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EXPERIMENTAL INVESTIGATION OF HYBRID DEEP BEAMS USING SELF-COMPACTING AND GEOPOLYMER CONCRETE UNDER VARIOUS PLACEMENT CONFIGURATIONS

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ABSTRACT

An experimental investigation was carried out for deep beams constructed from the hybrid concrete system, where self-compacting concrete (SCC) and geopolymer concrete (GPC) are prepared. Two-point loading was carried out on eighteen deep beam cases involving 1 control beam featuring SCC, as well as 3 hybrid configurations having different GPC locations. Group G1 used 70 mm GPC layers in the top, bottom, or top-bottom zones; Group G2 utilized 140 mm layers found in similar geometries. Group G3 had 200 mm and 300 mm of shear zones (GPC) from support. The mechanical response varied according to GPC location and thickness. In Group G1, the lower layer was better performing, and the top-bottom configuration is bad. Optimal capacity was found in Group G2 at top-and-bottom configurations, and the top-only configuration was the least effective. A 200 mm hybrid beam outperformed 300 mm in shear performance but exhibited a decreased structural efficiency and better deformability compared to 300 mm. After crack analysis, the failure was mainly due to diagonal shear compression and flexural action. In addition, the results showed that SCC-GPC hybrid deep beams exhibited satisfactory structural performance and sustainability after elimination of GPC from critical load paths

1. Introduction

Deep beams are structural elements with a small span-to-depth ratio and a nonlinear strain distribution across their depth. Unlike slender beams, where classical flexural theory applies, deep beams mainly transfer loads through compression struts between loading points and supports, and shear is the dominant force. As a result, their behavior is governed by complex stress fields, making it difficult to design and analyze.

The construction industry is increasingly driven by a high-performance and environmentally friendly structural material. Reinforced concrete is the most widely used structural material in modern day buildings,

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but conventional systems are challenged by cracking, durability problems, and environmental problems caused by Portland cement production. Hybrid concrete systems, geopolymer concrete (GPC) and self-compacting concrete (SCC), can help to increase structural efficiency and reduce material-related environmental costs in construction.

In this paper, the structural behavior of deep beams constructed using SCC and GPC in hybrid configurations is investigated. GPC is placed at the top, bottom, top-and-bottom, and shear-critical regions to determine the distribution of material, load-carrying capacity, load-deflection response, crack propagation, and failure mode. The interaction between the SCC-GPC interface and the main diagonal compression-strut mechanism was particularly studied, as it determines deep beam behavior.

1.1. Literature review

1.1.1. Hybrid concrete in deep beams.

Hybrid concrete systems are those that combine different concrete types in one structural element to optimize performance. For deep beams, such a strategy allows for high-performance materials to be put in the areas where critical stresses should be applied and is hence more efficient and durable at the same time. Hybrid concrete deep beams have been shown to have a high load-carrying capacity, toughness, and ductility. For example, Hassan and Faroun (2016) found that adding steel fibers ($\geq 2\%$) in critical regions significantly enhances shear resistance and reduces energy dissipation. Similarly, fiber-reinforced concrete and conventional concrete in less critical places have been proven to enhance material usage.

In addition, Smarzewski (2018) investigated hybrid fiber-reinforced high-performance concrete (HFRHPC) and found that hybrid fiber systems acting as web reinforcement substantially enhance crack control and shear performance, especially in regions with high stress concentrations. Shakir and Alghazali (2023) examined curved and arched hybrid deep beam models, which showed increases in load capacity of about 21% and 23% in comparison to non-hybrid beams. They also showed that in two-point loading systems, hybrid configurations increase failure load by up to 20% and toughness by close to 97%.

Hence, hybrid concrete is of great interest for performance optimization and cost-effective performance optimization, but more research is required to better understand material distribution schemes and reinforcement layout in practical applications.

1.2. Geo polymer concrete in deep beams.

GPC has emerged as a sustainable alternative to Portland cement concrete, utilizing industrial by-products such as fly ash and slag. This significantly reduces carbon emissions and environmental impact.

GPC can offer competitive mechanical and durability properties and has attracted the interest for structural applications such as beams and deep beams. Experiments on geopolymer structural members have demonstrated that their cracking and shear response is strongly influenced by mixture strength, reinforcement, fiber content, and the diagonal compression-strut mechanism. However, most investigations have considered members cast entirely with GPC rather than hybrid SCC-GPC sections.

At the structural-member level, Albidah (2023) experimentally tested six metakaolin-fly ash geopolymer deep beams using steel fibers and shear reinforcement and showed that steel fibers and shear reinforcement had a significant impact on shear strength, displacement capacity, and cracking behaviour. These findings highlight the feasibility of GPC in shear-critical deep beams and also point out the importance of the strut-and-tie load transfer mechanism.

Despite this progress, experimental evidence on hybrid deep beams with SCC and GPC is scarce. Most studies have focused on hybrid systems consisting of normal and high-strength cement-based concretes, or deep beams formed entirely from geopolymer concrete as explain in table 1. As a result, the influence of GPC layer position, layer thickness, and SCC-GPC interface location on a single deep beam is not documented.

Table 1: Summarization of researches

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Study	Structural system	Main variables	Experimental scope	Main finding	Gap relative to present study
Ali and Zghair (2015)	Hybrid NSC-HSC deep beams	HSC layer thickness, web reinforcement, casting method	Nine deep-beam models under two-point loading	Layer thickness, reinforcement, and casting method significantly affected shear behavior.	Cement-based hybrid system; no SCC-GPC combination.
Hassan and Faroun (2016)	Hybrid deep beams with fibrous concrete in critical regions	Fiber content and repeated loading	Experimental deep beams under monotonic/repeated loading	Strategic material placement influenced shear strength, cracking, and energy dissipation.	No geopolymer concrete and no layer-thickness comparison.
Smarzewski (2018)	Hybrid fiber-reinforced high-performance concrete deep beams	Hybrid fibers and openings	Experimental deep beams	Hybrid fiber systems improved crack control and shear performance.	Hybridization was based on fibers rather than two concrete matrices.

Husain et al. (2021)	SCC-NSC hybrid RC beams	SCC layer thickness and shear reinforcement	Eight two-layer beams under two-point loading	Increasing SCC layer thickness increased failure load relative to NSC controls.	Slender/ordinary beams; SCC-NSC rather than SCC-GPC deep beams.
Albidah (2023)	Geopolymer concrete deep beams	Steel-fiber content and shear reinforcement	Six GPC deep beams tested to failure	Fibers and shear reinforcement increased shear strength and displacement capacity.	Entire beam cast with GPC; no SCC-GPC interface or selective placement.
Shakir et al. (2023)	Precast hybrid concrete deep beams	Curved/arched hybrid configurations	Experimental hybrid deep beams	Hybrid geometry significantly affected load capacity and toughness.	Different material system and no geopolymer layer/interface study.
Present study	SCC-GPC hybrid deep beams	GPC position, layer thickness, shear-zone extent, interface location	Eighteen deep-beam cases under two-point loading	Demonstrates configuration-dependent interaction between GPC placement and diagonal compression-strut path.	Addresses selective SCC-GPC hybridization within both beam depth and shear-critical regions.

1.3. Research gap and objective of the study

Despite the growing interest in hybrid concrete and geopolymer structures, there has been little research on how they can interact in deep beams. Previous experimental studies have focused on the criticality of layer thickness, material location, shear zone strengthening, and casting process for conventional hybrid deep beams. In contrast, a good majority of geopolymer deep beam studies have focused on members cast with GPC. Thus, there is a clear gap regarding the use of SCC-GPC hybrid deep beams in which the geopolymer material is placed at the depth or in the shear-critical zones of the beam. This is the scope of this paper, which will investigate the influence of GPC position, thickness, and interface location on load-carrying capacity, load-deflection response, cracking, and failure mode of such deep beams, and is based on the main diagonal compression-strut mechanism.

1.4. Nomenclature and specimen designations

Table 2: Nomenclature and specimen designations

Symbol / designation	Definition
SCC	Self-compacting concrete
GPC	Geopolymer concrete
G1	Hybrid group with 70 mm GPC layers
G2	Hybrid group with 140 mm GPC layers
G3	Hybrid group with GPC placed in shear-zone regions
GPTC	GPC placed in the top region
GPBC	GPC placed in the bottom region
GPBTC	GPC placed in both top and bottom regions
Pu	Ultimate load
Δ	Midspan deflection
f'c	Concrete compressive strength

2. METHODOLOGY

2.1. Materials

There were two types of concrete used in this study: SCC and GPC. Ordinary Portland cement that meets Iraqi Specification No. 5/1984 was used in SCC. The cement had a fineness of 299 m²/kg with initial and final setting times of 1:10 h and 3.55 h, and compressive strengths of 16.9 MPa (3 days) and 26.33 MPa (7 days). Natural sand and crushed gravel that comply with IQ.S No. 45/1984 were used as fine and coarse aggregates, respectively. The sand was graded well with 3.61% fines, and the gravel met strength and cleanliness requirements.

Silica fume ($SiO_2 \geq 85\%$) with a specific gravity of 2.2-2.4 was used as a mineral admixture to enhance strength and durability. A polycarboxylate-based superplasticizer (HMP800X) with a density of 1.07-1.09 was used to achieve the required flowability of SCC.

For GPC, fly ash and ground granulated blast furnace slag (GGBFS) were used as binders. Fly ash had a specific gravity of 2.1-2.6 and high silica and alumina content, while slag had a fineness of 400-600 m²/kg and contributed to improved strength and durability. The alkaline activator consisted of sodium hydroxide (NaOH) solution with a molarity of 14M and sodium silicate (Na_2SiO_3) solution. A geopolymer-compatible superplasticizer (Sika ViscoCrete-180 GS) was used to improve workability.

2.2. Mix proportion

Trial mixtures were used to create suitable proportions for SCC and 14 M GPC to achieve the fresh and target compressive strengths. The selected mixtures had compressive strengths of 45 MPa in SCC and 34 MPa in GPC. The proportions of the mixtures are shown in Table 3.

Table 3. the mix proportion for SCC and GPC mixes.

Materials	SCC Kg/m3	GPC Kg/m3
Cement	432	/
Fly Ash	/	360
GGBFS	/	90

Materials	SCC Kg/m3	GPC Kg/m3
Fine aggregate	630	500
Course aggregate	740	1200
Limestone	38.88	/
Silica fume	24	/
Activator Ratio Na_2SiO_3/NaOH	/	1.5
SP %	1.6%	1.3%
Liquids / binder	0.32	0.45

2.3. Specimens description

In total, eighteen deep beam specimens were developed based on the strut-and-tie concept in ACI 318M-19. The experimental setup was based on an SCC control configuration and three groups (G1, G2, and G3). The specimen names used throughout the study are summarized in Table 3. Group G1: Hybrid beams with a 70 mm GPC layer at the top (GPTC-70), bottom (GPBC-70), as well as both top and bottom (GPBTC-70) regions, and SCC is used in the middle region of the beam. Group G2: Hybrid beams with the same placement configurations as G1, but with 140 mm GPC layers (GPTC-140, GPBC-140 and GPBTC-140). Group G3: Hybrid beams with GPC in a 200 mm or 300 mm shear zone measured from the supports. The configurations chosen are designed to examine how GPC placement and interface location affect the main compression strut and shear-critical regions. Fig1 summarizes the beam configurations investigated.

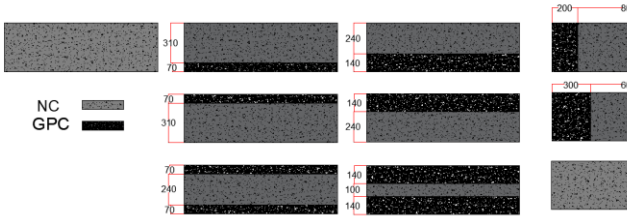


Figure 1. All beams that tested in this research.

2.4. Reinforcement, casting, curing and testing

Two reinforcement layouts were used. The SCC control beam and Groups G1 and G2 had the same flexural reinforcement configuration; however, Group G3 had the shear-reinforcement layout shown in Fig. 2. All steel cages and molds were prepared before concrete was placed. For the layered G1 and G2 samples, the first concrete region was placed at the boundary and held stable in order to maintain the geometry of the adjacent concrete and avoid unwanted intermixing at the interface. The second concrete was then placed and the continuity in the interface could still take place; no artificial separation was left in the last section. For the G3 specimens, the GPC shear-zone regions were first established using temporary zone boundaries and SCC was placed in the remaining central region, and the temporary boundaries were removed during casting so that the two concretes remained directly in contact while casting. The casting was done in a way that ensured not too much mixing between SCC and GPC. After casting, cubes and cylinders were water-cured, and the beams were covered with wet burlap and plastic sheets. All beam specimens were tested after 28 days under two-point loading.

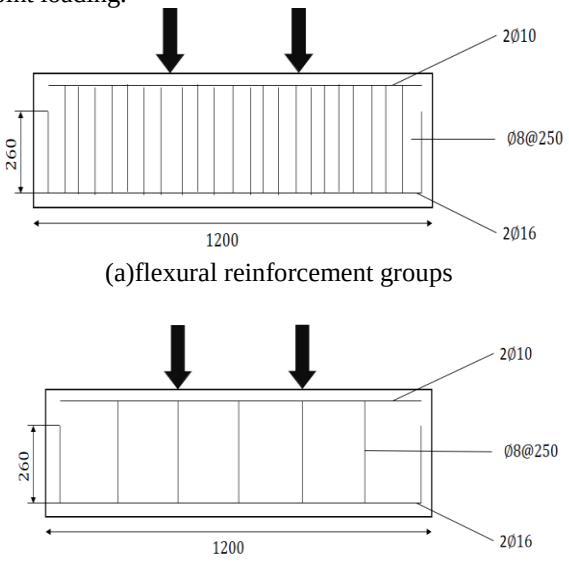


Figure 2. Reinforcement details for SCC beams.

3. Results and discussions

3.1. Group 1-70mm GPC (G1)

3.1.1 load-deflection

The load–deflection response of 70 mm hybrid beams (G1) relative to the SCC control beam is presented in Fig. 3. The control beam exhibited the best overall response, recording an ultimate load of nearly ~480 kN, exhibiting a deflection of about 19 mm. Among the hybrid beams, GPBC-70 mm exhibited the best response to the control as well, with about 480 kN, since placing GPC at the bottom zone had only a limited effect on the dominant load transfer because the region of tension may not be as critical as the zone of compression strut for the deep beam. The GPTC-70 mm beam experienced about 420 kN expansion because the 70 mm GPC layer did not fully cover the boundary compression strut region (about 80 mm), so most of the strut within the SCC zone was retained, and the strength decreasing factor was moderate. In contrast, the GPTB-70 mm beam exhibited the minimum capacity, about 260 kN, as the presence of two interfaces generated material discontinuity and weakened the internal stress field. We can conclude from these results that the beam behavior depends mainly on location and number of interfaces with respect to the principal compression strut, especially for the hybrid depth of 70 mm.

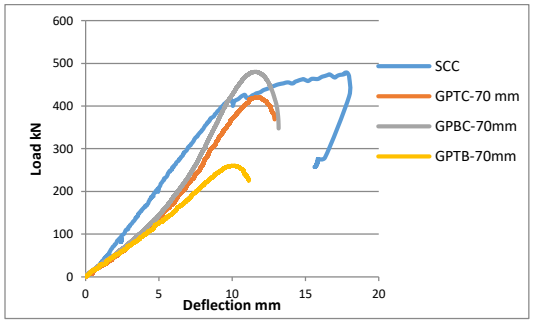


Figure 3. Load-deflection curves for G1

3.2. Cracks patterning and failure modes

The fact that the majority of G1 specimens collapsed chiefly due to diagonal shear-flexural cracking, similar to the above-mentioned SCC control beam, was found to be the same, while the majority of GPTBC-70 mm specimens failed primarily due to diagonal shear as shown in fig 4.

The control beam developed several inclined cracks extending from the supports toward the loading points, followed by widening of the dominant diagonal crack at ultimate load. Crack development of hybrid beams also depended on the GPC layer position. The GPBC-70 mm beam exhibited a crack pattern comparable to the control beam except for a minor interface effect, which explains its high load capacity, leading to a stable response.

In the GPTC-70 mm beam, cracks were more localized at the upper interface and central web region, showing that a higher GPC layer influenced the diagonal stress path. As per the findings, the GPTBC-70 mm beam displayed a highly disturbed crack signature due to the discontinuity of two interfaces across the beam height, which later caused earlier cracking in an extreme manner. Ultimately, the results show that 70 mm GPC at the bottom is the best configuration overall, yet adding GPC at the top and bottom resulted in a weak response because it interrupts the interface from the main load path.

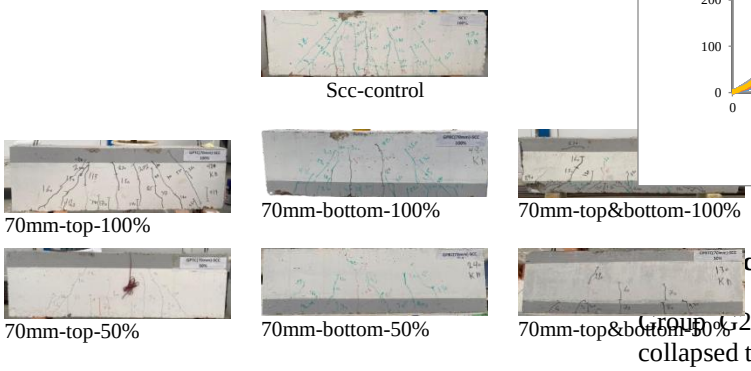


Figure 4. Cracks pattering for group1(70mm-GPC)

3.2 Group 2-140mm GPC (G2)

3.2.1. Load-deflection

Fig 5 shows the load deflection of the 140 mm hybrid beams (G2) and the SCC control beam. Among the hybrid beams, the top-and-bottom configuration (GPBTC-140) has the highest ultimate load, followed by the bottom configuration (GPBC-140), and the top configuration (GPTC-140) has the lowest capacity.

The lower response of GPTC-140 can be explained by the fact that the GPC layer is located in the upper part of the beam. At a thickness of 140 mm, the GPC penetrated a large part of the boundary compression zone and crossed the diagonal compression strut path. Therefore, much of the internal load transfer mechanism developed through GPC is weaker than that developed by SCC in terms of compressive strength. This reduced the efficiency of the compression strut mechanism and the ultimate capacity.

GPBC-140 exhibited a better response because the GPC was located mainly in the bottom of the beam and a large part of the critical upper compression zone was located in SCC. In this case, the lower compressive strength of GPC had less of an effect on the dominant load-transfer mechanism.

The GPBTC-140 specimen had the highest capacity among the 140 mm hybrid configurations. The GPC took up a greater part of the beam section, but it is clear that structural behavior is determined by the compressive strength of the concrete, as well as the position of the SCC-GPC junction with regard to the internal stress field. The larger GPC positions changed the interface locations, and the redistribution of stresses was better than in the thinner top-and-bottom configuration.

Thus, the response of the 140 mm hybrid beams was determined by the combined effects of material location, interface position, and the extent to which GPC intersected the principal compression-strut path.

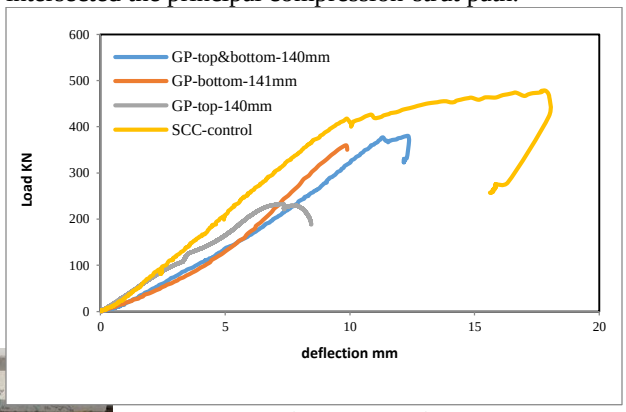


Figure 5. Load-deflection curves for G2.

cks patterning and failure mode

Group 2 crack patterns demonstrate that all beams collapsed to diagonal shear-compression predominantly, with fig 6 representing the failure pattern. At 50% loading, a fine flexural shear and diagonal crack formed in the web region that was relatively narrow.

At ultimate load, between the support area and loading zone, these cracks widened, indicating extension of the dominant diagonal compression strut. Cracks in the GPT-140 mm beam at the upper interface were highly concentrated, but local crushing occurred in the top hybrid region. These findings showed that geopolymer concrete was only put in the upper zone of the beam, which was able to meet the critical compression path at the interface, thus degrading earlier during the strut area development. In the GPBC-140 mm beam, the support area through the lower web region of the structures exhibits a relatively stable crack pattern, and so results were observed in the form of diagonal crack propagation. As the upper compression strut was mostly limited to the SCC region, the beam was found to perform significantly better than its top-only counterpart. In the GPBTC-140 mm beam, cracks seemed to be distributed more uniformly across the depth of the beam, and failure was later in the presence of larger cracks, which proved that a larger spreading of stress distribution had been achieved before by a higher stress redistribution, then leading to a collapse. The images illustrated that crack intensity and local damage were also heavily affected by the interface orientation. As the interface traveled along the main load transmission path, the cracking had become more localized, and the deterioration of the concrete intensified. The lying distance from the critical strut region caused a more stable response of the beam and increased the overall capacity. Consequently, the findings of Group G2 demonstrated that the performance of 140 mm hybrid deep beams was influenced by the geopolymer thickness as well as that of the section. Top-and-bottom had the best response performance among hybrid specimens, and top-only had the least effective configuration. This implies that the hybridization effect is determined not only by the material properties but also by the hybrid orientation and the natural diagonal path of the deep beam.

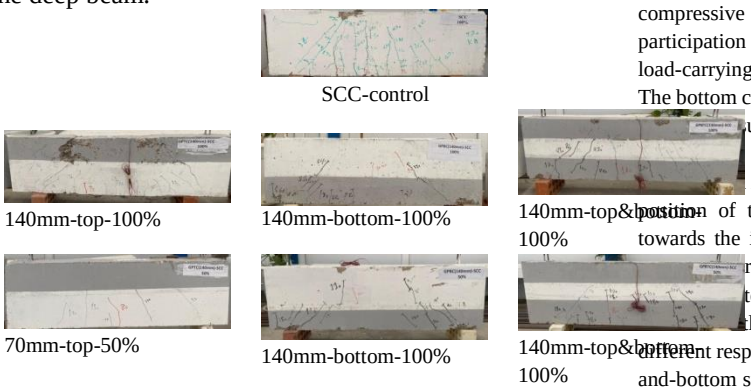


Figure 6 Cracks pattering for group2(140mm-GPC)

In fig 7, the overall load of hybrid beams is observed against 70 mm and 140 mm GPC layers at different positions. The impact of increasing the GPC thickness was not balanced and was related to the placement of the GPC in the beam. top (GPT) and bottom (GPB) combinations where the load capacity was lowered by increasing the GPC thickness from 70 mm to 140 mm by 14% and 21% respectivelly, which suggests that a greater proportion of the key compression strut was through the GPC, with lower compressive strength to SCC.

In contrast, the top-and-bottom (GPTB) configuration had a significantly higher capacity at increased thickness to 140 mm, which indicated that the external GPC layers were thicker to obtain increase in stress by 46% regarding the 70mm thickness, and also to reduce the negative influence of interfaces found the 70 mm specimen. Generally, the figure verifies that the effect of GPC thickness is influenced by the compatibility of the place of GPC with the path of the natural load-transfer through the deep beam.

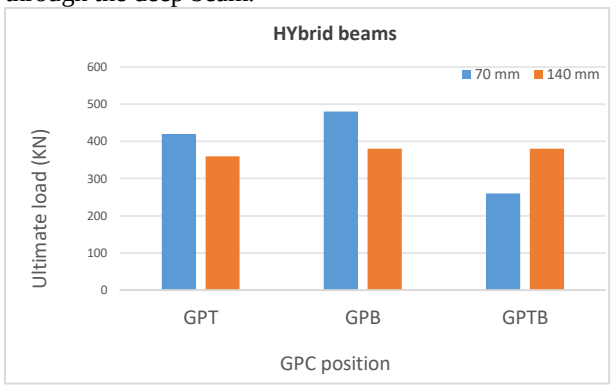


Figure 7 Effect of GPC position and thickness of the layer.

Figure 7 compares the ultimate load capacities of the hybrid beams with 70 and 140 mm GPC layers at different locations. The effect of increasing GPC thickness is not a single factor but strongly depends on the position of the GPC in the beam section.

For the top configuration, increasing the GPC thickness from 70 to 140 mm lowered the final load capacity by about 14%. This reduction can be attributed to the extension of the thicker GPC layer into a larger part of the main diagonal compression-strut region. Since GPC's compressive strength was lower than that of SCC, the increase in its participation in the critical compression path adversely affected the load-carrying capacity.

The bottom configuration was similar in this way, and raising the GPC ulted in a decrease of approximately 21% in ultimate load. region of the GPC is less important than the upper zone, but increasing the thickness of the GPC changes the tion of the SCC–GPC interface and extends the GPC region towards the internal diagonal stress field, thus increasing the stress reducing the overall capacity.

top-and-bottom had a 46% increase in ultimate capacity thickness was increased from 70 to 140 mm. This very different response implies that the poor performance of the 70 mm top-and-bottom specimen wasn't just because GPC was less strong. In the 70 mm sample, the two thin GPC layers formed a discontinuity in the internal stress-transfer field. As the GPC layer thickness was increased, the continuous GPC regions and interfaces moved away from the critical load-transfer path, which led to better stress redistribution and less discontinuity in the interface.

Therefore, the experimental results show that increasing the GPC thickness does not necessarily improve or decrease the capacity of the hybrid deep beams. Rather, it depends on the GPC thickness, material

position, SCC–GPC interface location, and the natural diagonal compression-strut mechanism. This is why increasing the GPC thickness has reduced the capacity of the top and bottom configurations, but it has significantly improved the performance of the top-and-bottom configurations.

3.3. Shear group (G3)

3.3.1. Load –deflection behavior

Fig 8 shows the load-deflection curves of the SCC control and Group G3 hybrid beams. The control beam had the strongest initial stiffness and reached an ultimate load of about 400 kN at a deflection of about 10 mm. The 200 mm GPC shear-zone region, on the other hand, reached about 330 kN and remained close to the control response. The 300 mm section was less stiff, but a larger deflection of about 16 mm was achieved before failure. Thus, increasing the GPC extent in the shear zone improved the deformability but not necessarily the stiffness or final strength. This difference is largely due to the positioning of the SCC-GPC interface in contrast to the critical shear-transfer region. If the interface crosses under a very stressed shear region, the difference in mechanical properties between SCC and GPC reduces the continuity of stress transfer and load capacity. When the interface was shifted away from the most critical region, much of the diagonal compression path was still within a continuous material zone, resulting in a stable response.

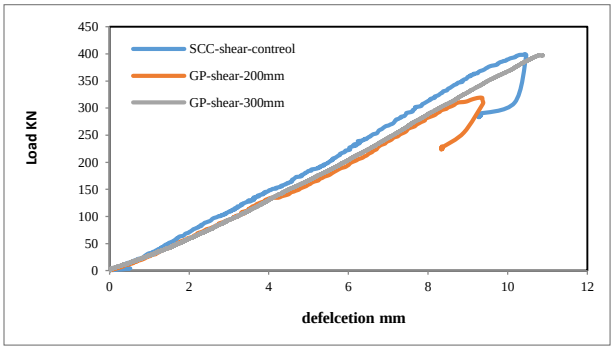
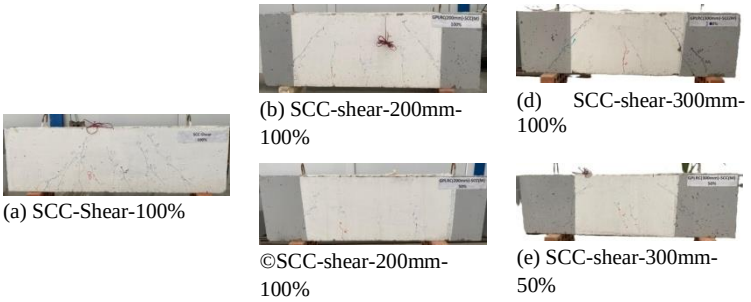


Figure 8. Load-deflection curves for shear group (G3)

3.3.2. Cracks pattering and failure mode

The crack patterns in Fig. 9 suggest that the G3 specimens mainly failed by diagonal shear compression. At about 50% of the final load, fine diagonal cracks were formed in the highly stressed shear spans. With increasing load, these cracks extended into the zone between the loading and support and widened out very far towards failure, which confirmed that the response was driven by the diagonal load transfer. In the 200 mm hybrid beam, the diagonal cracks were especially concentrated on the shear span and were heavily affected by the SCC-GPC interface. In the 300 mm beam, the interface was located further away from the most critical region, providing a broader continuous GPC zone, a more dispersed crack pattern, and more pre-failure deformation. These data demonstrate that the side-hybrid deep beam behavior is determined not only by the composition of the concrete, but by the location of the interface with respect to the compression strut and shear path. The SCC control beam exhibited the expected diagonal shear failure, with major inclined cracks spreading from supports towards the loading points.



(a) SCC-Shear-100%

(b) SCC-shear-200mm-100%

(d) SCC-shear-300mm-100%

©SCC-shear-200mm-100%

(e) SCC-shear-300mm-50%

Figure 9 Cracks pattern for shear group (G3)

4. Conclusions

Based on the experimental results, we can draw the following conclusions:

1. The behavior of SCC-GPC hybrid deep beams was governed by the GPC position, thickness, and extent, and by the location of the SCC-GPC interface with respect to the main compression-strut path.
2. The SCC control beam has the highest load capacity and the most stable load deflection response because the homogeneous material configuration allows the internal stress to be transferred continuously.
3. Within Group G1 (70 mm), the bottom GPC configuration had the best performance among the hybrid beams, and the top and bottom configurations were the lowest because the two interfaces caused more disturbance in the internal stress field.
4. In Group G2 (140 mm), the top-and-bottom configurations had the highest capacity among the hybrid specimens. In comparison, the top-only configuration had the lowest capacity since the thicker GPC layer occupied more of the main compression strut region.
5. Increasing the GPC thickness from 70 to 140 mm has a configuration-dependent effect: the final capacity declined by about 14% and 21% for the top-only and bottom-only configurations, respectively, but increased by about 46% for the top-and-bottom configuration. This confirms that thickness cannot be tied to the interface location or to load-path compatibility.
6. In Group G3, increasing the GPC shear-zone extent from 200 to 300 mm improved deformability but did not

improve stiffness or ultimate strength. The 200 mm configuration performed better in loading, and the 300 mm configuration was able to withstand more deformation before failure.

7. Failure was mainly due to diagonal shear-compression and diagonal shear-flexural cracking, showing that the propagation of the crack was strongly dependent on the position of the SCC-GPC interface relative to the diagonal load-transfer path.

8. The SCC-GPC interface had the most adverse effect when it met a critical shear region or the main compression strut. Interfaces located further away from such regions had a more stable structural response.

9. The experimental results show that SCC-GPC hybrid deep beams can be achieved if the geopolymer regions and interfaces are situated in such a way that the principal internal load transfer path is not disrupted.

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