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# STRUCTURAL BEHAVIOR OF HYBRID REINFORCED CONCRETE COUPLED BEAMS CONTAINING REACTIVE POWDER CONCRETE AND HIGH STRENGTH CONCRETE

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**Abstract:** Reactive powder concrete and high strength concrete have superior mechanical and structural properties, however, the major drawback of this new construction material is its high cost compared to traditional concrete. This study presents an experimental investigation on the structural behavior of hybrid rectangular cross section (coupled) reinforced concrete beams poured with normal and high strength concrete (HSC) at compression chord, normal strength concrete (NSC) at ribs, and reactive powder concrete (RPC) at tension chord. The experimental work consists of pouring and testing four specimens with dimensions (1100mm length, 100 mm width, and 400 mm height). First specimen, rectangular solid normal concrete beam for comparison with specimens, second specimen, coupled beam poured with normal strength concrete at top chord, and two other specimens of coupled beams cast with high strength concrete with two compressive strength (50 MPa and 70 MPa) at top chord. The effect of top chord concrete type at each specimen on ultimate load capacity, energy absorption, deflection and cracking load are studied in this investigation. Experimental results showed that the ultimate load carrying capacity and energy absorption increased to 76.9 % and 108.33 % respectively, compared with the solid specimen and recorded a reduction in deflection values through loading life and cracking load when using higher compressive strength of high strength concrete in compression chord in addition to reactive powder concrete in tension zone.

**Keywords** *hybrid, coupled beam, top chord, bottom chord, and rib.*

## 1. Introduction

To design a reinforced concrete structure, two main criteria must be satisfied, strength and serviceability. Strength is the ability of the structure to carry loads.Serviceability is the behavior of the structure at working loads, with particular consideration of cracking and deflection [1]. The coupled beams concept in this study is related to Vierendeel truss. But, the predictable sense of being an assemblage of a connected unit which is a type of frames, where coupled beam consists of elements just like in the reinforced concrete (RC) frames. Reinforced concrete frames consist of horizontal elements (beams) corresponding to top and bottom chords, and diagonal elements corresponding to ribs in coupled beams connected by rigid joints. These structures are cast monolithically—that is, top, bottom chords and ribs are cast in a single operation in order to act in unison. Members of Coupled beams subjected to bending moment, shear force, and direct tension or compression. Hybrid concrete beams are characterized by using different types of

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concrete layers for the purposes of increasing the resistance and improving the performance. Many researchers studied hybrid concrete beams with different sections using more than one type of concrete or using the same type of concrete but with many additives such as steel fibers (SF). Composite (or hybrid) structures are those that constructed by adopting many building materials that work behave jointly as one unit as much as possible. Structures that built by concrete and reinforced by steel bars are the most traditional example of composite structures; however, the composite structures of two types of concrete also exist [2]. In steel structure, a hybrid section is used in order to increase the load carrying requirement. The hybrid section concept in steel construction isn't a new idea. Salmon and Johnson [3] were defined a hybrid girder as one that has either tension flange or both flanges of steel section and this made with a higher strength grade of steel than used for the web. New layers of concrete are usually used to maintain or strengthen weak or old structural members. According to Bernard et al. [4], hybrid concrete structures are those with elements that involve old and new layers of concrete. Kawamata et al. [5] described a fiber reinforced concrete as a hybrid and compound material created by combining two steel fibers of various forms. Concrete structures reinforced by fibers are found to have better ductility and higher tensile resistance, due to the influence of crack restricted mechanisms of the steel fibers. An experimental work was performed to evaluate the structural response of hybrid (reactive powder concrete-high strength concrete-normal strength concrete) coupled beams which can be using as an alternative of solid beams to utilize the benefits of these concrete types in an optimal way and as a result light weight dead load structure for multi-storey building.

## 2. Experimental Program

Four beams were tested in an experimental investigation conducted at Al-Mustansiriyah University/Structures Laboratory of Faculty of Engineering. The primary variable influencing the specimen design was compressive strength of normal and high strength concrete which casted at the upper beam (top chord) of coupled beams. The experimental program studied the effect of using high strength concrete with two compressive strength at top chord, and benefits of reactive powder concrete at bottom chord. The dimension of these specimens are 1100 mm length, 100 mm width and 400 mm height, other dimensions are explained in Figure (1), reinforced with (4Φ8mm) at top chord, bottom chord and ribs, the details of reinforcement are shown in Figure (2) . All specimens tested under two point loads with clear span 1000 mm, as shown in Figures (3) and (4).The specifications and details shown in Table (1).

**Table 1.** Tested Beams Specifications

| *Specimen symbol* | *Bottom chord* | | *Top Chord* | | *Ribs* | |
|---|---|---|---|---|---|---|
| | *Concrete Type* | *Reinforcement* | *Concrete Type* | *Reinforcement* | *Concrete Type* | *Reinforcement* |
| RN | NSC | 4Φ8mm | NSC | 4Φ8mm | - | - |
| B1 | RPC | 4Φ8mm | NSC | 4Φ8mm | NSC | 4Φ8mm |
| B2 | RPC | 4Φ8mm | HSC (50 MPa) | 4Φ8mm | NSC | 4Φ8mm |
| B3 | RPC | 4Φ8mm | HSC (70MPa) | 4Φ8mm | NSC | 4Φ8mm |

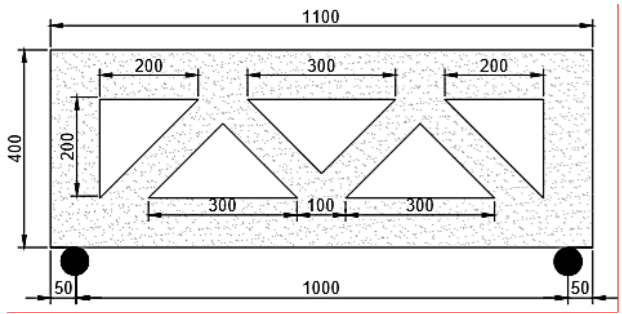


**Figure 1.** Details of Coupled Beams
(All dimensions in mm)

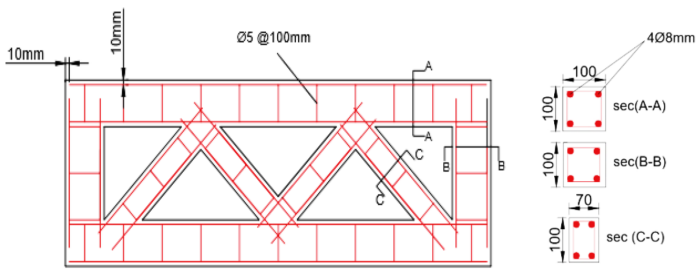


**Figure 2.** Reinforcement Details of Coupled Beams
(All dimensions in mm)

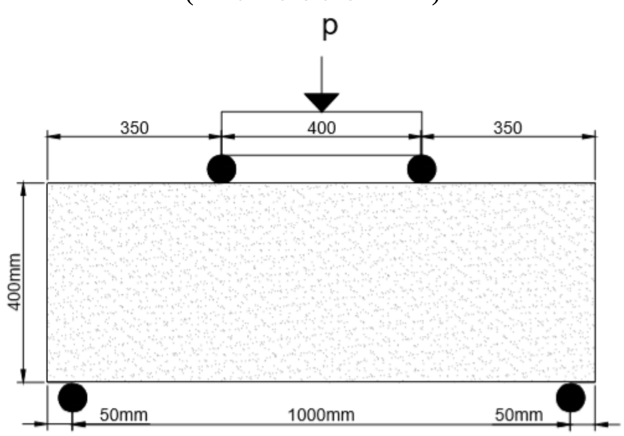


**Figure 3.** Testing Set-up of Reference Specimen RN

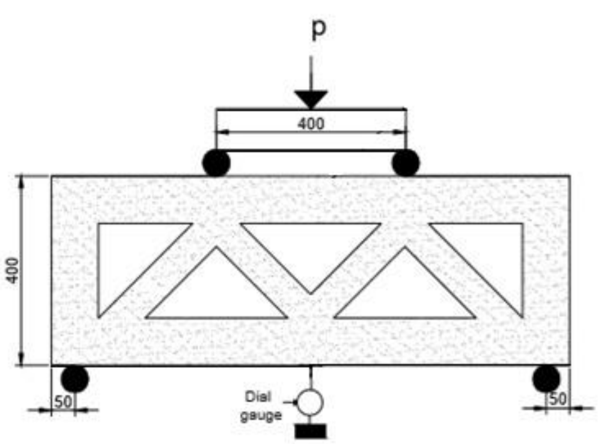


**Figure 4.** Testing Set-up of Coupled Beam Specimens

## 3. Materials

### 3.1 Cement

The cement kind employed in concrete manufacturing during this study's experimental work was ordinary Portland cement (Type I) for ordinary concrete strength, high concrete strength, and reactive powder concrete. The chemical structure of cement and its physical characteristics are shown in Tables (2) and (3) respectively. There is a conformance with the Iraqi standards specification No.5/1984 [6].

**Table 2.** Chemical Composition of Cement

| ***Compound composition*** | ***Chemical Composition*** | ***Percentage by weight*** | ***Limit of IOSNo.5 / 1984*** |
|---|---|---|---|
| Lime | CaO | 62.11 | ------ |
| Silica | $SiO_2$ | 21.37 | ------ |
| Alumina | $AL_2O_3$ | 5.2 | ------ |
| Iron Oxide | $Fe_2O_3$ | 4.42 | ------ |
| Magnesia | MgO | 1.73 | <5 |
| Sulfate | SO3 | 2.62 | <2.8 |
| Loss on Ignition | L.O.I | 2.76 | <4 |
| Lime Saturation | L.S.F | 0.94 | 0.66-1.02 |
| Insoluble residue | I.R | 0.71 | <1.5 |
| Tricalcium aluminate | C3A | 6.31 | ------ |
| Tricalcium silicate | C3S | 41.64 | ------ |
| Dicalcium silicate | C2S | 30.1 | ------ |
| Tricalciumal umona ferrite | C4AF | 13.43 | ------ |

**Table 3.** Physical Properties of Cement

| **Physical Properties** | **Test Result** | **Limit of IOS No.5/ 1984** |
|---|---|---|
| Finess using Blaine air permeability apparatus ($cm^2/g$) | 4420 | > 2300 |
| Soundness using autoclave method | 0.21% | < 0.8% |
| Setting time using Vicat's instrument for cement paste | | |
| Initial (min) | 190 min | > 45 min |
| Final(hrs) | 5 hr | < 10 hr |
| Compressive strength for cement paste at | | |
| 3 days (MPa) | 23 | >15 |
| 7 days (MPa) | 30 | > 23 |

### 3.2 Fine Aggregate

In this study two types of fine aggregates are used:

1. The maximum size and fineness modulus of Natural sand were (5 mm) and (2.35) respectively. The test results are in match with Iraqi standard (No.45 /1984) [7]. Both Tables (4) and (5) show the sand gradients and specifications.

**Table 4**. Sand Sieving Analysis

| ***Sieve size(mm)*** | ***Cumulative passing (%)*** | ***Limits of Iraqi specification No.45/1984 zone 2*** |
|---|---|---|
| 10 | 100 | 100 |
| 4.75 | 95.50 | 90-100 |
| 2.36 | 87.70 | 75-100 |
| 1.18 | 74.60 | 55-90 |
| 0.6 | 52.60 | 35-59 |
| 0.3 | 12.40 | 8-30 |
| 0.15 | 2.30 | 0-10 |

**Table 5.** Chemical and Physical Properties of Fine Aggregate

| **Physical properties** | **Test result** | **Limit of Iraqi specification No.45/1984** |
|---|---|---|
| Specific gravity | 2.5 | - |
| Apparent Specific gravity | 2.68 | - |
| Sulfate content($SO_3$) | 0.4 % | ≤ 0.5% |
| Absorption ratio | 0.78 % | - |
| Passing 0.075 mm (%) | 0.4 % | ≤ 5% |
| Clay (%) | 0.04 % | ≤ 1% |
| Organic (%) | 0.466 % | ≤ 0.5% |

2. Extra fine sand was used for manufacturing of reactive powder concrete, it have a particles with maximum size (600µm). The provider of this type of fine aggregate is Sika Company. The properties of extra fine aggregate conformed the IQS No.45/1984 [7]. The grading of extra fine aggregate are shown in Table (6).

**Table 6.** Grading of Fine sand

| Sieve size(mm) | Cumulative passing (%) | Limits of Iraqi specification No.45/1984 zone 4 |
|---|---|---|
| 10 | 100 | 100 |
| 4.75 | 100 | 95-100 |
| 2.36 | 100 | 95-100 |
| 1.18 | 100 | 90-100 |
| 0.6 | 100 | 80-100 |
| 0.3 | 47 | 15-50 |
| 0.15 | 6 | 0-15 |

### 3.3 Coarse Aggregate

For the NSC and HSC mixes, crushed aggregate with maximum size of 10 mm was detected by sieve analysis. The grading of the gravel used is consistent with the Iraqi Standard Specification No.45/1984 [7] as shown in Table (7).

**Table 7.** Grading of Course Aggregate

| Sieve size(mm) | Cumulative passing (%) | Limits of Iraqi specification No.45/1984 |
|---|---|---|
| 20 | 100 | 100 |
| 14 | 100 | 90-100 |
| 10 | 79 | 50-85 |
| 5 | 2 | 0-10 |
| 2.36 | --- | --- |

### 3.4 Silica fume

Silica fume is an extra fine powder. The silica fume is a product of manufacturing Ferro-silicon metal or silicon, using silica fume in this study in production of RPC as a good option to achieve good concrete properties. Table (8) explained the main chemical components of silica fume, which satisfied the American Standards ASTM C1240 [8].

**Table 8.** Main Components of Silica Fume*

| *Compound Composition* | *Chemical Composition* | Results % | *Specifications Limits (ASTM C 1240)* |
|---|---|---|---|
| Silica | $SiO_2$ | 92.1 | 85 (min) |
| Alumina | $Al_2O_3$ | 0.5 | --- |
| Iron oxide | $Fe_2O_3$ | 1.4 | --- |
| Lime | CaO | 0.5 | --- |
| Magnesia | MgO | 0.3 | --- |
| Potassium oxide | $K_2O$ | 0.7 | --- |
| Sodium oxide | $Na_2O$ | 0.3 | --- |
| Sulphate | $SO_3$ | 0.1 | --- |
| Loss on ignition | L.O.I | 2.8 | 6 (max) |

*According to editions by manufacturer.

### 3.5 Superplasticizer

High range water reducing agents (HRWRA), also called superplasticizer is usually employed to produce reactive powder concrete mixes and high concrete strength mixes, as used in this study. Glenium 51 has been adopted as one of the modern polymer-based superplasticizers, that is employed to produce RPC. Table (9) demonstrates the key characteristics of Glenium 51 that was employed to enhance mix flow ability. Glenium 51 (ASTM C494-ClassF) [9] is free from chlorides.

**Table 9.** Specifications of Superplasticizer*

| | |
|---|---|
| Commercial name | Glenium 51 |
| Form | Viscous liquid |
| Appearance/Color | Light brownish liquid |
| Labeling | No hazard label required |
| Relative density | 1.08 – 1.15 gm./cm$^3$@ 25°C |
| Viscosity | 128 +/- 30 cps @ 20°C |
| pH value | 6.6 |
| Chloride ion content% | Free |
| Transport | Not classified as dangerous |

*Supplied by the manufacturer.

### 3.6 Steel fiber

The steel fibers have typically been used in the combination of reactive powder concrete. Table (10) shows the characteristics of steel fibers which the (SIKA) company has proven. The hooked end steel fibers were used in the current study.

**Table 10.** Characteristics of Used Steel Fibers *

| | |
|---|---|
| Type of steel | Hooked-Ends steel fibers |
| Relative Density | 7850 kg/m$^3$ |
| Yield strength | 1100 MPa |
| Modulus of Elasticity | 210 000 MPa |
| Average length (L) | 35 mm |
| Nominal diameter (d) | 0.55 mm |
| Aspect Ratio(L/d) | 65 |

*According to editions by manufacturer.

### 3.7 Reinforcement Steel

Steel bars (deformed) of nominal diameter (ϕ8 mm) with yield stress of 475MPa are used as tension reinforcement, while steel bars (deformed) (ϕ5 mm) with yield stress of 352 MPa are used as stirrups.

## 4. Mix Design

The mix proportions are listed in Table (11) were used for three types of concrete.

**Table 11.** Mix Proportions

| Concrete type | NSC | HSC50 | HSC70 | RPC |
|---|---|---|---|---|
| Cement (C)(kg/m$^3$) | 418 | 510 | 650 | 851 |
| Sand (S) (kg/m$^3$) | 542 | 590 | 435 | --- |

| | | | | |
|---|---|---|---|---|
| Gravel (G)(kg/m$^3$) | 1200 | 1000 | 1130 | --- |
| Silica Fume (SF)(kg/m$^3$) | --- | --- | --- | 191 |
| Silica sand (kg/m$^3$) | --- | --- | --- | 1050 |
| Superplasticizer(SP) | --- | 1%* | 1%* | 3%** |
| Water(W)(Liter/m$^3$) | 192.28 | 163.2 | 195 | 153 |
| W/C Ratio (%) | 0.46 | 0.32 | 0.3 | 0.15*** |
| $V_f$ Steel Fiber (%) | --- | 0 | 0 | 1 |

*percent by weight of Cement (C)
**percent by weight of (C+SF)
***W/(C+SF)

## 5. Compressive Strength

According to ASTM C39 [10] and B.S 1881-part 116-83 [11] specifications, the compressive strength of concrete was evaluated. Standard cylinders (150x300) mm and cubes (100x100x100) mm were used to obtain the compressive strength of the concrete. The concrete compressive strength test results are mentioned in Table (12). These tests were made in the Structures Laboratory of Civil Engineering Department /Al-Mustansiriyah University.

**Table 12.** Compressive Strength Test Results

| Concrete type | Cube Strength $f_{cu}$ (MPa) | Cylinder Strength $f_c'$ (MPa) |
|---|---|---|
| NSC | 32.50 | 28.59 |
| HSC 50 MPa | 54.33 | 46.14 |
| HSC 70 MPa | 77.26 | 68.13 |
| RPC | 126.00 | 106.80 |

## 6. Results and Discussions

### 6.1 Cracks Pattern and General Behavior

The mode of failure was typical shear failure in all tested beams. As illustrated in Fig. (5) to Fig. (8).

For reference specimen (RN), the specimen initially being stiff through low deflection readings. At load (122.5 kN), the flexural cracks began to appear, these cracks are thin and limited in height may be due to low tensile stresses compared with shear stresses, shear cracks initiate at supports and extend diagonally to the upper zone of the beam, and finished at load points, as shown in Figure (5). These cracks increased in width, thus increasing in crack dimension resulted a decrease in beam stiffness. In a specific load, the cracks stable due to transfer the stresses to the steel reinforcement, this indicates yielding of reinforcing bars. After that, the crack width increased dramatically until the failure of the beam by diagonal shear mode.

The specimen B1 that contains normal strength concrete at top chord have first crack load 85 kN, the first crack appeared at shear span near supports, these cracks pass in a diagonal direction until joint of ribs with the bottom chord, this was attributed to the horizontal and the vertical components of the ribs compressive force that caused tension and shear respectively in the bottom chord. At load 185 kN, a crushing of concrete occurred at load points, as shown in Figure (6). The crushing is may be attributed to the effect of the difference in mechanical properties of concrete in different layers, i.e. high tensile strength of RPC compared with low compression and tensile strength of NSC, caused compression failure at load 215 kN.

In the same way, the beam B2 having the failure process as mentioned in the specimen above, which shown in Figure (7). The first crack load ($P_{cr}$) appeared near supports at loading 90kN in bottom chord. While, the crack in top chord appeared at 200 kN, then extend diagonally; at 210 kN, another crack appeared in support extend vertically passes through the vertical rib, this crack passes parallel to the main reinforcement of vertical rib, it may occur because of low resistance of normal strength concrete at ribs. All cracks widened in fast rate until failure of the beam at (217.5 kN).

For coupled beam (B3), at 102.5 kN loading, the first crack appeared at supports with inclination about 45°, thin crack passes through a bottom chord and extends through ribs to a specific height then vanished at mid length of ribs at 275 kN, the cracks extended to the ribs is may be attributed to low compressive strength and tensile strength of concrete rib, that manufactured with normal strength concrete, in comparison with top and bottom chord with high strength concrete (HSC 70 MPa) and reactive powder concrete (RPC) respectively. At 225 kN, shear cracks initiated at the top chord under load points as shown in Figure (8), the cracks extended diagonally to the support through a rib until failure of the specimen at 287.5 kN.


**Figure 5.** Mode Failure of Reference Specimen RN


**Figure 6.** Mode Failure of Specimen B1


**Figure 7.** Mode Failure of Specimen B2


**Figure 8.** Mode Failure of Specimen B3

### 6.2 Ultimate Load Capacity

The ultimate load carrying capacity of the tested beams B1, B2 and B3 are compared with the reference beam and reported below in Table (13). The effect of concrete compressive strength at the top chord on the ultimate load carrying capacity is considered, the difference in ultimate load with respect to reference specimen is discussed in this section.

The specimen B1 achieved an increase in ultimate load about 32.3% over the reference specimen RN, specimen B1 are poured with normal concrete at the top chord. Using high strength concrete with compressive strength 50 MPa in specimen B2, improved the ultimate capacity of the specimen by 33.8% in contrast with normal strength concrete beam RN. While increasing the strength of concrete in the top chord to 70 MPa in specimen B3, improved the ultimate carrying capacity of about 76.9% in comparison with normal strength concrete specimen RN. Due to increase in compressive strength of the top chord (compression zone), beam stiffness was increased resulting in high resistance to the deformations under loading.

### 6.3 First Crack Load

The first crack load is an important factor to determine the stage of reaching the concrete to its tensile strength. The first crack load means that the applied stresses exceed the concrete tensile strength [12].

The test results are shown below in Table (13), normal strength concrete solid beam (RN) recorded a first crack load of 122.5 kN, it was observed that cracking load of all coupled beams B1, B2 and B3 less than that of the solid reference specimen RN, it about 30.61%, 26.53%, and 16.33% respectively; this reduction is may be due to the geometry of section and the decrease in the inertia of gross concrete section. The first crack appears at the bottom chord, it is dependent on the material at the bottom chord. Since all specimens were cast with reactive powder concrete at the bottom chord, so there is no significant variation between coupled specimens in term of first crack load.

### 6.4 Energy Absorption

Energy absorption can be defined as the energy that the specimen can absorb through loading life before failure. It gives indicates the ductility of the specimen. Mathematically, the energy absorption value can be calculated from the area under the load-deflection curve [13]. The section below discussed the effect of top chord concrete type on the energy absorption, the calculated values are shown below in Table (13).

The reference specimen (RN) recorded energy absorption about 233.04 kN.mm, the specimen B1, that having normal strength concrete NSC at top chord achieved energy absorption about 373.33 kN.mm; in specimen B2, where the top chord cast with (HSC 50MPa), the compressive strength of top chord in this specimen is lower than that of specimen B3, the increase in energy absorption reached to 41.59%, while using of high strength concrete (HSC 70 MPa) at top chord of specimen B3, resulted an increase in the energy absorption of the specimen about 108.33% over than the reference specimen (RN).

In general, the energy absorption increased when the load increment accompanied with large deflections. Also, increase the energy absorption is depending on increasing the tensile strength for the bottom chord of the specimens which casted with reactive powder concrete.

**Table 13.** Experimental Results

| Specimens | First Crack Load Pcr (kN) | Ultimate Load Pu (kN) | Energy Absorption (kN.mm) |
|---|---|---|---|
| RN | 122.5 | 162.5 | 233.04 |
| B1 | 85 | 215 | 373.33 |
| B2 | 90 | 217.5 | 329.95 |
| B3 | 102.5 | 287.5 | 485.50 |

### 6.5. Load-Deflection Relationship

The structural behavior is defined as the deformation response exhibited by a structure under loading [14], the vertical displacements of specimens were measured at mid-span of bottom chord by using dial gauge with accuracy 0.01mm. By observing the load-deflection characteristics of the tested beams, it is seen that the ductility of the beams increased when the concrete type changed from normal strength concrete to high strength concrete.

Generally, three stages that cracking load, yielding load and ultimate load capacity within load-deflection curve history. In the precracking stage, deflection increases linearly in all loaded beams, which means that the materials in the compression and tension zones are in the elastic state. There is also linearity in the post cracking stage, but with different slopes up to yielding of longitudinal reinforcement, after noticing a curvature in a load-deflection relationship till failure.

Generally, the deflections of beams B1, B2 and B3 less than the reference specimen RN at same loading levels, and the maximum value of deflection at failure in coupled beams is more than of reference beam, see Figure (9).

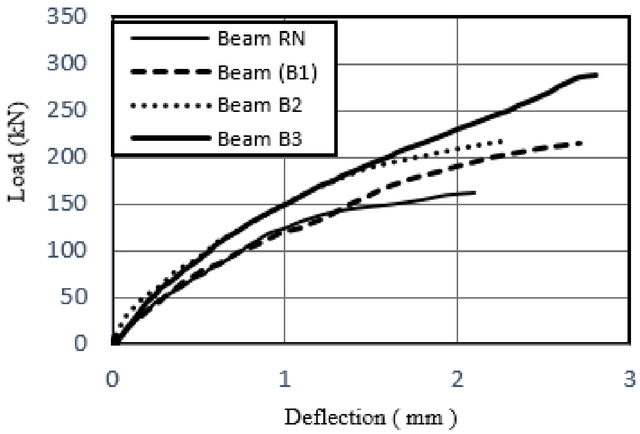


**Figure 9.** Load-deflection curves of specimens

## 7. Conclusions

1. Change concrete type with high strength concrete (70 MPa) at the top chord of a coupled beam resulted good enhancement, it recorded an increase about 76.9% in ultimate load in comparison with normal strength concrete solid beam.
2. The good mechanical properties of concrete type (i.e high strength concrete and reactive powder concrete) at the top chord and bottom chord produced deflection readings through-loading life lower than normal concrete specimen due to the resulted increase in stiffness.
3. In general, there was a decrease in first crack load for hybrid coupled beams depending on the geometry section and inertia.
4. The ultimate value of deflection for coupled beams is higher than of reference beam accompanied with high ultimate load.
5. the coupled beams achieved energy absorption higher than the reference specimen, depending on strength of compression zone where the ability to absorb energy increased by about 108.33% as compressive strength increased to 70 MPa, according to enhance in mechanical properties of concrete at the top chord in addition to the bottom chord.
6. All the hybrid coupled beams failed by shear regardless of the concrete type used.

**Conflict of interest**

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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