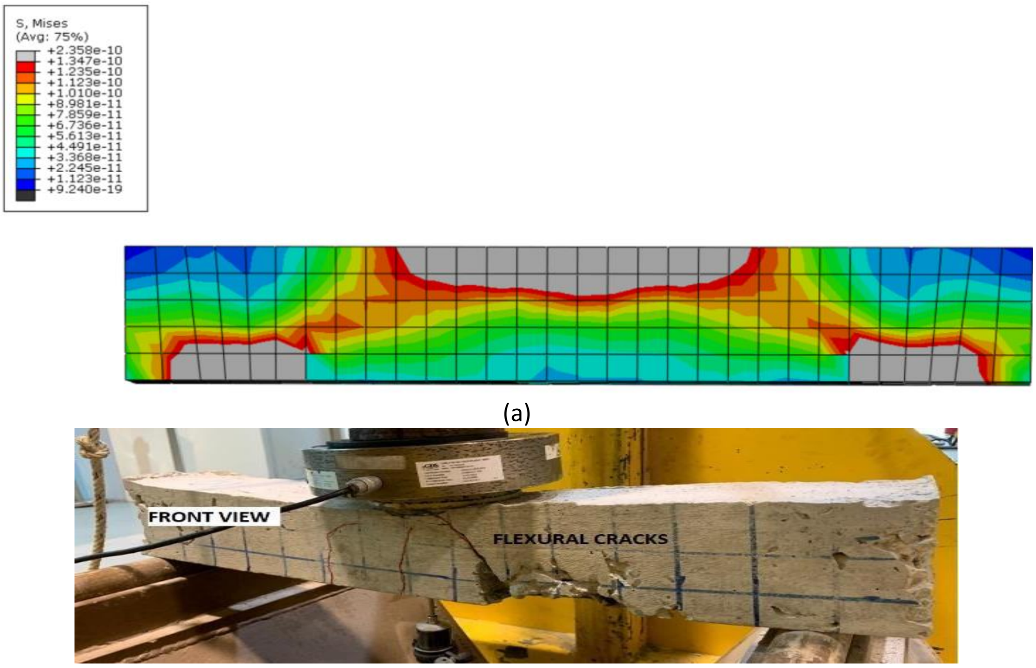
In summary, the study revealed that the RC beam with 40% SG had fewer defects, while the RC beam with 10% SG had more defects. The failure of the beam with 20% SG was more apparent than that of the beam with 30% SG. Among the other percentages of SG, the RC beam with 10% SG had the main failure, as evidenced by the significant damage and harm to the beam in both the simulation and experiment results. As the proportion of SG increases, the harm to the beam decreases.



(a)

(b)

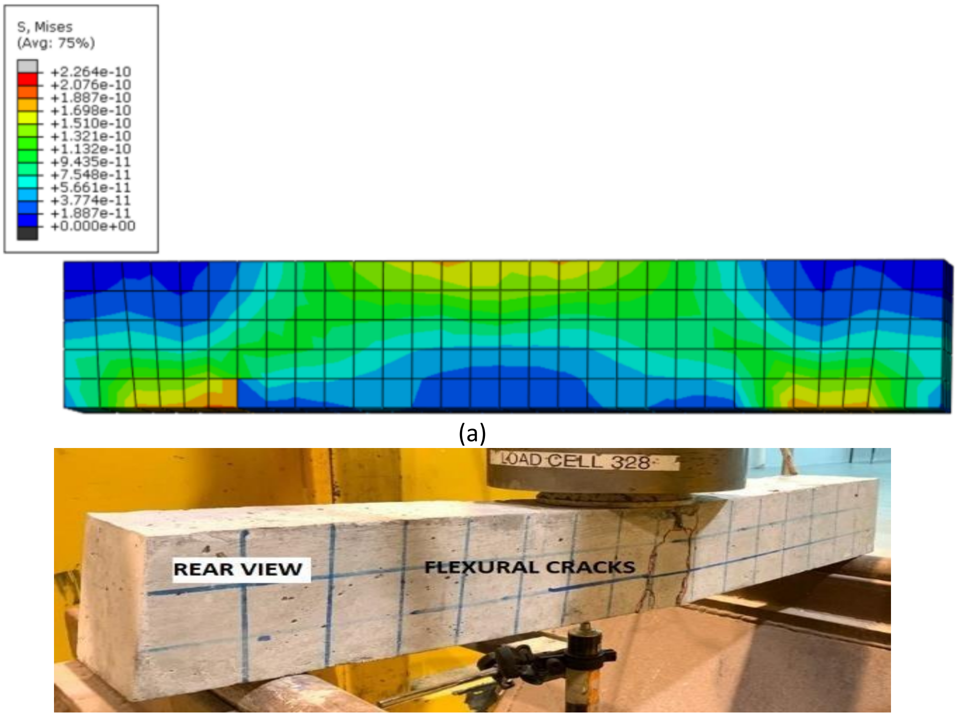
Fig. 11. Result for RC beam with 0% of SG (a) FEM model (b) Experimental



(a)

(b)

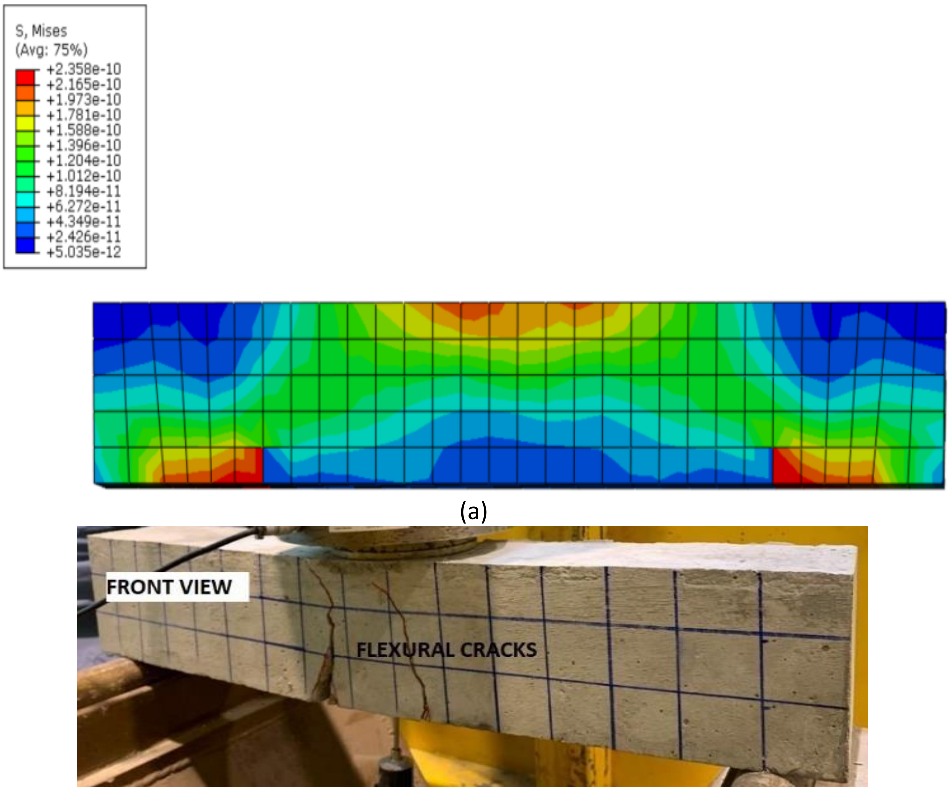
Fig. 12. Result for RC beam with 10% of SG (a) FEM model (b) Experimental



(a)

(b)

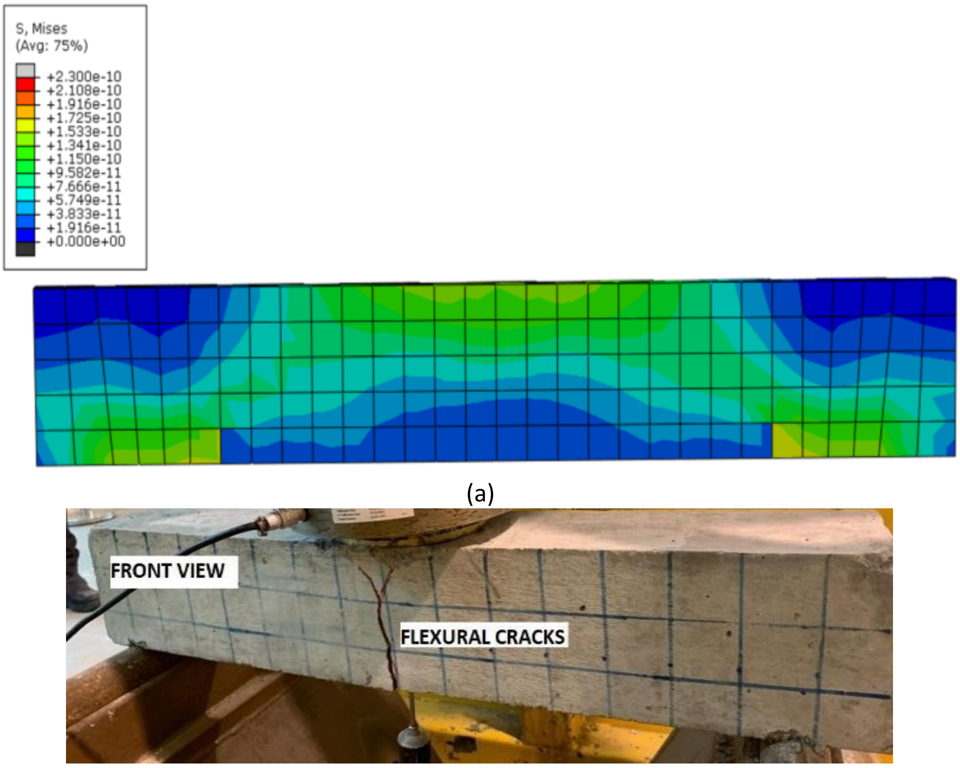
Fig. 13. Result for RC beam with 20% of SG (a) FEM model (b) Experimental



(a)

(b)

Fig. 14. Result for RC beam with 30% of SG (a) FEM model (b) Experimental



(a)

(b)

Fig. 15. Result for RC beam with 40% of SG (a) FEM model (b) Experimental

4. Conclusions

This study has successfully used a CDP model to simulate the behaviour of an RC beam containing SG under low-velocity impact loads. The CDP model proved to be a suitable approach for this purpose. However, the simulation's failure mode of the RC beam differed slightly from that observed in the actual experiment, which could be due to various factors such as the accuracy of the model or the experimental setup. Nevertheless, the minor inconsistencies are still tolerable.

The study showed that the percentage of SG in the concrete mix had an impact on the beam's failure profile. Incorporating SG into the concrete mixture produced positive outcomes in terms of flexural and shear cracking, leading to reduced failure and damage as the proportion of SG increased. More specifically, utilizing 40% of SG in the concrete mixture proved to be particularly effective in minimizing failure and damage. Overall, the presence of SG in concrete improved its behaviour, allowing it to withstand more impact. These findings could have practical implications for the design of structures that may be subjected to low-velocity impact loads, as the addition of SG could potentially improve their durability and resilience.

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