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Flexural Performance of Alccofine-based Self-Compacting Concrete Reinforced with Steel and GFRP Bars

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Abstract

Self-compacting concrete (SCC) is a type of special concrete with enhanced workability that eradicates the need for external compaction. Utilization of Supplementary Cementitious Materials (SCMs) in SCC production is considered to be important on a financial, technical, and environmental basis. In that aspect, Alccofine is a new promising mineral admixture based on slag which can be used as an SCM. In the case of reinforced concrete structures, Glass Fiber Reinforced Polymers (GFRP) rebars can be an appropriate substitution to steel rebars for emphasizing concrete buildings in worse environments. This paper intends to study the flexural behaviour of reinforced Alccofine based SCC beams with steel and GFRP rebars that have not yet been attempted before. The influence of reinforcement and SCC mix proportions on the load-bearing capacity, deflection, cracks, strains of concrete and reinforcement, and moment were examined. From the significant findings, it was determined that beams reinforced with steel failed under flexure whereas GFRP caused the brittle failure.

Disciplinary: Civil Engineering (Structural Engineering & Construction Materials).

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1 Introduction

Self-compacting concrete (SCC) is one of the most significant innovations in the construction industry (Domone 2006, 2007; Su and Miao 2003). During the pouring process, SCC can flow through and fill gaps in reinforcement and corners of moulds without the need for vibration or compaction (Dinakar 2012). It is capable of compacting itself purely by its own weight, without any need for vibration (Okamura and Ouchi, 2003). The use of SCC has many advantages in manufacturing: the elimination of compacting work decreases placement costs, a reduction in construction time, and, as a result, increased productivity (Dinakar, 2012). SCC was produced by replacing cement with industrial by-products or supplementary cementitious materials (SCMs) such as rice husk ash, marble powder, fly ash, silica fume, metakaolin, and Ground Granulated Blast Furnace Slag (GGBS) etc. (Vivek et al., 2017). One of the most significant technical developments in the concrete manufacturing industry is the use of SCMs as a partial or full replacement for cement in concrete manufacturing (Sagar and Sivakumar 2020). In that aspect, SCC utilizes a larger quantity of SCMs as a binary, ternary, or quaternary combination. The utilization of SCMs provides both financial and environmental advantages without compromising the strength properties.

Alccofine, a new slag-based micro-fine mineral admixture, can be used as an SCM in concrete. It is a low-calcium silicate material with a high glass content and high reactivity that is eco-friendly. It's a highly processed GGBS material with ultra-fine particles obtained through a regulated granulation process (Balamuralikrishnan and Saravanan, 2019; Parveen et al. 2018; Saloni et al. 2020; Sharma et al., 2016). In recent investigations, cement is replaced by an alccofine maximum of 25% with additional SCMs in normal concrete and SCC (Abraham et al., 2019; Balamuralikrishnan and Saravanan 2019; Kavitha and Kala 2016; Kavyateja et al., 2020; Narender et al., 2018; Sagar and Sivakumar 2020; Upadhyay and Jamnu 2014). Prithiviraj and Saravanan (2020) attempted 10-60% replacement of Alccofine in SCC and they achieved optimum results at 30% without any additional SCMs. Based on Prithiviraj and Saravanan (2020) mix proportions, beams were cast in this investigation with steel and Fiber Reinforced Polymer (FRP) reinforcements.

Fiber Reinforced Polymer (FRP) reinforcement is a new modern building material with opportunities to invade the construction market (Golafshani et al., 2014), becoming very popular in RC structures. The enhanced mechanical performance, lightweight, tolerable durability in a harsh environment of FRP bars are all factors that contribute to their success (Golafshani et al., 2014). Previous studies (Alsayed 1998; Ascione et al., 2010; Hassan et al., 2019; Kalpana, 2011; Mazaheripour et al. 2016; Roja et al. 2014) have shown that FRP is an ideal replacement to steel in fields such as deicing salt-treated concrete pavements, buildings constructed in/near seawater (e.g., Marine walls, underwater constructions), wastewater, etc. FRP bars have a higher tensile strength in the lengthwise direction because it is made up of continuous unidirectional aligned fibres integrated by a matrix. FRP made of Aramid (AFRP), Basalt (BFRP), Carbon (CFRP), and Glass (GFRP) are the most widely used as FRP rebars in civil engineering. Varieties of production techniques are used to produce FRP reinforcing bars. Every processing technique results in a unique surface condition. The physical properties of the FRP bar's exterior are essential to the mechanical bond with the concrete. Plane, ribbed, grooved and sand-coated are the most common surface deformation patterns.

However, FRP bars having unique properties there are only a small number of investigation has been done in the flexural behaviour of GFRP bars in SCC. In particular, there is no research so far studied the flexural behaviour of Alccofine based SCC with GFRP. To concentrate on this subject matter, this paper describes the flexural performance of conventional steel and sand-coated GFRP bars in conventional SCC and Alccofine based SCC under static monotonic loading experimentally. During the static monotonic tests, the load, deflection, and corresponding strain data were also recorded. Load vs. deflection, load vs. Strain, moment vs. Curvature, curves and deflection profiles have been plotted based on test data were reported.

2 Experimental Investigation

2.1 Test Specimens

In this study, four beams were cast and evaluated under the two-point loading condition. All the beams were 3000mm in length and had a 150mmx250mm rectangular cross-section. Figure 1 depicts the cross-sectional details for the beam. The Alccofine replacement in the SCC and replacement of reinforcement were used to divide the beams into four. Beam I and Beam II are made of conventional SCC mix and reinforced at the tension face by two 12mm diameter Steel and GFRP bars respectively. Beam III and Beam IV are made of Alccofine-replaced (30%) SCC mix with two 12mm diameter Steel and GFRP bars at the tension face, respectively. The hanger bars for Beam I and Beam III beams were made of 2nos steel bars with a diameter of 10mm. 2nos GFRP bars with a diameter of 10mm were used as hanger bars for Beam II and Beam IV beams. For beams, I and III, 8mm diameter steel stirrups of 150 mm c/c spacing confine the longitudinal reinforcements. The longitudinal reinforcements are surrounded by 8mm diameter GFRP stirrups of 150 mm c/c spacing for beams Beam II and Beam IV. Table 1 summarises the beam details.

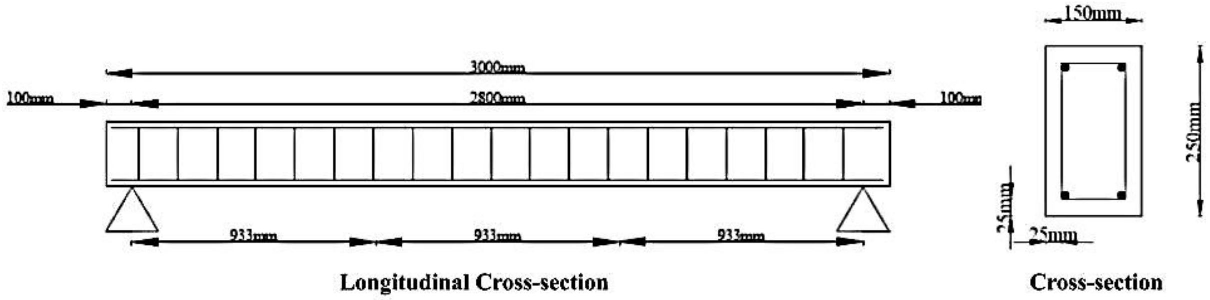

Figure 1: Cross-section of the beam.

Table 1: Beam details

Mix	Beam ID	Longitudinal bars No and #diameter (mm)	
		Steel	GFRP
SCCA0	SCCA0-STEEL	2#12	-
	SCCA0-GFRP	-	2#12
SCCA30	SCCA30-STEEL	2#12	-
	SCCA30-GFRP	-	2#12

2.2 Material Properties

For the preparation of beams Ordinary Portland Cement (OPC) 53 grade was used as per IS 12269-1987. Which is purchased from Ultra-Tech Pvt. Ltd. and the specific gravity was 3.15. The pozzolanic material Alccofine 1203 is used as per IS 16715-2018 as a replacement for cement with a specific gravity of 2.86. Normally available river sand was used as a fine aggregate confirming Zone III with a specific gravity of 2.68 and a fineness modulus of 2.88 as per IS: 383–1970. Crushed angular aggregates of size passing from 20mm sieve and retained in 4.75mm sieve were used as coarse aggregates which has a specific gravity of 2.7 as per IS: 383–1970. Polycarboxylic ether-based superplasticizer (BASF-Master Glenium sky 8233) is used as a chemical admixture conforming to IS 9103-1999. Tap water available in the laboratory, which is not contaminated by chemicals or other substances, was used to compose the concrete specimens. The Fe550 (TMT bars) grade of the steel was used as main bars and stirrups and their mechanical properties are given in Table 2.

Table 2: Mechanical properties of rebars

Rebars	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's Modulus (N/mm^2)
Steel	550	567	200000
GFRP	-	3400	71000

2.2.1 Alccofine 1203

Alccofine 1203 is a specially processed ultra-fine slag based product with high glass content and better reactivity which is purchased from Counto Micro fine products Pvt. Ltd. Goa. The particles of alccofine were irregular in shape with sharp edges. The specific surface area of alccofine is 1200 cm^2/g.

2.2.2 GFRP Rebars

GFRP bars have a variety of properties. They're not the same as the process or the constituents. Table 2 lists the mechanical properties of GFRP bars. In a plain GFRP bar surface treatment is essential to increase a sufficient bond between GFRP and concrete. As a result, in the current investigation, the plain smooth bars are initially layered with an epoxy resin and after the surface is covered by dry sand by rolling the bars as shown in Figure 2.

Figure 2: Steel and Sand-coated GFRP bars.

2.3 Structure of the Reinforcement

Before casting the concrete beams, the main reinforcement bars and hanger bars were properly positioned, and the stirrups were properly bound with binding wires. The structure of reinforcement is shown in Figure 3. Two strain gauges with 5 mm gauge length were fixed in the centre of each of the tension reinforcement bars to obtain the strains at the reinforcement level.

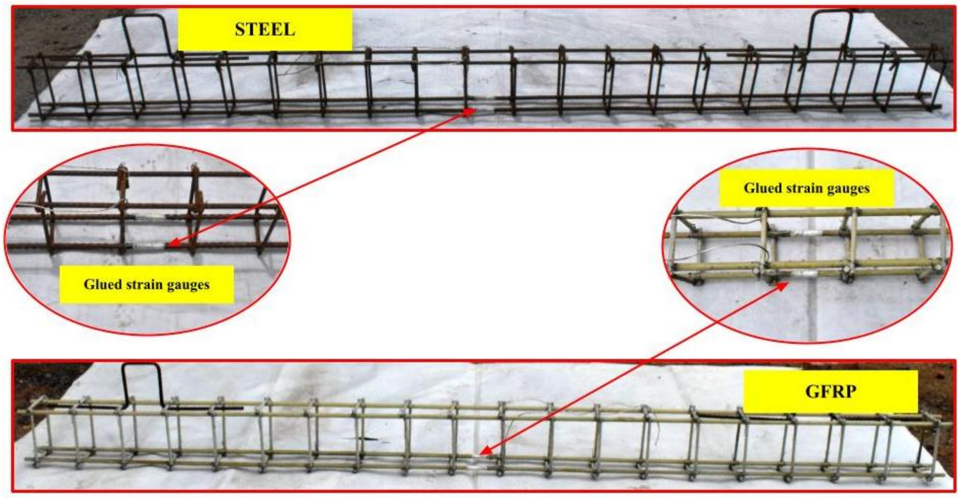

Figure 3: Reinforcement Structure.

2.4 Mix Design

According to EFNARC recommendations, fresh properties such as flowability (flow table), filling ability (V-funnel), and passing ability (L-box) are examined in the laboratory and these results were compared with recommendation (EFNARC 2005). The constituent materials for SCC beams were seen in Table 3. Details of the fresh and hardened properties of SCC had already been studied by the authors (Prithiviraj and Saravanan 2020). The characteristic compressive strength of the proposed mix proportions of SCCA0 and SCCA30 is 30.69 and 48.13 N/mm^2 respectively.

Table 3: Mix proportions of SCC (kg/m^3)

Mix	Cement	Alccofine	Fine aggregate	Coarse aggregate	Water	Superplasticizer
SCCA0	465	0	915	836	186	4.65
SCCA30	325.5	139.5	915	836	186	4.65

2.5 Test Setup

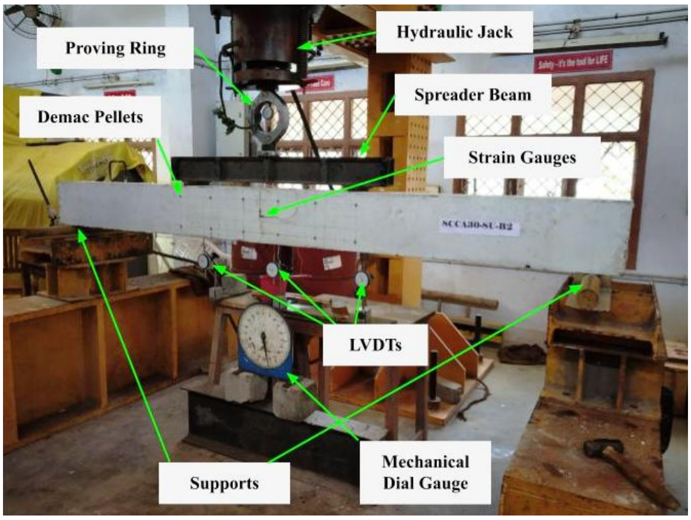

Figure 4: Experimental Arrangement

Before installation of beam specimen into the loading frame the length of the beams was measured and dived into three sections (L/3). Then the grid patterns are drawn in the flexural zone of the beam to measure the crack dimensions. Based on the length of the beam specimen the position of the supports (hinged and roller) in the loading frame was adjusted. After that, the beam is placed in the loading frame. A two-point loading condition was implemented to determine the capacity of the simply supported beams (Figure 4). The designed beams are under-reinforced with steel and GFRP bars. By using a hydraulic jack (500kN capacity) the load was applied gradually and the load is transferred to the beam specimen with the help of a steel spreader (I-section). Two surface strain gauges of Linear and Lateral with 5 mm gauge length were fixed on the concrete surface of all beams and connected in the stain indicator to measure the strain deviation during loading. Also, Demac gauge pellets are fixed on the concrete surface to measure the surface concrete strain manually. The deflection at mid-span was observed using Linear Variable Differential Transformer (LVDT). The surface of the concrete strain is measured with the help of a Demec gauge. The load was applied by the hydraulic jack in 2.5kN intervals and deliberated with a load cell. Observations such as deflections, concrete surface strain, rebar strain, cracks on the beam's face were documented at every load increment. The first crack load, ultimate crack load, failure type, load-bearing capacity, etc., were vigilantly observed and documented.

3 Results and Discussion

Deflection, displacement, strain deviation in the rebars as well as on the beam surface, moment, curvature, and other parameters were used to assess the performance of the GFRP and steel-reinforced concrete beams. This section contains the average consequence for each group, as well as the ultimate load average values, see Table 4.

Table 4: Observations of Readings at Ultimate Load

Beam ID	Ultimate Load (kN)	Bending Moment (kN-m)	Deflection (mm)	Crack Width (mm)	Number of Cracks
SCCA0-STEEL	60	28	21.42	0.6	16
SCCA0-GFRP	40	18.67	36.11	1.3	3
SCCA30-STEEL	65	30.33	18.42	0.6	14
SCCA30-GFRP	47.5	23.33	36.2	1.3	4

3.1 Load vs. Deflection Behaviour

Figure 5 illustrates the graphical representation of load-deflection behaviour of the SCC beams with two different mix proportions and reinforcements respectively. Before loading the beams are rigid and un-cracked. When the applied load is increased the beam undergoes deformation with the development of cracks in the tension zone. Further addition of load leads to the formation of new cracks and expansion of existing cracks. From the test observation, the deflection behaviour of the steel-reinforced beams is very parallel up to the service loads, indicating beam stiffness. Similar behaviour was observed in the GFRP reinforced beams with differed loading conditions. At the ultimate stage, it was experienced that the deflection of beams is more rapid at a minimum rate of load increment. Up to failure, the beams reinforced with GFRP showed partial linear elastic behaviour and steel showed nonlinear elastic behaviour for both the mix SCCA0 and SCCA30. Steel and GFRP bars embedded in the SCCA30 mix performed well in deflection than the bars embedded in the SCCA0 mix. However, beams reinforced with GFRP showed not as good as reinforced with steel. Table 5 shows the load at the initial crack, ultimate load, and deflections. To understand its flexural behaviour, the deflection profile of steel and GFRP reinforced SCC beams at ultimate load was drawn. Figure 6 depicts the ultimate load-deflection profile.

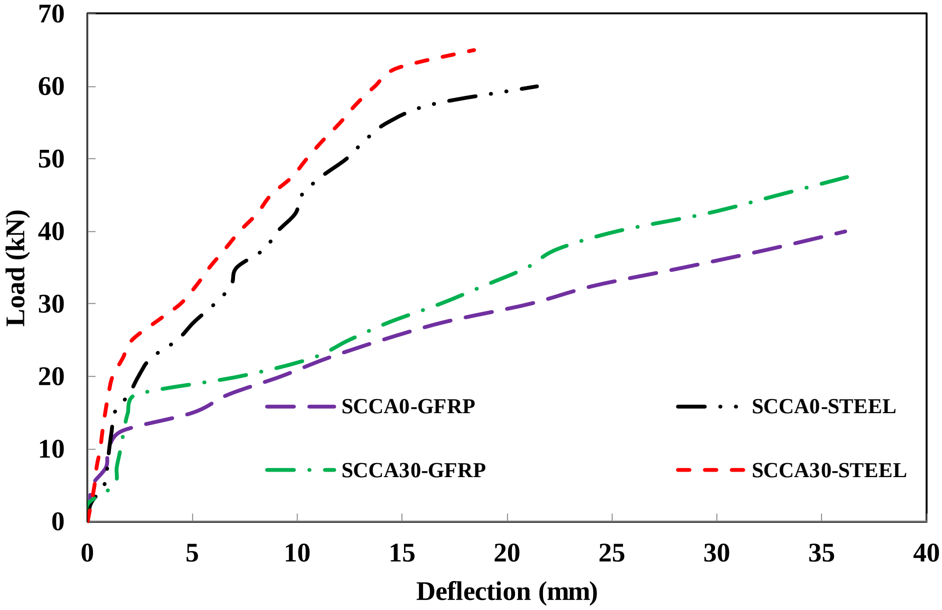

Figure 5: Load vs. Deflection of SCC Beams

Table 5: Load vs. Deflection at First Crack and Ultimate Load

Beam ID	Load at the first crack (kN)	Ultimate Load (kN)	Deflection at the first crack (mm)	Deflection at Ultimate Load (mm)	Moment at the first crack (kN-m)	Moment at Ultimate Load (kN-m)
SCCA0-STEEL	17.5	60	1.96	21.42	8.16	28
SCCA0-GFRP	15	40	1.99	36.11	7	18.67
SCCA30-STEEL	25	65	2.11	18.42	11.67	30.33
SCCA30-GFRP	17.5	47.5	10.66	36.2	8.17	23.33

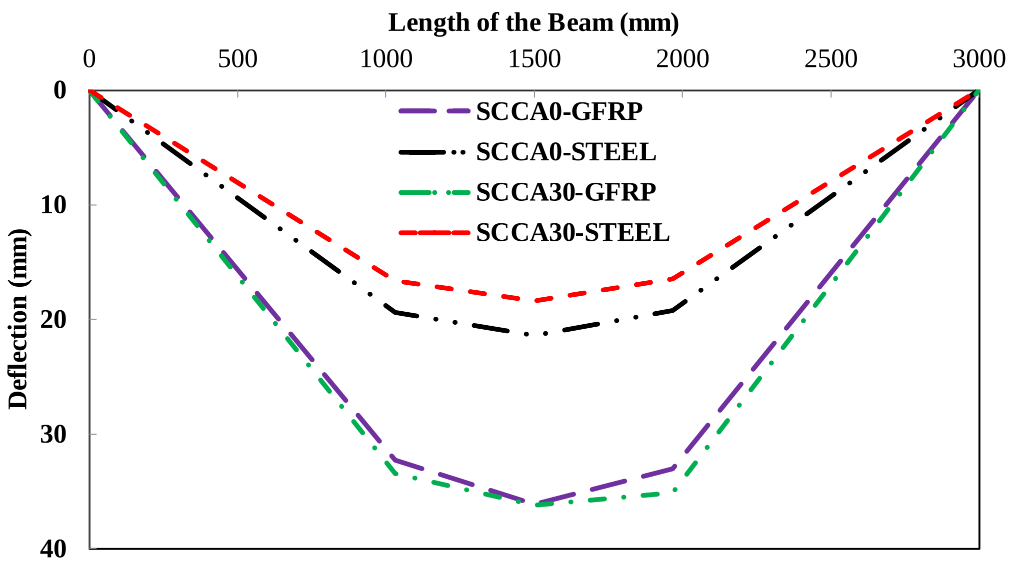

Figure 6: Ultimate Load Deflection Profile.

3.2 Load Bearing Capacity

As compared to conventional SCC (SCCA0) beams, the Alccofine-based SCC (SCCA30) beams significantly increased the ultimate load-bearing capacity. In terms of rebars, Steel reinforcement performs significantly better than GFRP rebars. As GFRP reinforced SCCA0 and SCCA30 beams decreased the ultimate load by about 50% and 37%, respectively compared to steel reinforced beams. When compared to mix proportions SCCA0 and SCCA30, the load is increased about 8% and 16%, respectively. This indicates that there is no discernible enhancement by mixed proportions in beam load-bearing capacity. Table 6 shows the load-bearing capability of GFRP beams and steel-reinforced beams intended according to ACI 440.1R-06 and ACI 318.10 standards. This change in results may be due to the properties of rebars.

Table 6: Comparisons of Ultimate Load

Beam ID	Theoretical ultimate load (kN)		Experimental Ultimate Load (kN)
	Steel (ACI318)	GFRP (ACI 440)	
SCCA0-STEEL	42.7	-	60
SCCA0-GFRP	-	42.5	40
SCCA30-STEEL	44.8	-	65
SCCA30-GFRP	-	44.5	47.5

3.3 Load Cracking Behaviour

Smaller cracks are initially become visible within the constant moment region. Depending on the type of reinforcement and concrete strength cracks were formed. Mainly flexural cracks are perpendicular to the beam concerning loading. When the applied load is increased, the formation of cracks appeared at the bottom of the beam. If the additional load is applied old cracks were expanded and new cracks were developed. As the load on the beam increased further, the cracks away from the flexural zone become inclined, and these inclined cracks gradually propagate to the loading point on the compressive zone of the beam.

Figure 7: Crack Patterns of SCC Beams.

All the SCC beams are failed due to the crushing of concrete and the crack patterns are shown in Figure 7. The premature cracks were observed in GFRP reinforcement beams as compared to beams with steel reinforcement. This was due to the lower young's modulus of GFRP bars. Beams reinforced with GFRP have larger crack widths and the number of cracks is within the range of 3-5 (Table 4).

3.4 Load Strain Behaviour

Figure 8 demonstrates the load-strain behaviour of the rebars and concrete. The concrete strain at failure for the under-reinforced SCC beams was found to be less than 0.003. As per ACI (ACI Committee 440.1R-06 2006), the assumed highest compressive strain value of concrete is 0.0035. There was a significant fall in strain value when the crack is formed in GFRP bars. However, the strain in the reinforcement was unaffected by concrete strength. The maximum GFRP and steel reinforcements strain was found to be 0.008 and 0.003.

Noted the negative strain values represent the compression and positive strain values indicate tension. To differentiate the strain in concrete compression and reinforcement tension, the graph is plotted. Also, the negative strain values can be attained when it is measured in the surface.

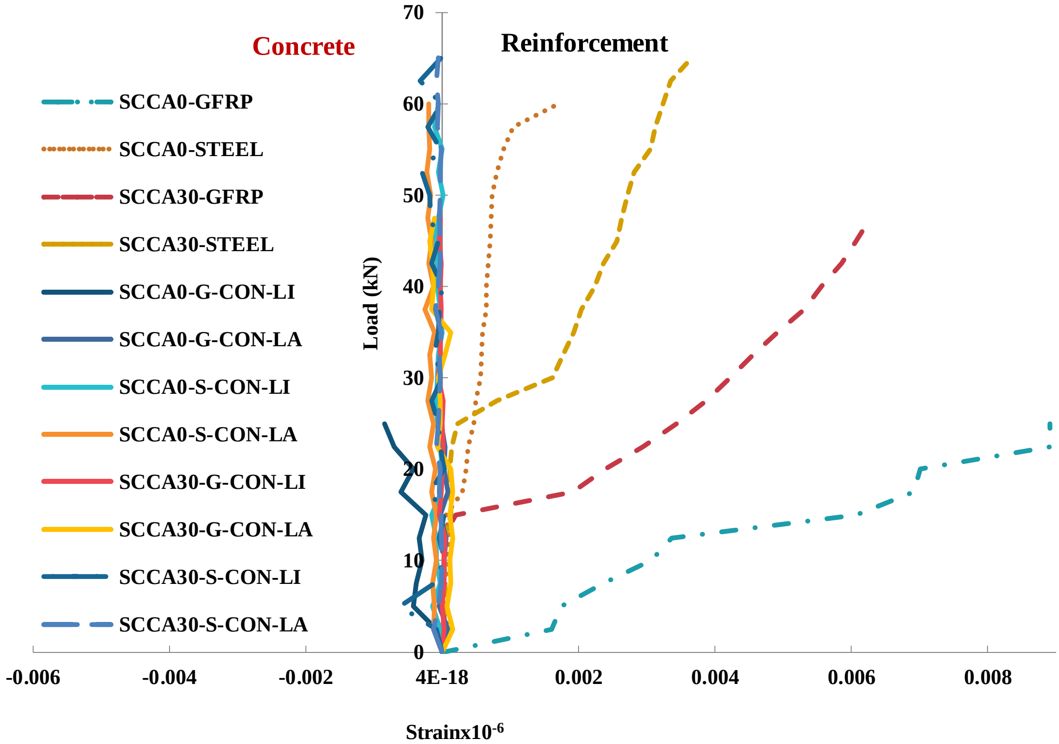

Figure 8: Strain Behaviour of Concrete and Reinforcement.

3.5 Moment Curvature Behaviour

Figure 9 shows the moment-curvature relationship for SCC beams with steel and GFRP reinforcement. Table 5 shows the moment of crack initiation and the ultimate moment of resistance for SCC beams. The curvature Φ (rotation per unit length) was calculated from

$$\Phi = \frac{(\varepsilon c + \varepsilon st)}{d} \quad (1),$$

where

εc is the compressive strain in the extreme concrete fibre;

εst is the strain in the tension steel;

d is the effective depth of the beam section.

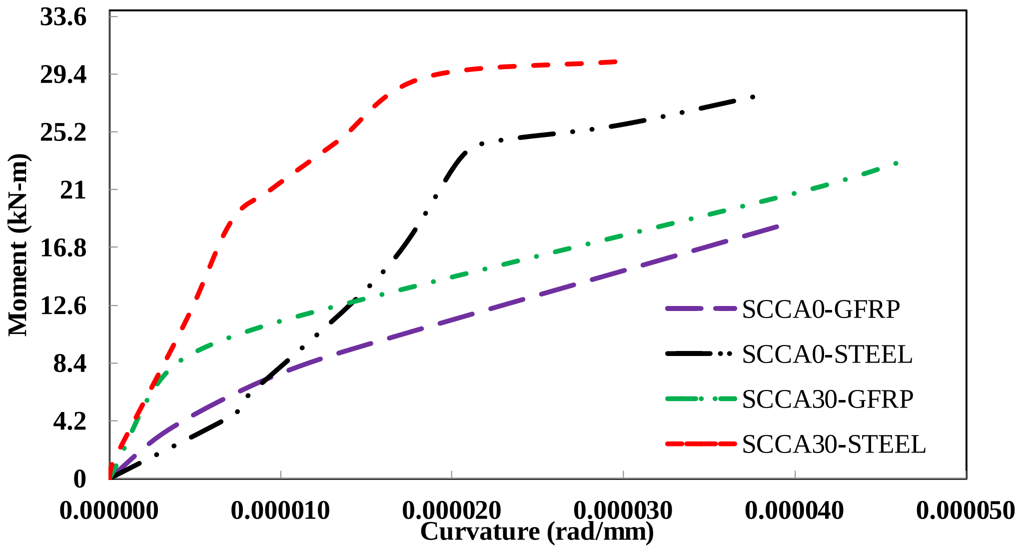

Figure 9: Moment Curvature of SCC Beams

4 Conclusion

The study examined the flexural performance of SCCA0 and SCCA30 steel and GFRP reinforced beams under static loading. Based on the findings, all SCC beams exhibited a nonlinear relationship up to fail. Beams reinforced with steel fails under flexure whereas GFRP causes brittle failure in concrete and rupture in reinforcement. This GFRP failure was due to partial linear elastic behaviour.

There is no significant increase in load-bearing capacity beams with concrete strength. With reference to deflection and load-bearing capacities, beams are highly influenced by the steel compared to GFRP reinforcements.

When cracks occurred, bending stiffness decreased regardless of the SCC mixture (SCCA0 or SCCA30). GFRP rebar had stiffness loss, which leads to wider crack widths occurred in beams. However, the maximum crack width will not affect the GFRP bars because non-corrosive by the surrounding environment hence the limitation of crack width can be relaxed.

Owing to the lower young's modulus of GFRP, the strain values of GFRP reinforcement bars increased significantly as compared to steel. At the same time, there is no major variable in concrete surface strain (less than 0.003).

Due to the limitations of serviceability requirements, the use of GFRP rebars is merely restricted to very few structures, and further study on the tolerability of GFRP bars in the building industry is currently ongoing around the world.

5 Availability of Data And Material

Data can be made available by contacting the corresponding author.

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