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An Experimental Study on Web Hardening Technology Using Encasement by RPC and Lacing Reinforcement

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Abstract

Over the past ten years, cold-formed steel two-channel sections featuring edge-stiffened castellated cellular web apertures have been developed and are now widely used in New Zealand. Previous research on vertical compression has shown that using edge-stiffened web openings in these channel sections increases their vertical load capacity. Subsequent studies expanded to include hexagram web holes; however, the literature still lacks investigations on the effect of applied vertical pressure on web openings in two-channel sections with perforated webs. This research addresses that gap. The aim of this study is to evaluate the structural response of symmetrical castellated two-channel (2C) sections. Six specimens of castellated 2C beams made of cold-formed steel and encased in reactive powder concrete with diagonal reinforcement on both sides were examined. The concrete encasement and reinforcement enhanced the beam's resistance to buckling, bending, and both horizontal and vertical shear, and also improved joint performance. Two concentrated loads were applied at the beam center to investigate the structural behavior of each specimen. The results showed that the presence of a joint gap enhanced load resistance. The ultimate load increased by 6.75% compared with the reference specimen SCB2C-rLG20% in G3, by 30.86% compared with SCB2C-rL in G2, and by 1064.73% compared with SCB2C/R1 in G1. The specimen with a 30% gap demonstrated the best load capacity and the highest ductility compared with the reference specimen and the other specimens.

Keywords: Cold-Formed Steel; Steel Plates; 2C-Channale Castellated Steel Beams; Reactive Powder Concrete.

1. Introduction

Beams are integral components of structures for load transfer. They can be made in various forms and from different materials. Castellated steel beams are one type widely used in the construction industry. This type of beam is named for the web pattern that resembles the openings historically designed in castle walls. In the past, castellated steel beams were not practical because of the high costs associated with manual fabrication and the lack of automated manufacturing processes. Over time, however, researchers and construction professionals recognized the many advantages of automation in speeding up production. As a result, castellated beams in various configurations are now widely used around the world.

This study investigates a strengthening technique using encasement with reactive powder concrete (RPC) and lacing reinforcement. Researchers and experts in the field have concluded that castellated steel beams offer many benefits, such as reducing building height by allowing services to pass through the web openings, lowering material costs through weight reduction, improving structural aesthetics, and increasing beam flexural stiffness. A great deal of work has focused on the structural behavior of these beams in their different configurations. Previous studies by Gulam &

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Alshimmeri found that wider flanges in two-channel castellated beams increased stiffness and strength, with ultimate loads reaching 99.3–117.2% of those of solid beams [1].

Al-Tameemi & Alshimmeri reported that using 10% and 20% gaps in RPC-encased asymmetric beams increased load capacity by 3.39% and 11.25%, respectively, while the absence of a gap reduced capacity by 19.87% [2]. Al Shamaa et al. showed that web reinforcement using high-strength concrete and laced bars significantly improves the performance of cellular beams, doubling flexural and axial capacity and increasing web strength by 165% [3]. Chandramohan et al. studied the axial capacity of cold-formed steel (CFS) channels with elongated edge-stiffened (EEH) and unstiffened (EUH) holes. Their finite element models were validated, followed by a 990-case parametric study. The results were compared with AISI 2016 and AS/NZS 2018 specifications, and new effective width method (EWM) and direct strength method (DSM) equations were proposed and verified for reliability [4].

Chandramohan et al. examined cold-formed steel (CFS) channel beams with web holes. Beams with edge-stiffened holes showed a 14.5% increase in bending capacity, while un-stiffened holes caused a 13.6% reduction. AISI and AS/NZS standards predict capacity well for beams without holes, but the Moen and Schafer equations are overly conservative for beams with holes [5]. Seven asymmetrical castellated steel beams with concave soffits were tested under two mid-span loads. The beams were either unconfined, encased in RPC, or encased in RPC with 45° laced reinforcement; some had web openings that increased the post depth by 10–30%. Encasement improved buckling, shear, flexure, Vierendeel bending, and lateral–torsional strength. Larger web gaps increased load capacity, and the beam with a 122 mm gap performed best [6]. A VPS-based program was proposed to minimize the cost of composite deck slabs and castellated beams by considering material, fabrication, and serviceability. Major and minor cost-saving strategies were applied, and LRFD design ensured strength. Three examples confirmed its effectiveness [7]. Another study analyzed the effect of castellation and strengthening on steel beam performance using ABAQUS. One solid and three castellated beams were tested under two-point loads. Castellated beams showed higher load capacity (a 39.11–124.77% increase) and lower deflection (up to a 36.36% reduction) compared with the solid beam. The beam strengthened with high-strength concrete and lacing bars achieved the best performance, with a 124.79% higher ultimate moment and 165.65% higher ductility. Castellation and strengthening significantly enhanced stiffness and overall structural behavior [8].

In 2014, Ismail et al. conducted research by applying vertical stresses to continuous composite castellated beams and studying how these loads affected specimen behavior under bending and at ultimate conditions. A nonlinear model was developed using the three-dimensional finite element method in ABAQUS [9]. Naji and Al-Shamaa tested seven beams, six of which were castellated, and found that fewer openings and a 52° cutting angle maximized load capacity and stiffness. Castellated beams improved load capacity by up to 68.9% compared with regular beams, making them efficient for long spans [10]. These findings allowed researchers to track how such variations influenced the behavior of 96 hybrid castellated beams. The authors also provided recommendations on both modeling methods and beam design [11]. Another study numerically assessed RHS cold-formed stainless-steel beams with a mid-span web hole at temperatures from 22 to 900 °C. Finite element analysis of 400 austenitic and lean duplex beams under bending showed that current design rules are generally conservative but not always safe, except for Eurocode 3, which proved reliable [12]. Cold-formed steel I-section castellated beams with various cellular openings were also studied using ABAQUS and design codes (AISI S-700 and AS/NZS 4600). Beams with openings equal to 0.4 times the depth showed better strength, but failure was mainly local [13].

One study investigated the use of crushed concrete as aggregate in reactive powder concrete. Using 25% crushed concrete improved compressive strength by about 17% and flexural strength by about 11%, while 100% replacement significantly reduced strength. Micro-steel fibers and fine sand were also used [14]. Another study presented a new method for calculating the elastic critical moment of steel–concrete castellated composite beams under hogging moments. Finite element simulations in ANSYS showed the method to be accurate, with an average deviation of less than 3.5%, while accounting for slab stiffness and neutral axis shifts [15]. Additional research developed simple equations to optimize the cross-section and longitudinal profile of fully composite steel beams for both shored and unshored supports using GRG and ASD methods, with an example based on residential loads [16]. A numerical study analyzed the lateral–torsional buckling of cellular beams using ANSYS and proposed a new torsional constant. Among four calculation methods, the weighted average based on the proposed constant gave the best agreement with analytical results. Beam height was found to have the greatest effect on the elastic critical moment [17]. Another study incrementally applied cyclic loads to specimens to compare normal and reduced beam sections and further investigated the placement of beam segments on the supporting surface [18].

The tests ultimately revealed that, during the failure phase, the highest horizontal load that could be applied at each drift ratio was 12.0 kN. The system met the earthquake specification requirements for a 3.2% drift ratio [19]. One study used 432 finite element (FE) models to examine distortional buckling of slotted cold-formed steel (CFS) channels under bending. Current DSM standards were evaluated, and modified design formulas were proposed [20]. Another study investigated the impact of nonlinear high-temperature steel behavior on the global buckling capacities of cold-formed steel columns. Using 1,320 finite element analyses, it examined pinned and fixed columns under flexural, torsional, and flexural–torsional buckling. Current standards (AS/NZS 4600, AS 4100, and EC3) were assessed, and new design rules for elevated-temperature conditions were proposed [21]. Laminated beams were also tested as composite reinforced concrete (RC) beams subjected to low-speed impact. A 42.5 kg mass was repeatedly dropped from different heights to study the impact response. For all specimens with higher bending energy, the strain energy showed lower values. The inertial force, measured strain strength, and estimated strain strength were all very close for all beams [22].

Another study examined how castellation, with or without strengthening, affects the structural behavior of steel beams compared with a solid reference beam. Numerical analysis using ABAQUS was conducted on four beams: one solid beam and three castellated beams with different shapes. Compared with the solid beam, the castellated beams carried up to 124.77% more load and showed reduced mid-span deflection (up to 36.36%). The castellated beam strengthened with high-strength concrete and lacing reinforcement performed best, achieving the highest ultimate moment (a 124.79% increase) and ductility (a 165.65% increase) [8, 23]. Another study compared castellated beams with conventional I-beams for a 12 m span under floor loads. Using AISC design and cradle-to-gate embodied carbon analysis, the castellated beam (CB18×14) satisfied strength and deflection requirements, showed better deflection performance, and reduced embodied carbon by 27%. Thus, castellated beams offer improved structural efficiency and sustainability [24].

A further study investigated cold-formed steel channel beams with hexagonal web openings, comparing unstiffened and edge-stiffened configurations. Finite element analysis showed that edge stiffening increased moment capacity by about 10%, while current DSM provisions underestimated this capacity by up to 47%. More accurate and reliable design equations were proposed [25]. Another study examined CFS lipped channel columns with web holes under axial compression. Circular holes showed better strength than rectangular ones, and buckling occurred near the hole regions. Finite element analysis results agreed with experimental data (with less than 4% deviation). BS 5950 provided the most accurate design predictions [26]. One more study proposed an efficient and sustainable cold-formed steel cantilever beam with a high load capacity (185.4 kg/kN), outperforming RC beams and offering cost-effective and environmentally friendly construction solutions [27].

Previous analyses indicate that web openings improve access to essential services; however, only a limited number of studies have evaluated the flexural characteristics of such beams. This work therefore aims to experimentally investigate the flexural performance of beams using reactive crushed concrete and tie reinforcement, with particular emphasis on the effectiveness of 2 mm thick steel plates. The primary objective of this research is to examine the structural performance of cold-formed double-channel (2C) steel beams encased in reactive powder concrete with tie reinforcement. The influence of web openings on beam reinforcement and the effectiveness of using 2 mm thick steel plates are evaluated to identify methods for restoring beam strength. Figure 1 shows the flowchart of the research methodology through which the objectives of this study were achieved.

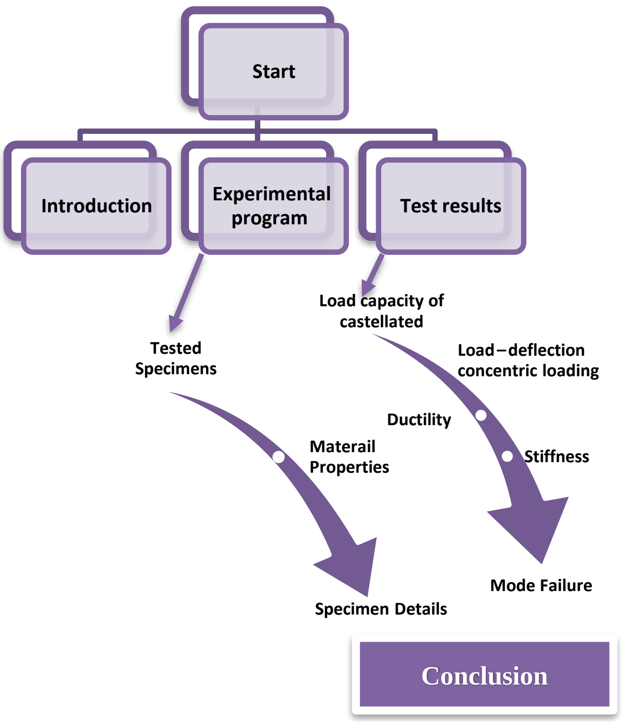

Figure 1. The flowchart explains the whole experimental design

2. Experimental Program

Beams of cold-formed 2C steel were used in this study. A 2 mm thick steel web was cut in a zigzag pattern along the centerline to create these castellated steel beams. As shown in Plate 1, a computer numerically controlled (CNC) plasma machine was used for cutting in order to produce regular and smooth hole patterns. After cutting, the two beam sections were separated and repositioned so that a 2C-shaped steel section was formed by joining the upper points of the web pattern using continuous 3 mm thick electric welding. As a result, the total height of the beam increased, and the new section's modulus of elasticity and flexural stiffness became higher than those of the original rolled 2C-shaped steel section.

2.1. Tested Specimens

The experimental program included six specimens manufactured from inverted steel beams. The main criterion adopted in this work was the stability of specimen dimensions and length. All six specimens were tested as simply supported beams with a clear span of 2830 mm under two-point loading. Two strengthening techniques were applied: strengthening by adding polymer-reinforced concrete (PRC), and strengthening using PRC combined with connecting reinforcing bars. The specimens were divided into three main types, as shown in Figures 2 to 11 and Table 1.

Figure 2. Cutting plates into geometric sections

Figure 3. Cutting by CNC machine

Figure 4. Lacing reinforcement by welding

Figure 5. Final shapes of castellated beams for the test

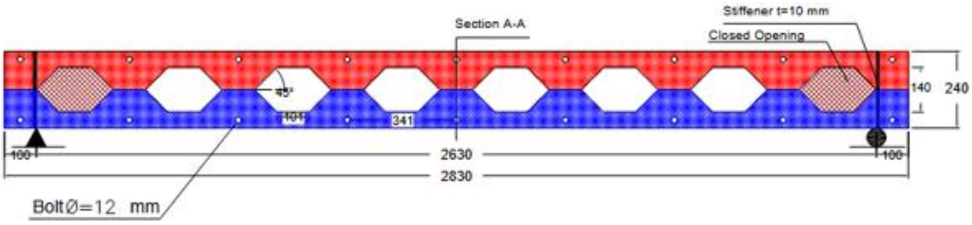

Figure 6. Details of (SCB2C) specimen

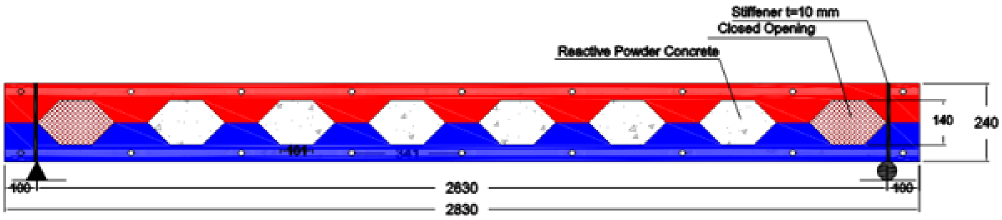

Figure 7. Details of (SCB2C-r) specimen

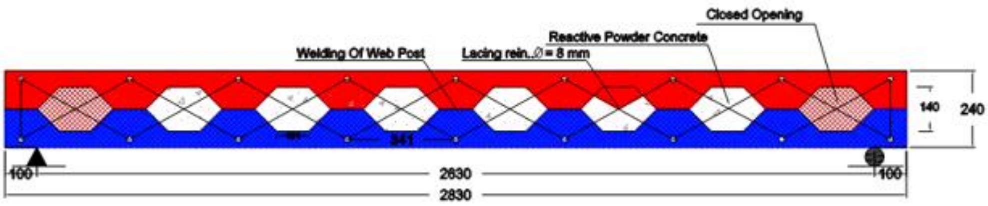

Figure 8. Details of (SCB2C-rL) specimen

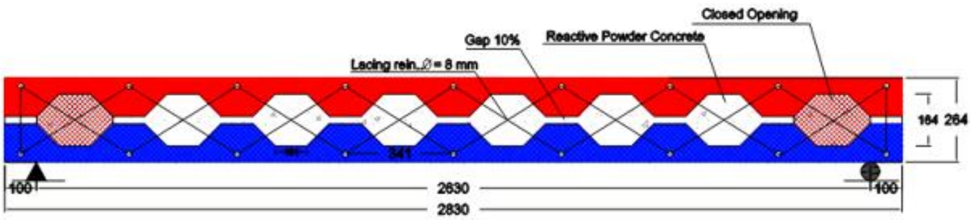

Figure 9. Details of (SCB2C-rLG10%) specimen

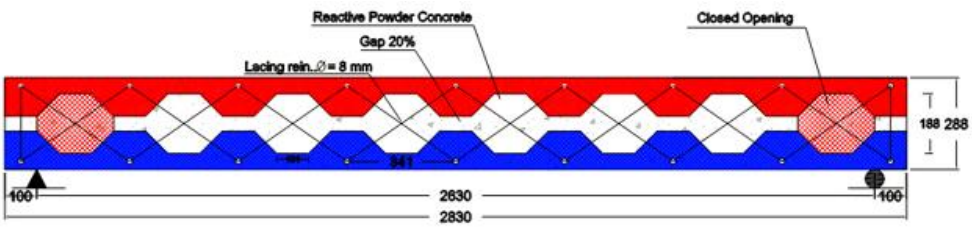

Figure 10. Details of (SCB2C-rLG20%) specimen

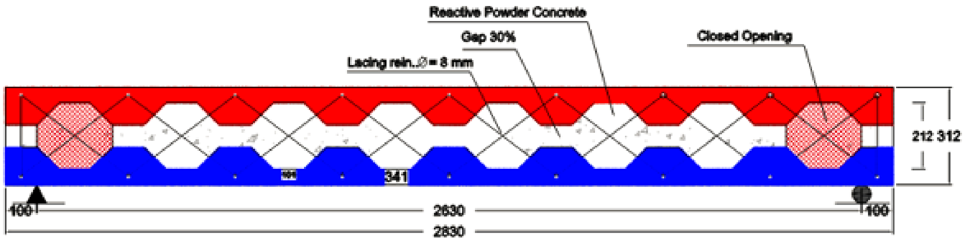

Figure 11. Details of (SCB2C-rLG30%) specimen

Table 1. Details of Specimen

Group	Specimen	Type of Material
G1	SCB2C/R1	Steel
	SCB2C-r	Steel &RPC
G2	SCB2C-rL	Steel & RPC & L. Rein.
	SCB2C-rLG10%	Steel & RPC & L. Rein.
G3	SCB2C-rLG20%	Steel & RPC & L. Rein.
	SCB2C-rLG30%	Steel & RPC & L. Rein.

Group One:

- **First model:** 2C cold-formed steel section castellated beam without web strengthening.
- **Second model:** 2C cold-formed steel section castellated beam with web strengthening using Reactive Powder Concrete (RPC) and without lacing reinforcement.

Group Two:

- **First model:** 2C cold-formed steel section castellated beam with web strengthening using Reactive Powder Concrete (RPC), lacing reinforcement, without welding of the web post joint, and with 0% gap.
- **Second model:** 2C cold-formed steel section castellated beam with web strengthening using Reactive Powder Concrete (RPC), lacing reinforcement of the web post joint, and with a 10% gap.

Group Three:

- **First model:** 2C cold-formed steel section castellated beam with web strengthening using Reactive Powder Concrete (RPC), lacing reinforcement of the web post joint, and with a 20% gap.
- **Second model:** 2C cold-formed steel section castellated beam with web strengthening using Reactive Powder Concrete (RPC), lacing reinforcement of the web post joint, and with a 30% gap.

2.2. Material Properties

2.2.1. Modified Reactive Powder Concrete

The study required producing high-strength concrete. It was mixed using a mechanical mixer. Column specimens were produced with an average cylindrical compressive strength of 62 MPa. The concrete mixture contained 1% micro-steel fibers. A dosage of 2 liters of superplasticizer per 100 kg of cementitious material was used. The mixtures shown in Table 2 contained 11% silica fume relative to the cement weight (80 kg/m^3), a cement content of 720 kg/m^3, and a water-to-cement ratio of 0.24. The specified design strength for MRPC was 68.9 MPa. Table 2 presents the MRPC mix design [27].

Table 2. Mix design of MRPC

Cement (kg/m^3)	W/Cm %	Sp Lit/100 kg	Sand (kg/m^3)	Silica Fume % by Weight of Cement	Fine aggregate (kg/m^3)
720	0.24	2	712.5	11	237.5

2.2.2. Steel Bars

Steel bar lacing with an 8 mm diameter was welded to the web face on both sides of the double steel channel web, with an inclination angle of 45° relative to the longitudinal axis, as shown in Table 3. The physical properties of the certified reinforcement samples were tested according to ASTM (A615/A615M-06a).

Table 3. Rebar's lacing

Type diameter (mm)	Yield strength (Fy) (MPa)	Ultimate Tensile strength (Fu) (MPa)	Elongation Tested Values (%)	Percentage (%)
Rebar Lacing: 8	420	623.5	20.3	≥10

2.2.3. Steel Stiffeners

Steel plates with a thickness of 2 mm were used as braces in only two specimens, (SCB2C) and (SCB2C-r). The braces were welded to the beam web at the supports on each side. The physical properties of the certified brace samples were tested in accordance with ASTM standard (A370-05) and are presented in Table 4.

Table 4. Steel stiffeners

Type Maximum deformation (mm)	Yield strength (Fy) (MPa)	Ultimate Tensile strength (Fu) (MPa)	Elongation Percentage (%)
Stiffeners: 18.729	281	322	31.215

2.2.4. Steel Sheets

The steel properties used in the experimental work are shown in Table 5. In addition, coupon samples were cut from each web and flange edge and tested according to ASTM E6 to determine the mechanical properties of the steel sections.

Table 5. Mechanical properties of steel

Thickness (mm)	Yield strength (Fy) (MPa)	Ultimate Tensile strength (Fu) (MPa)	Elongation Tested Values (%)	Percentage (%)
2	277	458	23	≥20

2.3. Specimen Details

All 2C-shaped cold-formed steel arched beams, strengthened with reactive powder concrete, were painted white to facilitate observation of crack formation during testing. Each beam specimen was tested after 28 days. The tests were conducted to evaluate failure under loading with fixed-end supports. The load was applied using a 2000 kN load cell placed between the loading head and the hydraulic jack. To measure the axial displacement of the beam specimens, a linear variable differential transformer (LVDT) with a gauge length of 803 mm was installed at the fixed end of the beams prior to testing. An automated data acquisition system was used to record the applied load and all resulting deformations. Figures 12 and 13 show the test setup and equipment, while Figure 14 shows the specimens after demolding and curing.

Figure 12. The LVDT

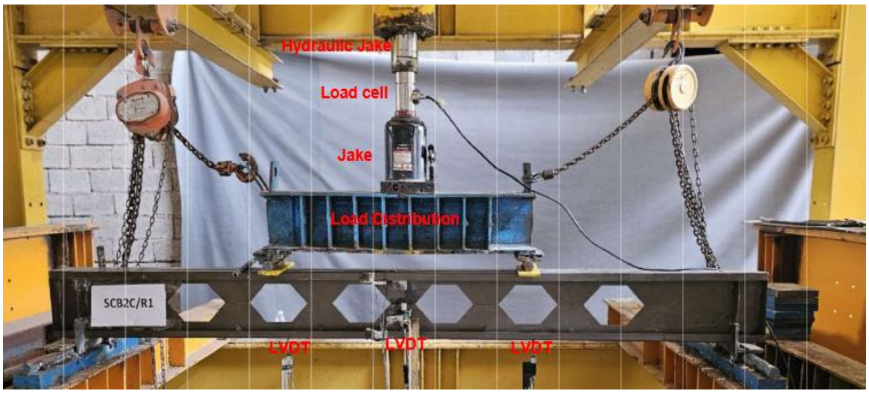

Figure 13. Castellated Beam test step

Figure 14. The samples after mold opening and curing

3. Test Results

3.1. Load Capacity of Castellated

Table 6 shows the difference in ultimate strength between the strengthened and unstrengthened castellated beams. The experimental load–deflection curve for sample SCB2C-rlG30% showed the highest maximum load, with an increase of 11.65%. The other samples (SCB2C-rlG20%, SCB2C-rlG10%, SCB2C-rl, and SCB2C-r) showed load increases of 10.91%, 9.93%, 8.9%, and 8%, respectively, compared to the reference sample (SCB2C/R1). This improvement is attributed to the presence of reactive powder concrete and tie reinforcement, which provide higher compressive strength in the beams.

Table 6. Excremental load capacity

Group	Specimen	Ultimate load (kN)
G1	SCB2C/R1	10.95
	SCB2C-r	87.61
G2	SCB2C-rL	97.47
	SCB2C-rLG10%	108.78
G3	SCB2C-rLG20%	119.48
	SCB2C-rLG30%	127.55

3.2. Load–Deflection Concentric Loading

The experimental results for the beam specimens are shown in Figures 15 to 17 for all tested samples. To ensure load concentricity and prevent movement or displacement at the loading point, the ends at each support were securely fixed, and the plates were positioned and welded before testing. The maximum load recorded for specimen SCB2C-rLG30% was 127.55 kN, achieving the highest ultimate load among all specimens. After reaching the maximum load, the load was maintained until sudden failure occurred in the compression region of the beam. Specimen SCB2C-rLG20% was the second specimen tested, reaching a maximum load of 119.48 kN. Specimen SCB2C-rLG10% was the third specimen tested, with a maximum load of 108.78 kN. Specimen SCB2C-rL was the fourth specimen tested, reaching 97.47 kN. Specimen SCB2C-r was the fifth specimen tested, with a maximum load of 87.61 kN. Specimen SCB2C/R1 was the last specimen tested and showed the lowest load capacity among all specimens, reaching 10.95 kN.

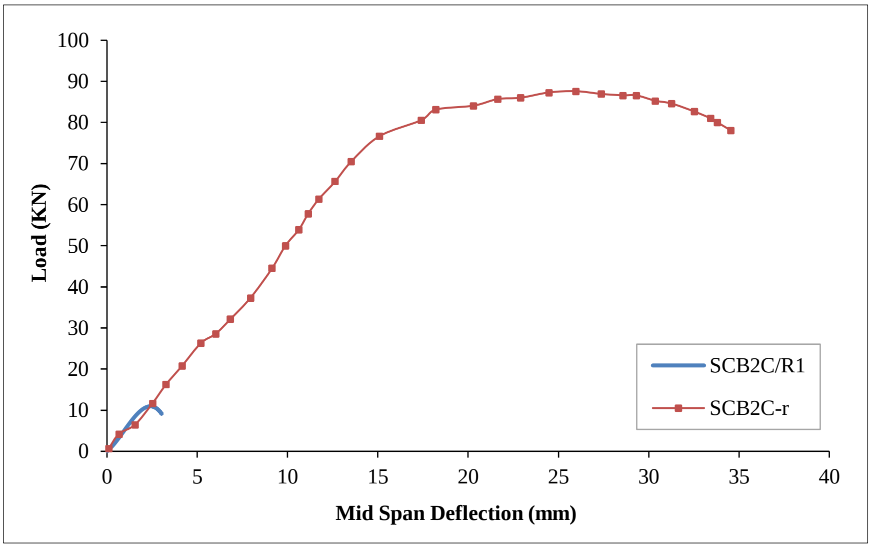

Figure 15. Load-deflection curve of SCB2C/ r1& SCB2C–r

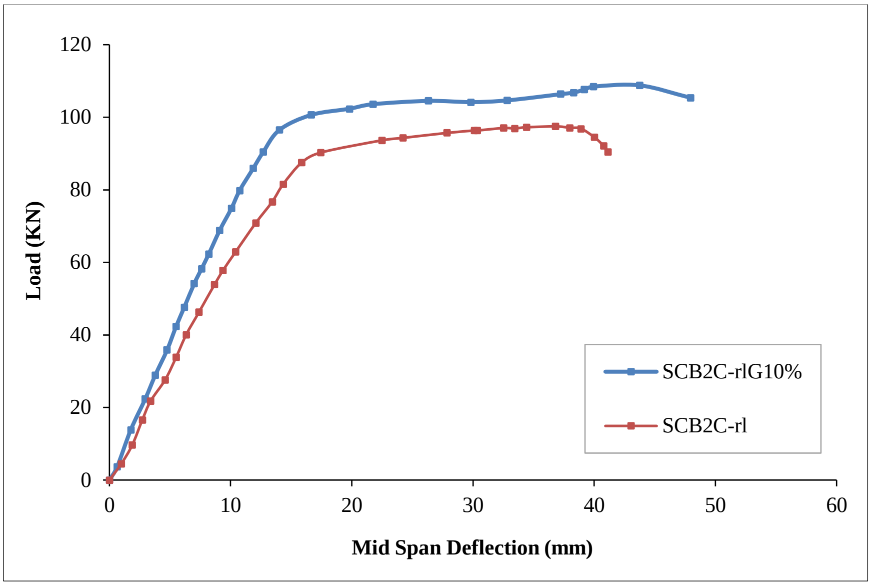

Figure 16. Load-deflection curve of SCB2C-rL & SCB2C - rLG10%

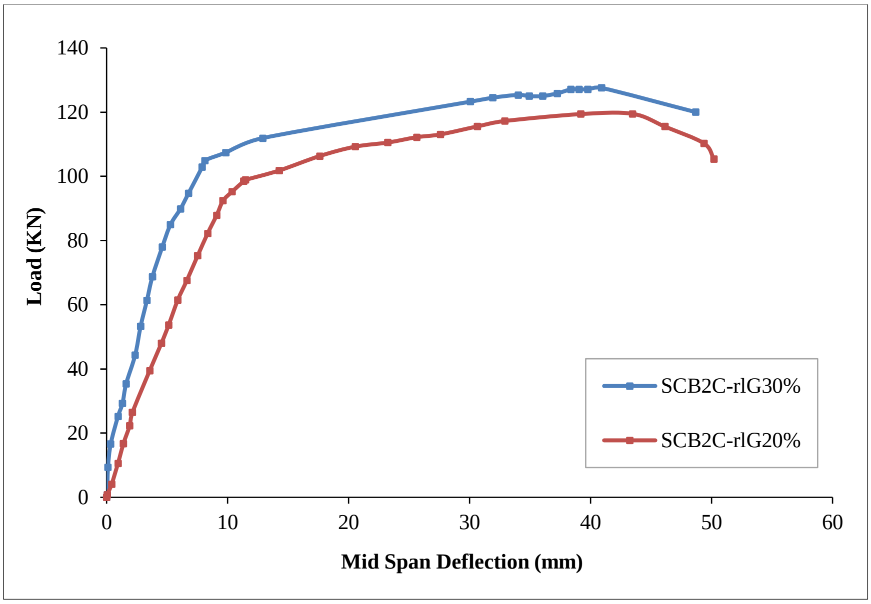

Figure 17. Load-deflection curve of SCB2C-r LG20% & SCB2C-r LG30%

3.3. Ductility

The ductility index was calculated as the ratio of the displacement at 84% of the post-peak load to the yield displacement. The castellated beam strengthened with reactive powder concrete and lacing reinforcement had the highest ductility, as shown in Table 7 and Figure 18.

Table 7. Ductility factor for specimens

Group	Specimen	Yield defl. Δy (mm)	Ult. defl. Δu (mm)	Ductility factor $\mu = \Delta u / \Delta y$
G1	SCB2C/R1	2.057	2.407	1.17
	SCB2C-r	17.395	25.964	1.492
G2	SCB2C-rL	15.852	36.817	2.322
	SCB2C-rLG10%	14.038	43.756	3.11
G3	SCB2C-rLG20%	10.370	43.456	4.190
	SCB2C-rLG30%	7.900	40.911	5.178

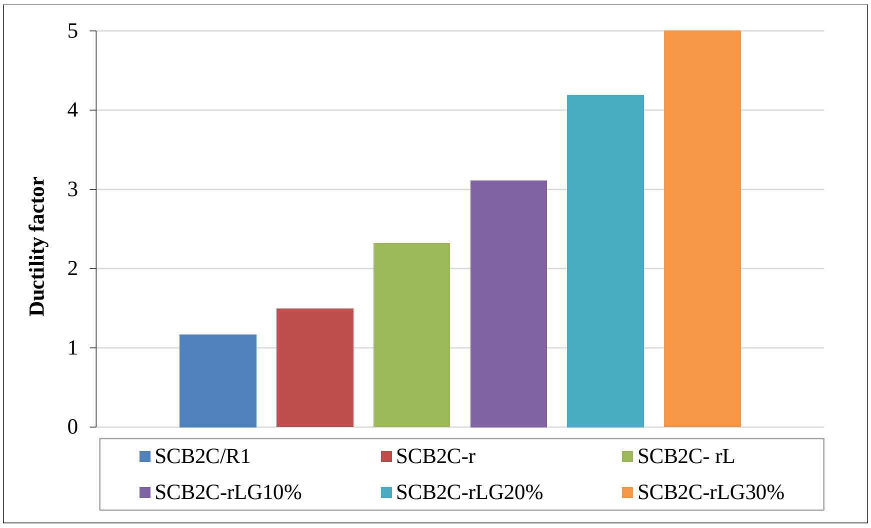

Figure 18. Ductility factor for specimens

3.4. Stiffness

Initial stiffness was derived from the slope of the linear portion of the load–displacement curve. Post-yield stiffness was computed from the second slope after the yield point. The 2C cold-formed castellated beam exhibited higher stiffness in both phases (Table 8 and Figure 19).

Table 8. Stiffness factor for specimens

Group	Specimen	Ult. load Pu (kN)	Ult. defl. Δu (mm)	Stiffness = Pu /Δu (kN/mm)
G1	SCB2C/R1	10.95	2.407	4.54
	SCB2C-r	87.61	25.964	3.37
G2	SCB2C-rL	97.47	36.817	2.64
	SCB2C-rLG10%	108.78	43.756	2.48
G3	SCB2C-rLG20%	119.48	43.456	2.75
	SCB2C-rLG30%	127.55	40.911	3.11

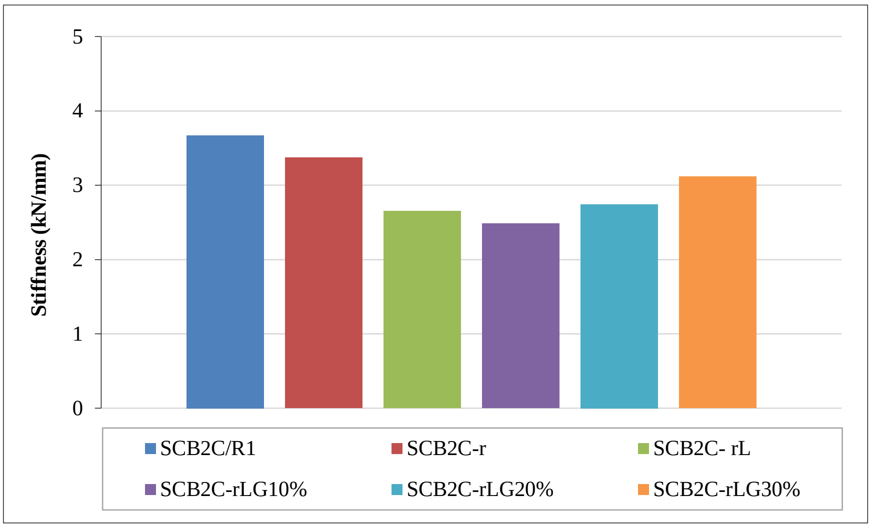

Figure 19. Stiffness values for all specimens

The results show a difference in stiffness between specimens G1, G2, and G3 compared with the reference specimen. The increase in deflection values is related to the strengthening techniques used in the welded web columns in these specimens, as the web sections were confined in reactive crushed concrete. Elastic deflection primarily depends on stiffness (E) rather than plasticity. Plastic deflection is the determining factor in ductility: a structure with high ductility may experience large deflections before failure, providing warning signals (fail-safe mode). On the other hand, a structure with low ductility collapses suddenly at small deflections (brittle and critical).

3.5. Mode Failure

The crack patterns of the cold-formed 2C concrete beams were illustrated before and after their confinement using reactive powder concrete. The first fissure was observed to form at the periphery of the loading zone at the beam's center. The cracks developed at approximately 20% of the final failure load. In beams constructed without reactive powder concrete, failure occurs at the welded joints in the web post, whereas in beams encased in reactive powder concrete, cracks manifest within the tension zone around one or more corners, as illustrated in the accompanying plate. As the stress intensifies following the emergence of the initial fracture, additional cracks begin to appear and extend diagonally toward the corners beneath the point of load application. Under increased loads, these fissures propagated, resulting in the formation of further cracks in various orientations. Concurrently, cracks begin to appear at the perimeter of the applied load in the tension zone, attributable to shear effects and extensive flexural cracking in the tension zone, resulting in yielding of the tensile reinforcement steel. The SCB2C-rLG30% specimen has a broader crack distribution owing to its superior load capacity relative to the other specimens, as shown in Figures 20 to 25.

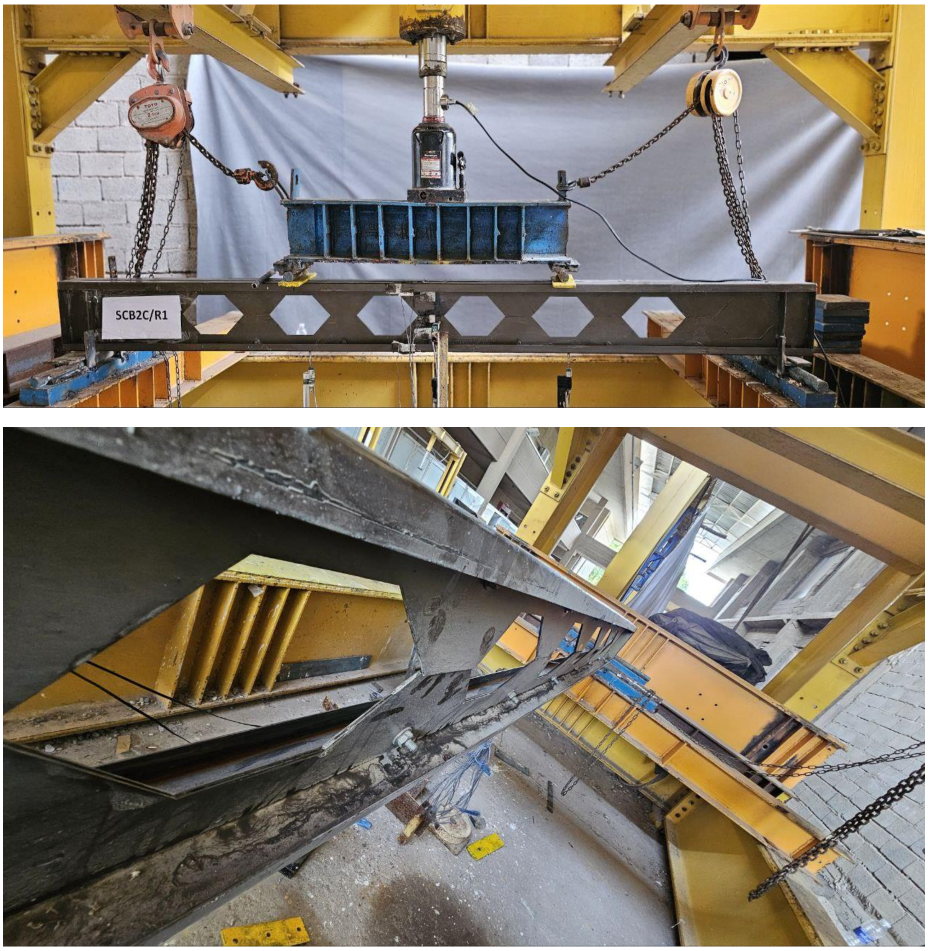

Figure 20. Tested specimen SCB2C/R1 and Failure mode

Figure 21. Tested specimen SCB2C-r and Failure Mode Flexure

Figure 22. Tested specimen SCB2C-rL and Failure Mode Flexure

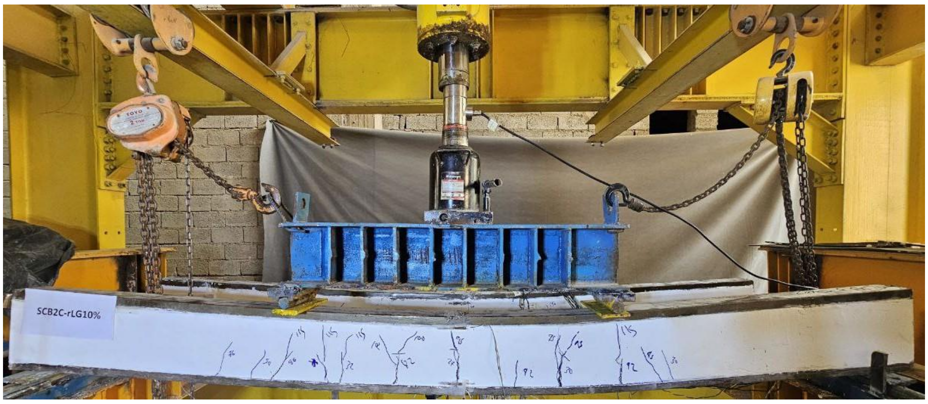

Figure 23. Tested specimen SCB2C-rLG10% and Failure Mode

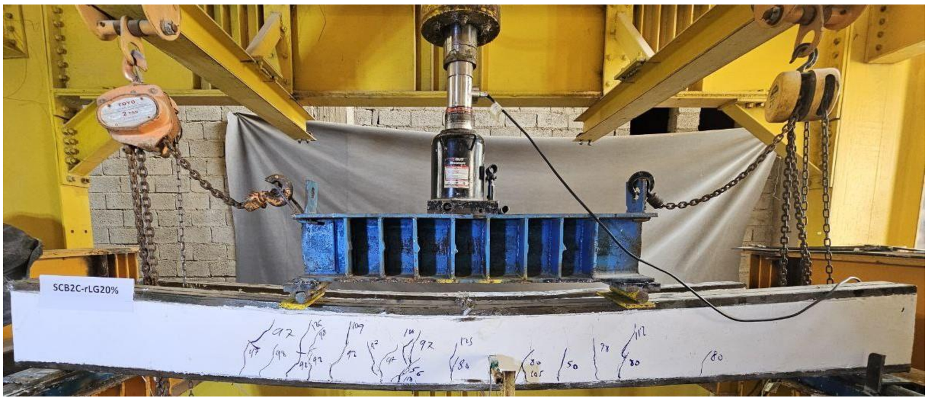

Figure 24. Tested specimen SCB2C-rLG20% and Failure Mode

Figure 25. Tested specimen SCB2C-rLG30% and Failure Mode

4. Conclusions

The breadth is the main factor controlling the section's structural characteristics. Because the moment of inertia for a 2C-section is directly proportional to the cube of its depth, it is essential for serviceability. The experimental examination of symmetrical castellated 2C cold-formed steel beams has yielded the following findings:

- The application of reactive powder concrete enhances the compressive strength of both cube and cylinder specimens while keeping the tensile strength at failure nearly the same.
- The effect of RPC on crack formation is beneficial, as most of the cracks were fine and difficult to detect visually.
- Increasing the gap between the upper and lower sections of the castellated beam results in an increase in load-bearing capacity from 80 kN to 130 kN; the optimal results were achieved when the gap measured 72 mm.
- The influence of reinforcement was evident in improving load capacity and resulted in a 36% reduction in deflection.
- In general, the effect of reinforcement on deflection values was minimal, as the values were significantly lower compared to the applied loads and beam section capacity.

5. Declarations

5.1. Author Contributions

Conceptualization, Y.B.J. and A.J.H.A.; methodology, A.J.H.A.; software, Y.B.J.; validation, Y.B.J. and A.J.H.A.; formal analysis, Y.B.J.; investigation, Y.B.J.; resources, A.J.H.A.; data curation, Y.B.J.; writing—original draft preparation, Y.B.J.; writing—review and editing, A.J.H.A.; visualization, Y.B.J.; supervision, A.J.H.A.; project administration, A.J.H.A.; funding acquisition, A.J.H.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Conflicts of Interest

The authors declare no conflict of interest.

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