Behaviours of hybrid deep beams with RPC Layers in the tension region

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Abstract. This paper presents an experimental study that included casting and testing six reinforced concrete simply supported deep beams under two-point loads. Two of these, with homogenous cross-sections, were made using normal strength concrete (NSC) only. The other four deep beams of hybrid cross-sections were cast using reactive powder concrete (RPC) in the tension layer and normal strength concrete (NSC) in the compression layer. Experimental results showed that the partial use of RPC noticeably increased both the first cracking load and ultimate load. The ultimate load was found to be increased further as the thickness of the RPC layer increased. The behaviours in terms of load-deflection also became stiffer as the shear span to overall depth ratio (a/h) decreased.

Keywords: Deep Beams, Reactive Powder Concrete, Hybrid Beams.

1. Introduction
Reinforced concrete deep beams are structural members that carry heavy loads over short spans, and as such are used as transfer girder in bridges and tall buildings. They are widely used in infrastructure, bridges, and buildings, forming wall footings, foundation pile caps, floor diaphragms, bunkers, and tanks [1]. According to the American Concrete Institute code 318:14 [2], deep beams have the following characteristics:

a) The clear span/overall depth ratio (ln/h) is not more than 4 in a distributed load case, and
b) The shear span to effective depth ratio (a/d) is not more than 2 in a point load case.

For deep beams, a large amount of load is transmitted directly from the points of loading to the support points by the compression force that joins the loads to the reactions. Hybrid layered systems are defined as existing when the cross-section consists of more than one layer of different concrete.

2. Background
In 1965, De Paiva and Siess [3] tested the effect of several structural parameters on the behaviours of deep beams. These parameters included the amount of longitudinal reinforcing steel, concrete strength, the ratio of the web reinforcement, the format mode of the web reinforcement (vertical or inclined stirrups), and length/depth ratio. The experimental results indicated that increasing the ratio of longitudinal reinforcement led to an increase in the loading capacity of the beams. Moreover, the failure type was found to be shear failure rather than flexural failure in these cases. The increase in concrete strength had a negligible effect on the ultimate strength of beams failing in flexure, but it changed, in some cases, the mode of failure for beams failing in shear. There was also no effect of web reinforcement on the formation of inclined cracks, and it had only a marginal effect on the ultimate strength of the beams. Denarié et al., [4] investigated the behaviours of hybrid concrete beams composed from high performance fibre reinforced cement composites (HPFRCC) and normal concrete. Their experimental results showed that the behaviours of these types of beams in their service and ultimate states were comparable to, or better than, those of beams reinforced with ordinary reinforced concrete. The
experimental study carried out by Sarsam and Mohammed [5] concluded that the load-deflection behaviours of hybrid beams containing RPC layers in cross-section were stiffer than in beams of normal concrete. Furthermore, they stated that increasing the thickness of the RPC layer led to an increase in the stiffness of the hybrid deep beams. Also, the ultimate load of the hybrid beams increased with increasing the thickness of RPC layer. Ammar and Maha [6] investigated the overall shear behaviour of reinforced concrete deep beams made from hybrid concrete strength in which the normal concrete strength (NCS) was in the tension zone and the high strength concrete (HSC) in the compression zone. The test variables included the thickness of the high strength concrete layer, the casting technique of the various concrete layers, and the effect of the presence of web reinforcement. The experimental results indicated that when the HSC layer was cast with a thickness of 25 to 50% of the total beam depth, the ultimate shear strength increased by around 11.2 to 19.5% for beams without web reinforcement, and by 16.75 to 22.25% for beams with minimum web reinforcement. The increase in the first cracking load was nearly 32.8 to 48% and 43.4 to 57.9% for beams with and without web reinforcement, respectively. Furthermore, beams where both layers (HSC and NSC) were cast at the same time (monolithically) exhibited an increase in ductility by around 13.3 to 22.6% and 17.3 to 26.3% for specimens with and without web reinforcement, respectively. On the other hand, hybrid concrete beams with construction joints and an epoxy resin layers of 1 mm thickness exhibited higher increases in ductility of 28.7% and 30.2% for specimens with and without web reinforcement, respectively. Hassan and Faroun [7] investigated the behaviour of hybrid deep beams when steel fibre was added to the shear spans both experimentally and theoretically, as well as examining other variables. Those variables included type of loading (monotonic or repeated), type of deep beam (hybrid or non-hybrid), quantity of steel fibres, and quantity of web reinforcement. The experimental results concluded that, under a monotonic loading system, the ultimate load was increased by 29.73% and 50.81% when the steel fibre contents were 1% and 2% located at a shear span, respectively. Compared with a no-steel-fibre beam, the increase in the web reinforcement ratio moved from 0.0 to 0.003 led to an increase in the ultimate load by around 34.08%, and 42.46% as the web reinforcement ratio moved from 0.0 to 0.004. The experimental results also showed that the ultimate load was greater than the expected ultimate load using the ACI 318M-11 Code [8]. Under monotonic loading, the maximum load of the deep beams with steel fibre of 1% throughout was greater than the maximum load of the hybrid deep beams containing steel fibre in the shear zone only, by around 5.21%. There was little effect seen on eliminating the web reinforcement of the hybrid deep beam under repeated loads, with a decrease of only 1.96%.

3. Experimental programs

3.1 Description of the tested deep beams
The experimental program included casting and testing three groups of simply supported reinforcement concrete deep beams: group A included two deep beams with normal cross-sections made from normal strength concrete (NSC), designated NDB-1 and NDB-2; group B included another two deep beams with hybrid cross-sections made of two different types of concrete: a reactive powder concrete (RPC) of 75 mm in the tension zone and (NSC) of 225 mm in the compression zone designated HDB-3 and HDB-4; and group C included another two deep beams with hybrid cross-sections made of two different types of concrete: (RPC) of 125 mm in the tension zone and (NSC) of 175 mm in the compression zone designated HDB-5 and HDB-6. Each beam's dimensions were as follows: total length = 800 mm, clear span (ln) = 600 mm, overall depth (h) = 300 mm, width (b) = 150 mm, and shear span to overall depth ratios a/h equal to 2/3 for NDB-1, HDB-3, and HDB-5, and to 1.25/3 for NDB-2, HDB-4, and HDB-6, to S All beams were tested under two points of loading at the top edge, as shown in Figure 1. Five deformed bars of Ø12 mm diameter were used as longitudinal tension reinforcement in order to ensure the occurrence of shear failure rather than flexure failure, and compressive reinforcing bars of 2012 mm were used to hold the stirrups and to prevent abrupt crushing failure of the compression zone. All beams had vertical and horizontal shear reinforcement of Ø6 mm @ 50 mm c/c.
3.2. Properties of Materials

3.2.1. Cement
A type-V Portland cement manufactured by the LAFARGE company, known commercially as AL-JESSER, was used in the current study. This conforms to the Iraqi standard specification No. 5/1984 [9].

3.2.2. Fine Aggregate
Natural washed sand, obtained from the Al-Ekhaider region in the Karbala governorate, was used in the current work for both (NSC) and (RPC). It conforms to Iraqi standard specifications No. 45/1984 [10].

3.2.3. Coarse Aggregate (Gravel)
The crushed natural gravel used in casting the normal concrete mixture (NSC) was supplied from the Al-Ekhaider region in the Karbala governorate, and it was within the requirements of Iraqi standard specification No. 45/1984 [10].

3.2.4. Superplasticizer
A superplasticizer commercially known as Glenium 51 was used in the (RPC) mixes; this confirms to the ASTM specification C494 Types A [11].

3.2.5. Fibre
Polypropylene fibre was used in the (RPC) mixes. Table 1 shows the specifications of the polypropylene fibre as supplied by the manufacturer.
### Table 1. Specification of polypropylene fibre.

| Properties | Melting point | Tensile strength, N/mm² | Diameter, µm | Specific gravity, g/cm³ | Length, mm | Modulus of elasticity, N/mm² |
|------------|--------------|-------------------------|--------------|-------------------------|------------|----------------------------|
| Polypropylene fibre | 1,600°C | 300 – 400 | 18 | 0.91 | 12 | 4000 |

3.2.6. Silica Fume  
Silica fume was used in the (RPC) mixes that conforms to the specification ASTM C1240-04 [12].

3.2.7. Water  
Tap water available from the water network was used in mixing and curing.

3.2.8. Steel Reinforcement  
Ukrainian steel bars were used in the experimental work. The test on the steel bars were carried out in the laboratory of mechanical engineering, University of Kerbala. Table 2 shows the test results.

### Table 2. Properties of reinforcement bars.

| Diameter of bar, mm | Yield strength (fy), N/mm² | Maximum strength, N/mm² | Measured Diameter, Mm |
|---------------------|-----------------------------|-------------------------|-----------------------|
| 6                   | 510.4                       | 540.5                   | 5.622                 |
| 12                  | 636.2                       | 706.8                   | 11.89                 |

3.3 Mix Proportion  
The quantities of materials used in this work for (NSC) and (RPC) mixtures are shown in Table 3.

### Table 3. Mix proportions for the NSC and RPC mixes, kg/ m³.

| Ingredients                      | Concrete Type |
|----------------------------------|---------------|
|                                  | NSC | RPC |
| Cement                           | 550 | 960 |
| Sand (4.75 mm)                   | 660 | --- |
| Fine Sand (600 µm)               | --- | 1000|
| Gravel                           | 770 | --- |
| Water                            | 231 | 288 |
| Polypropylene Fibre              | --- | 9.6 |
| Silica fume                      | --- | 192 |
| Superplasticizer                 | --- | 23.04|

3.3.1. Mixing  
The mixing was performed as follows:
3.3.1.1 Normal concrete (NSC)
A mechanical rotary mixer of 0.1 m³ capacity was used to mix the (NSC) mix. The total time of mixing was seven minutes, during which the sand and gravel were mixed during the first two minutes before cement was added to the dry ingredients for mixing for another two minutes. After obtaining an adequate dry mix, water was added during the rotating process of the mixer for mixing for another three minutes to obtain a homogeneous mix.

3.3.1.2. Reactive powder concrete (RPC)
Mixing of this type of concrete was done using an electric mixer. The total mixing time was eighteen minutes: the first three minutes were allocated to mixing the dry silica fume and cement. Then, the fine sand was added to the mix for another three minutes. After gaining a homogeneous mix, 50% polystyrene fibre and 50% of water and superplasticizer solution (a solution formed from water and Glenium 51) were added and mixing continued for 5 minutes. After that, electric mixing was halted for two minutes to allow mixing of the materials manually to incorporate any materials that the mixing arms could not reach. The remaining fibre and water and Glenium 51 were added, and mixing continued for another 5 minutes to obtain a homogeneous mix. After obtaining a homogeneous mixture, the placing and compacting process was thereafter completed using an electric vibrator for each layer until the casting process was complete. The upper face of the moulds was levelled and refined using steel plate.

3.4 Casting of specimens

3.4.1. Casting of control specimens
The control specimens were deep beam homogeneous sections consisting of normal strength concrete. The normal strength concrete mix was placed inside the moulds in three layers. The thickness of a layer is 10 cm, with air voids expelled by using the electric vibrator for each layer. The upper face was levelled and smoothed using a steel trowel. Three cubes of (10 × 10 × 10) cm and three cylinders of (10 × 20) cm were cast. All samples (cubes, cylinders, and specimens) were covered with polyethylene sheets after casting to retain moisture.

3.4.2. Casting of hybrid specimens
The hybrid specimens were composed of two different types of concrete. The first layer consisted of RPC in the tension region with thickness 75 mm for two specimens, and 125 mm for the other two specimens, and the upper layer consisted of NSC located in the compression region. RPC was cast in two layers with expulsion of air voids using the electric vibrator for each layer before the upper face was levelled. The normal strength concrete was then cast into two layers with the expulsion of the air voids using the electric vibrator for each layer. The upper face was levelled and smoothed using a steel trowel. Six cubes were cast for each stage, with three cubes (10 × 10 × 10 cm) for NSC, and three cubes (5 × 5 × 5 cm) for RPC. Moreover, six cylinders were cast for each stage (10 × 20) cm, with three cylinders for NSC, and three cylinders for RPC. All samples (cubes, cylinders, and specimens) were covered with polyethylene sheets after casting to retain moisture.

3.5. Curing
Curing included the following steps:
1- For NSC, after 24 hours from casting, all samples (cubes, cylinders, and normal deep beams) were extracted and placed in the curing tank at a room temperature of not less than 20 °C throughout the curing period (28 days of casting).
2- For RPC, all samples (cubes, cylinders, and hybrid deep beams) were removed and placed in the curing tank, and the water temperature was gradually increased to 60 degrees. The curing continued for 72 hours, after which the water temperature was gradually reduced to 20 degrees and the samples continued curing for 28 days after casting.
4. Results and discussions

4.1. Testing of control specimens
After the completion of the treatment period (28 days from the date of casting) the control models were removed from the treated water basins. The following tests were performed:

4.1.1. Compressive strength
Three cubes of \((10 \times 10 \times 10)\) cm and three of \((5 \times 5 \times 5)\) cm were tested to represent the compressive strength of NSC and RPC, respectively. The test was executed according to B.S: 1881: part 116 [13]. A hydraulic compression testing machine of 2,000 kN capacity was used as shown in Figure 2a. The outcomes of the test are given in Table 4; each value in this table represents the average of three samples.

4.1.2. Splitting tensile strength,
Three cylinders of \((10\times20)\) cm was used to represent the splitting tensile strength of NSC and RPC. The test was executed according to ASTM C496/C496M: 2004 [14]. A hydraulic compression testing machine of 2,000 kN capacity was used as shown in 'Figure 2'. The results of the test are given in Table 4, where results represent an average of the three cylinders' results.

![Figure 2. Compressive and splitting testing machine.](image)

| Deep beam type | Cube compressive Strength. \(f_{cu}(N/mm^2)\) | Cylinder compressive strength. \(f'_{c}(N/mm^2)\) * | Tensile splitting strength. \(fsp (N/mm^2)\) |
|---------------|---------------------------------|---------------------------------|---------------------------------|
|               | NSC | RPC | NSC | RPC | NSC | RPC |
| NDB-1         | 36.8 | / | 29.5 | / | 3.1 | / |
| NDB-2         | 36.8 | / | 29.5 | / | 3.1 | / |
| HDB-3         | 40.5 | 75.25 | 32.4 | 60.2 | 3.4 | 5.3 |
| HDB-4         | 40.5 | 75.25 | 32.4 | 60.2 | 3.4 | 5.3 |
| HDB-5         | 40.5 | 75.25 | 32.4 | 60.2 | 3.42 | 5.33 |
| HDB-6         | 40.5 | 75.25 | 32.4 | 60.2 | 3.42 | 5.33 |

\*\(f'_{c} = 0.8f_{cu}\) (BS 8110-85) [15]
4.2. Results for tested deep beams and discussions
The purpose of the current work was to investigate the effect of shear span to depth ratio and the thickness of RPC layer on the behaviors of hybrid deep beams with RPC in the tension region. The test included examining load-deflection behavior, first cracking load, and ultimate load. All deep beams were tested using a hydraulic machine of 2,000 kN capacity as shown in Figure 3.

![Hydraulic testing machine](image)

**Figure 3.** Hydraulic testing machine.

4.2.1. Effect of shear span to the total depth ratio (a/h).
Ratios of 2/3 and 1.25/3 for shear span to depth (a/h) were used in the current work. Figure 4, Figure 5, and 'figure 6' show the effect of (a / h) on the load-deflection curve. Table 5 shows the influence of (a / h) on the first cracking load and the ultimate load of the tested deep beams.

4.2.1.1. Load-deflection response.
Generally, the deep beams showed more stiffness and the vertical midspan deflection amount for the same load was lower as the (a/h) decreased from 2/3 to 1.25/3 due to the effect of the tied arch action, as shown in Figure 4, Figure 5, and Figure 6. The vertical deflection in midspan of deep beams at the first cracking load and at the ultimate load, this increased with decreased a/h. The ductility index was increased with decreases in a/h, as shown in Table 5.
Figure 4. Effect of a/h of NSC deep beam.

Figure 5. Effect of a/h of hybrid deep beam with RPC layer of 75 mm.
4.2.1.2. First cracking load and ultimate load
The experimental results suggest that the ultimate load and the first cracking load in hybrid deep beams decrease with increased a/h, due to a decreased effect of the tied arch action with increased a/h. The first cracking load and ultimate load of the examined deep beams are included in Table 5.

4.2.2. Effect the thickness of RPC layer
The thickness of the RPC layers used in this study were 75 mm and 125 mm.

4.2.2.1. Load-deflection response
Generally, the behaviors of hybrid deep beams showed more stiffness with increased RPC thickness in the first stages of loading. The hybrid deep beams with RPC 125 mm showed more stiffness than with hybrid deep beams with RPC 75 mm. The behavior of the hybrid deep beams demonstrated more ductility than the normal deep beams, as shown in Table 5 and Figure 7, and Figure 8.

Figure 6. Effect of a/h of hybrid deep beam with RPC layer of 125 mm.
Figure 7. Effect of RPC thickness on hybrid deep beam where a/h = 2/3.

Figure 8. Effect of RPC thickness on hybrid deep beam where a/h = 1.25/3.
Table 5. Mechanical properties for NSC and RPC mixes.

| Beam specimens | First Cracking Load, Pcr (kN) | First crack deflection, Δf (mm) | Ultimate Load, Pu (kN) | Ultimate deflection, Δu (mm) | Ductility index, \( \frac{Δu}{Δf} \) | Perc/Pu * 100% |
|----------------|-------------------------------|---------------------------------|------------------------|-------------------------------|--------------------------------|----------------|
| NDB-1          | 180                           | 0.52                            | 435                    | 1.354                         | 2.60                           | 41.4           |
| NDB-2          | 180                           | 0.36                            | 528.52                 | 1.192                         | 3.31                           | 34.1           |
| HDB-3          | 205                           | 0.612                           | 588                    | 2.942                         | 4.81                           | 34.9           |
| HDB-4          | 207                           | 0.343                           | 749.23                 | 2.515                         | 7.33                           | 27.6           |
| HDB-5          | 192                           | 0.448                           | 664                    | 2.844                         | 6.35                           | 28.9           |
| HDB-6          | 212                           | 0.248                           | 814                    | 2.262                         | 9.12                           | 26.0           |

4.2.2.2. First cracking load and ultimate load
The first cracking load and ultimate load increased with increases in the thickness of the RPC layer.

5. Failure shape
The failure type for all deep beams was shear failure. The inclined shear cracks in the shear zone were the first visible cracks in all deep beams. As the loading increased, the inclined shear cracks evolved towards the loading points between the loading and support points along the strut region until the formation of the diagonal shear crack at failure. The arch formation in deep beams with a/h=2/3 was more pronounced than in the deep beams with a/h=1.25/3. Figure 9, Figure 10, Figure 11, Figure 12, Figure 13, and Figure 14 show the development of cracking with the increase in loads and the final failure patterns.

Figure 9. Cracking pattern and failure mode for beam NDB-1 (a/h=2/3).
Figure 10. Cracking pattern and failure mode for beam NDB-2 (a/h=1.25/3).

Figure 11. Cracking pattern and failure mode for beam HDB-3 (a/h=2/3).

Figure 12. Cracking pattern and failure mode for beam HDB-4 (a/h=1.25/3).

Figure 13. Cracking pattern and failure mode for beam HDB-5 (a/h=2/3).
6. Conclusions

From the experimental results, several points can be concluded:

1. Decreasing then a/h led to an increase in the stiffness of deep beams as shown in the load-deflection curves. For the same deflection, the load capacity is increased with the decrease in a/h.
2. At the first stages of loading, the increase in RPC thickness led to an increase in the stiffness of hybrid deep beams. In contrast, the effect of RPC thickness on the load-deflection curve is marginal.
3. It was found that decreasing a/h can increase the first cracking load; decreasing a/h from 2/3 to 1.25/3 saw the first cracking load increase by 10.41% and by a further 1% at 125 mm and 75 mm of RPC thickness, respectively.
4. The first cracking load increases with increases in the RPC thickness. When a / h is equal to 1.25/3, the first cracking load increased by 15% and again to 17.78% when the RPC thickness was 75 mm and 125 mm, respectively. Whereas, when a / h was equal to 2/3, the first cracking load increased by 13.8 and 6.67% when the RPC thickness was 75 mm and 125 mm, respectively.
5. The ultimate load increased with increases in the RPC thickness. When increasing the RPC thickness from 75 mm to 125 mm, the ultimate load was increased by 12.9% and 8.6% at a/h= 2/3 and 1.25/3, respectively.
6. The ultimate load increased with the decrease in a/h. When the a/h decreased from 2/3 to 1.25/3, the ultimate load of the NC deep beam increased by 21.5% and by 29.11% and 22.59% for the hybrid deep beam of RPC thicknesses of 75 mm and 125 mm respectively.
7. The ultimate load in hybrid deep beams was greater than in normal deep beam. At a/h=2/3, the ultimate load in a hybrid deep beams with RPC thicknesses 75 mm and 125 mm were greater than the ultimate load in normal deep beams by 35.1% and 52.6%, respectively. At a/h=1.25/3, the ultimate load in the hybrid deep beam with RPC thickness of 75 mm and 125 mm was greater than the ultimate load in normal deep beams by 41.8% and 54.0%, respectively.
8. The ductility index increased with increases in the thickness of RPC layer.

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