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# EFFECT OF LAP SPLICING HIGH TENSILE STEEL BARS IN REACTIVE POWDER CONCRETE BEAMS EXPOSED TO REPEATED LOADING

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**Abstract:** This research is an experimental study to evaluate the effect of lap splice of high-strength steel bars in reactive powder concrete beams exposed to repeated loading. Seven Reactive Powder Concrete (RPC) beams whose tension steel bars were spliced at mid-span and one RPC beam without lap splice were casted and tested. These beams were simply supported and tested up to failure under the action of two point loads (two beams exposed to monotonic load and five beams exposed to repeated load). The studied parameters were : the repeated loading regime (two different repeated loading regime depending on the minimum to maximum applied load),the lap splice length ( 20 and 30 times diameter of bar diameter), the concrete cover thickness (30mm and 40mm) and adding steel stirrups within the lap splice region. The mid span deflection as well as cracks propagation were recorded for each load step in tested beam. The main results showed that the adopted spliced length of tension steel bars was sufficient in monotonic load but insufficient under the action of greater number of cycles of the repeated load. Also the results showed that better structural performance can be achieved by increasing the length of the lap splice, or increasing concrete cover and providing stirrups within the splice region and that the latter method is the most efficient strengthening method when the beam is exposed to larger number of repeated load cycles.

**Keywords**: *lap splice; Reactive Powder Concrete; High Tensile Steel Bars; repeated loading.*

# تاثير وصلات تراكب القضبان الفولاذية عالية الشد في عتبات خرسانة المساحيق الفعالة المعرضة لأحمال متكررة

**الخلاصة** :هذا البحث يتعلق بدراسة مختبريه لتقييم تاثير وصلات تراكب حديد تسليح الشد عالي المقاومة في عتبات مصنعة من خرسانة المساحيق الفعالة ومعرضة لأحمال مكررة باتجاه واحد. تم صب وفحص سبع عتبات من هذا النوع تحتوي عند وسط فضائها على وصلات شد لحديد تسليح عالي المقاومة وواحدة بدونها. أسندت هذه العتبات إسنادا بسيطا وتم فحصها تحت تأثير حملين مركزين لحد الفشل ( عتبتان تحت حمل رتيب (ساكن) وخمس عتبات تحت حمل تكراري). المتغيرات التي تم دراستها هي: طريقة تسليط الحمل المكرر (حيث استخدمت طريقتان لتسليط الحمل اعتمادا على نسبة الحمل الأدنى إلى الحمل الأقصى), طول وصلة التراكب ( 20× قطر الشيش و 30×قطر الشيش), سمك الغطاء الخرساني ( 30ملم و40ملم) و اضافة اتاري ضمن منطقة وصلة تراكب حديد التسليح . تم اخذ قراءات الهطول ( deflection) عند منتصف العتبة وكما تم تأشير التشققات الحاصلة أثناء الفحص. تبين بعد إجراء الفحص أن طول وصلة تراكب حديد تسليح الشد العالي المقاومة الذي تم تبنيه كان كافيا تحت تاثير الفحص الستاتيكي ولكن هذا الطول لم يكن كافيا عند تعرض بعض النماذج لعدد كبير من دورات التحميل المتكرر. تبين ايضا انه بالامكان الحصول

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على اداء انشائي افضل بزيادة طول وصلة التراكب او زيادة الغطاء الخرساني او بتوفير حديد اتاري ضمن منطقة التراكب والمعالجة الاخيرة هي افضل الطرق عند تعرض العتبة الى دورات تحميل كبيرة.

## 1. Introduction

Reactive powder concrete (RPC) is a new building material with high-strength, good crack resistance, high toughness and good durability. This concrete type is produced without coarse aggregate by using cement , silica fume , very fine sand (as aggregate) , very low water cement ratio ,super plasticizer with short cut steel fibers. The very low porosity of RPC gives it considerable durability [1] **.** In spite of these advantages, large unreinforced RPC members can exhibit brittle behavior with crack localization and insufficient structural ductility leading to sudden failure**.** So the possible solution for these related problems is adding conventional or high- strength embedded bars as reinforcement to the section [2].

A number of types and grades of steel reinforcement with yield strengths exceeding 550MPa are commercially available. By using steel with this higher capacity could provide various benefits to the concrete construction industry[3]. When high strength reinforced steel rebar is used along with RPC, the excellent performance such as high strength of both materials will be utilized, and would significantly improve the safety and durability of the structure, economize steel and enhance the construction of low-carbon buildings [4]. This leads to an important development of sufficient bond capacity between the high strength steel bars and matrix which affect the structural behavior of the RPC members.

El-Hacha et al. studied the bond characteristics of high-strength steel reinforcement with normal concrete strength, and concluded that high strength steel bars require a longer development length due to the higher bar stress to be developed, but simply increasing development length without providing confinement is an inefficient means of developing greater stresses [5].

Seliem et al. reported that confining reinforcement around development regions or splices in normal concrete strength is required to control the splitting cracks associated with a bond failure . With higher strength steel, greater bar strain and slip will occur prior to development of the bar. The associated displacement of the bar lugs drives the splitting failure beyond that where yield of conventional bars would occur, thus, confining reinforcement is critical in developing higher strength bars [6].

## 2. Research Significant and Parameters

The present study was performed to evaluate the effect of lap splicing high tensile steel bars in reactive powder concrete beams exposed to repeated loading. Because of lack of information on the subject for this kind of concrete by both researches and code requirements, a minimum lap length equal to 20 times diameter of bar was adopted. Different parameters were studied experimentally including:

1. Two different repeated loading regimes depending on the ratio of minimum to maximum applied repeated load. The first loading regime had 0 kN minimum load was while the maximum load was that corresponding to yielding of steel bars. The second repeated loading regime was with 20% ratio (the minimum 12 kN and the maximum 60 kN).
2 .Two lengths of the lap splice ( 20 and 30 times diameter of bar 20db and 30db)
3. Two concrete covers (30mm and 40mm)
4 .Adding steel stirrups within the lap splice region.

## 3. Properties of Materials and Mix Proportion

The properties of the steel bars (as a flexural reinforcement , top reinforcement and stirrups) used in this study are shown in Table 1, while Table 2 shows the proportion of the materials used in preparing the RPC of the tested beams.

Table 1. Properties of the Steel Bars

| Nominal diameter (mm) | Actual diameter (mm) | Yield stress (MPa) | Ultimate strength (MPa) | Total elongation (%) |
|---|---|---|---|---|
| 10 | 10.03 | 769 | 887 | 10.63 |
| 12 | 11.98 | 655 | 739 | 11.0 |

Table 2. Mixed Materials Proportion Used in the Experimental Work.

| Portland Cement kg/m3 | Fine Sand kg/$m^3$ | Silica Fume kg/$m^3$ | W/B* | Super Plasticize (Glenium51) % | Steel Fibers Content % | Steel Fibers Content kg/$m^3$ |
|---|---|---|---|---|---|---|
| 900 | 990 | 225 | 0.16 | 6 | 2 | 156 |

*W/B: water to binder ratio where the binder is the mixture of cement and silica fume .

## 4. Preparation of Test Beams Specimens

Eight RPC beams were molded and tested, each with cross section (180*180) mm, 2100 mm length, reinforced with two longitudinal high strength steel bars of diameter 12 mm as main reinforcement at the bottom. The bottom bars of six beams were as follows: five beams were lap spliced at mid-span for a length equals 20 times the bar diameter, and one beam was lap spliced by length 30 times the bar diameter, while the seventh beam had no lap splice. Each beam had two steel bars of 10 mm diameter as top reinforcement. Bars of 10 mm diameter closed steel stirrups with 75mm spacing were provided outside the lap region for all beams except one beam lap splice region was also supplied with the same stirrups. All reinforcement had 30mm side, top and bottom concrete covers except one beam whose concrete cover was 40mm instead. Figure1. shows the details of the RPC beam (B-R.) while the other beams differ from this beam by only one parameters (the parameter that is under study ) as listed in Table 3.

All beams were simply supported and subjected to two symmetrical point loads to obtain a constant moment zone over 700 mm length, this allowed studying the behavior of lap splice without shear effects. For monotonic loading, this condition has been shown to represent the most serious case because both ends of splice are stressed at the same value [7]. Two types of repeated loading regimes (L-R.) were applied on the tested beams, namely;

L-R.(1): whose maximum load caused yielding of steel bars, which was found 105-115 kN and minimum load equal to 0 kN.

L-R.(2): whose maximum load 60 kN ,and minimum load equal 12 kN.

A designation system was used to identify the variable parameters as follows. The two reference beams, designated as (B-N.L.) and (B-R.) had $V_f$ =2% and clear cover 30mm and listed as beams No.1in table 3, but the beam (B-R.) having lap splice equal to 240mm, while the beam (B-N.L.) had no lap splice. The beams No.2 are contained the two RPC beams : (B-L.R.1) and (B-L.R.2) having Vf =2%, clear cover 30mm and lap splice length 240mm. The beam No.3 is the RPC beam (B-Ls30db) having $V_f$ =2% , concrete clear cover 30mm and lap splice length 360mm. The two beams No.4 are the RPC beams (B-Cov40) and (B-W.T.R.) having $V_f$ =2% , lap splice length 240mm, but the first beam had concrete cover equal 40mm, while the other had concrete cover 30mm and this is the only beam that is provided with transverse reinforcement (stirrups) within the lap splice. All beams were tested up to failure under repeated load except two reference beams No.1 which were subjected to monotonic load. Table 3 shows the details of all the tested beams.

Table 3. Details of all the tested beams.

| Beams No. | Beam Designation | Steel Fiber Ratio (%) | Transverse reinforcement within lap splice region | Lap splice length mm | Clear cover mm | Type of Loading |
|---|---|---|---|---|---|---|
| 1 | B-N.L. | 2 | nil | nil | 30 | Monotonic |
| | B-R. | 2 | Nil | 240 | 30 | Monotonic |
| 2 | B-L.R.1 | 2 | Nil | 240 | 30 | L.R.1 |
| | B-L.R.2 | 2 | Nil | 240 | 30 | L.R.2 |
| 3 | B-Ls30db | 2 | Nil | 360 | 30 | L.R.1 |
| 4 | B –Cov.40 | 2 | nil | 240 | 40 | L.R.1 |
| | B-W.T.R. | 2 | Ø10@75 mm | 240 | 30 | L.R.1 |

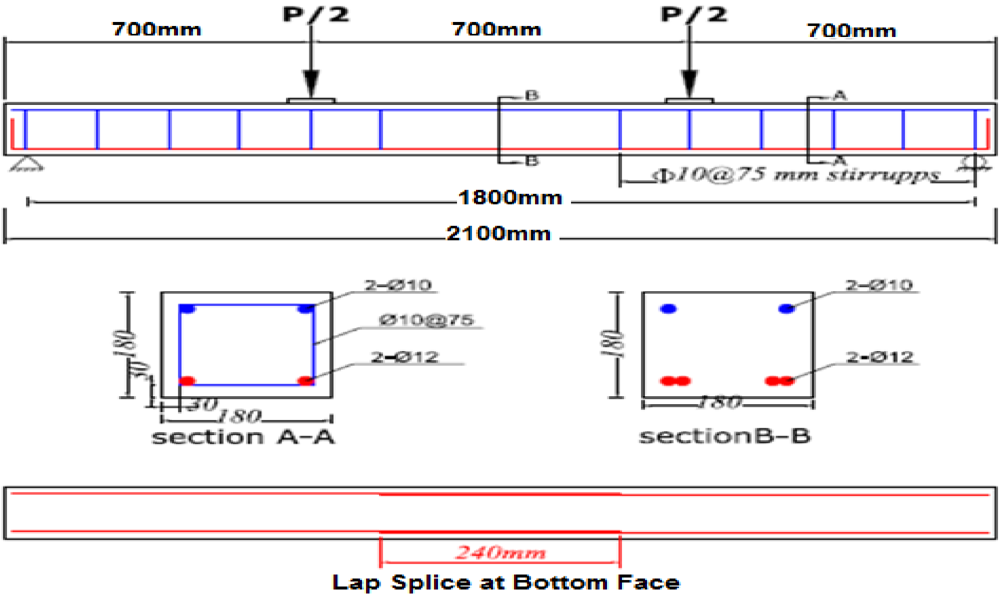

Figure 1. Geometry Details of Beam (B-R.), (all dimensions in mm)

## 5. Test setup, Loading and Results

The two reference R.P.C. beams (B-N.L.) and ( B-R.) were tested under monotonic loading while the remaining five RPC beams were tested under repeated loading system with two values of loads (maximum and minimum load) were applied throughout each cycle. Two repeated loading regimes were adopted throughout the experimental work as mentioned earlier. All loading systems were applied using ANCA machine with a capacity of 100 tons in Al-Nahrain University. The loading machine was equipped with LVDT to record the mid-span deflection at every load step.

With each beam casting, three concrete cylinders (100*200) mm were also cast as control specimens. They were cured with the beam in water and tested under uniaxial compression at the day of beam test. The average of the three cylinder tests was considered to represent the compressive strength of the beams concrete as listed in Table 4.

Table 5 lists the ductility ratio of each beam according to experimental results, which was calculated as the ratio of deflection at failure to deflection at first crack.

Table 4, Summary of Experimental Results

| Beams No. | Beam Mark | Cylinder Compressive Strength MPa | Total No. of cycles | Failure Load kN | Failure Deflection mm | Applied Max. Load kN | Loading Regime | Failure mode |
|---|---|---|---|---|---|---|---|---|
| 1 | B-N.L. | 139.2 | - | 138.8 | 24.6 | - | monotonic | Tension failure |
|  | B-R. | 129.5 | - | 136.5 | 23.9 | - | monotonic | Tension failure |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 | B-L.R.1 | 128.6 | 12 | 105.3 | 23.7 | 110 | L.R.1 | Tension failure |
| | B-L.R.2 | 138.5 | 41 | 126.1 | 16.1 | 60 | L.R.2 | Splice Failure |
| 3 | B-Ls30 | 128.4 | 38 | 111 | 30.9 | 115 | L.R.1 | Tension failure |
| 4 | B-Cov.40 | 128.1 | 34 | 103.7 | 30.7 | 105 | L.R.1 | Tension failure |
| | B-W.T.R. | 125.5 | 41 | 109.2 | 27.9 | 105 | L.R.1 | Tension failure |

Table (5) Ductility Ratio of the Tested Beams.

| Beams No. | Beam Identity | First crack deflection (mm) | Deflection at failure (mm) | Ductility Ratio |
|---|---|---|---|---|
| 1 | B-R. | 4.41 | 24.6 | 5.56 |
| | B-N.L. | 4.3 | 23.9 | 5.59 |
| 2 | B-L.R.1 | 5.3 | 23.7 | 4.47 |
| | B-L.R.2 | 4.59 | 16.1 | 3.51 |
| 3 | B-Ls30db | 4.48 | 30.88 | 6.89 |
| 4 | B-Cov40 | 5.2 | 30.7 | 5.9 |
| | B –W.T.R. | 3.9 | 27.9 | 7.15 |

## 6. Discussion of Results

### 6.1 *Flexural Response of the Beams Tested Under Monotonic Load*

The two reference beams (B-N.L.) and (B-R.) were subjected to the same loading condition. Fig.2 shows the load deflection curves of these two beams, which can be seen that they are in good agreement regardless of the presence of lap splices in beam (B-R).These two beams collapsed at close values of ultimate loads and exhibited similar ductility as indicated Tables 4 and 5. The very small difference in ultimate load may be due the difference in the compressive strength between the two beams. This difference did not affect the whole response as the two beams collapsed by bar tension failure.

As a result it can be said that the splice length within this beam was sufficient to develop the required full bond to insure tensile flexural failure of the beam and avoid slipping between the lapped bars and the concrete. The two beams reached the first peak load which was characterized by yielding of the tension steel bars and with increasing the load, flexural cracks started to form within the constant moment region of the beam. Both beams eventually collapsed by the flexural tensile failure type.

Fig.3 shows the crack pattern of these two beams which was distributed within the constant moment region with major crack appeared to be outside the lap region. The typical cracks pattern of splice failure in normal concrete strength appear as longitudinal cracks parallel to the spliced reinforcement at the splice location [8] , but this is not the case in ultra high strength concrete. In ultra high strength concrete, the bonding mechanism of the lap splices failed by few splitting cracks which were induced from the flexural cracks. When the lap splice failure was observed, rapid progress of splitting crack(s) was simultaneously occurred in the concrete within the lap splice [9]. This crack pattern as well as the decreasing in ductility with respect to ductility value of the reference beams (B-N.L. and B-R.) will be the two indicators that define the lap splice failure in the beams that were tested under repeated load(if happened) .

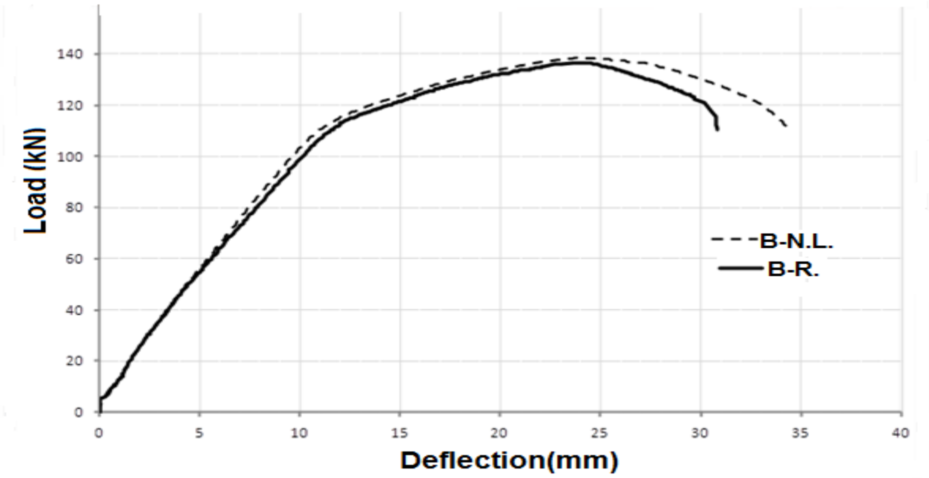

Figure 2. Load-Deflection Curves of RPC Beams (B-N.L.) and (B-R.)

Figure 3. Crack Pattern of RPC Beams: a) B-N.L. and b) B-R.

### 6.2 *Flexural Response of the Beams Tested Under Repeated Load*

The five remaining beams were subjected to repeated load. It should be mentioned that the maximum adopted number of cycles forty cycles ( according to lab time limitation ) and if the beam did not collapse within this range the beam was thereafter exposed to an increasing load (monotonic manner) until failure. As indicated in Table 4 all beams were tested under loading regime L.R.1 except beam (B-L.R.2) which was tested under repeated load L.R.2. Among these five RPC beams there were only one beams collapsed by splice failure type which was beam (B-L.R.2), while the other four beams (B-L.R.1), (B-Ls30db), (B-Cov40) and (B – W.T.R.) failed by bar tension failure.

### *6.2.1 Effect of Loading Regime and Number of Cycles*

The RPC beam (B-L.R.1) failed during the cycle number twelve at load 105.3kN (before approaching the maximum value of the repeated load which equal to110kN). At this ultimate load, the beam's mid-span deflection was 23.7mm. The RPC beam (B-L.R.2) that was exposed to the repeated loading regime L.R. 2 managed to withstand the 60 kN maximum load for forty cycles and then was forced to collapse by increasing the load on it. This beam collapsed by splice failure at load 126.1kN with corresponding mid-span deflection equal 16.1mm. It is obvious from Table 5 that this beam suffered decreasing in ductility compared with the reference beams . The small value of the maximum repeated load did not affect the carrying capacity of the beam by considerable amount, as compared with beam (B-R.) which was tested under monotonic load and did not suffer splice failure. It seems that the large numbers of repeated load cycles applied on the beam, influences lap behavior since the other RPC beam (B-L.R.1) with exactly the same properties did not collapse by splice failure. Consequently, it can be argued that the loading regime was not the cause of such splice behavior but large number of cycles was the reason behind changing the failure mode from flexural failure type to lap splice failure.

### 6.2.2. *Effect of Increasing the Lap Splice Length*

The failure of RPC beam (B-Ls30db) occurred at load value equal to (111)kN and corresponding mid-span deflection (30.88)mm within the thirty eighth cycle. This beam has larger lap splice length and tested under higher maximum repeated load value than the RPC beam (B-L.R.1) ,however both beams did not suffer lap splice failure. This comparison may lead to the fact that using, concrete cover 30mm , 2%steel fiber volumetric ratio and no stirrups within the splice region will insure the 20 bar diameter splice length is only critically sufficient to provide splice failure when the RPC beam is exposed to repeated load. A comparison with the RPC beam (B-L.R.2) which had shorter lap splice ,12mm bar diameter (and the other parameters were unchanged) achieved forty cycles but failed by lap splice mode. This mean that the lap splice needs to be strengthened in order to change the mode of failure from lap splice failure to bar tension failure if the beam exposed a large number of repeated load cycles . One of the strengthening method is to increase the lap splice length beyond 20 bar diameter. The higher ductility ratio gave indicator that this beam failed by bar tension failure.

### 6.2.3. *Effect of Increasing Concrete Cover*

The RPC beam (B-Cov40) reached the failure during the thirty fourth cycle at ultimate load equal 103.7kN and mid-span deflection 30.7mm with bar tension failure mode. A comparison with the two RPC beams (B-L.R.1) and (B-L.R.2) assures the just mentioned hypothesis. This time the RPC beam strengthened by increasing the concrete cover and this step has the same effect on the response of the RPC beam by preventing the lap splice failure. This beam exhibited high value of ductility .

### 6.2.4 *Effect of Providing Stirrups Within Lap Splice Region*

The RPC beam (B–W.T.R.) resisted the maximum number of forty cycles that was adopted throughout this study and finally was forced to collapse by increasing the load up to 109.2kN during the forty one cycle.

Again strengthening the lap splice by stirrups within the lap splice region, enabled the beam to fail by this failure for more cycles than beam (B-Cov40). The higher value of ductility is achieved by this beam. The strengthened method by providing transverse reinforcement within the lap splice region seems more efficient than increasing concrete cover.

In a previous research[3], it was observed that the presence of confining reinforcement effectively mitigates potential splitting failures and results in suitably conservative splice capacity when the high strength steel bars used in normal strength concrete.

Another previous research [9] suggests that the bonding mechanism established in the UHSC is remarkable enough to permit a short-distanced splice length but soon impaired after concrete splitting unless the concrete splitting is not delayed by the steel fibers.

Also, the bonding strength cannot be redistributed over the splice length because the splice length was short-distanced. Approximately agreement results with both references were obtained throughout this study.

Fig. 4 to Fig. 7 illustrate the load deflection curves of these beams which were tested under repeated loading. Each beam curve demonstrates the response of splice strength and its capacity to deform at ultimate load.

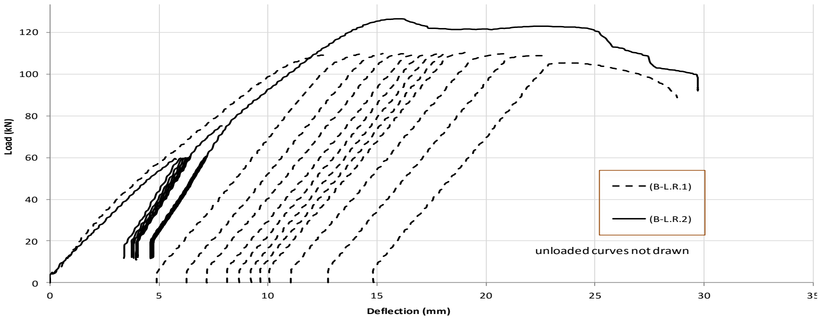

Figure 4. Load-Deflection Curves of Beams (B-L.R.1) and (B-L.R.2)

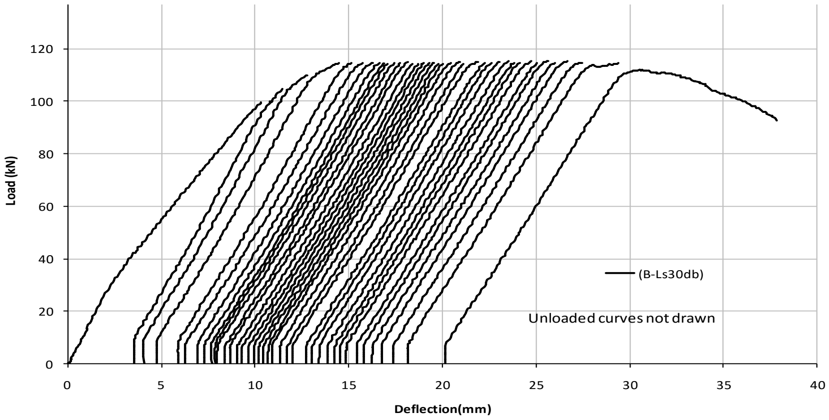

Figure 5. Load-Deflection Curves of Beam (B-Ls30db).

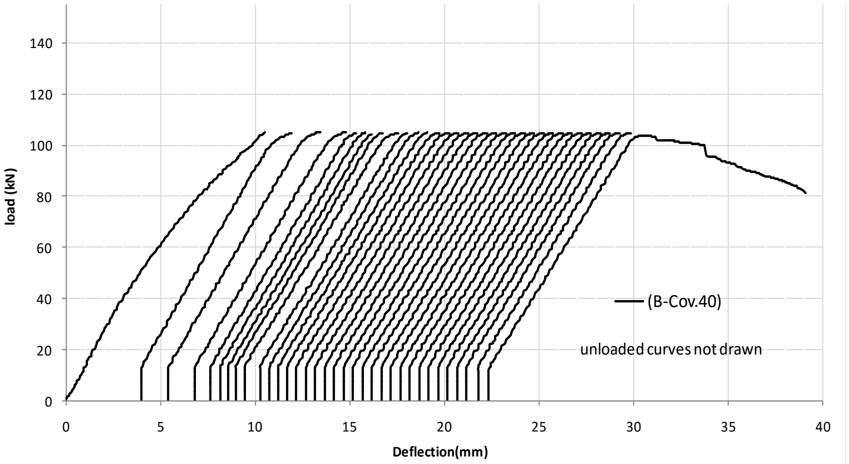

Figure 6. Load-Deflection Curves of Beam (B-Cov.40).

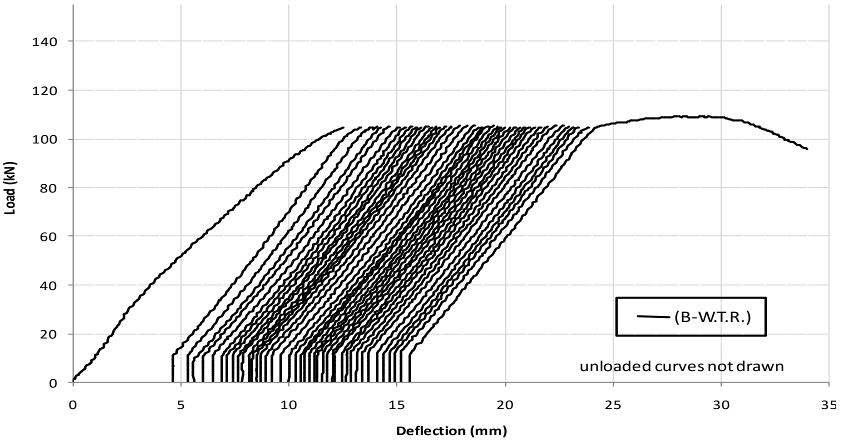

Figure 7. Load-Deflection Curves of Beam (B-W.T.R.).

The cracks patterns for the beam that failed by lap splice failure is shown in Figure 8. There are some flexural cracks within the constant moment region while The major splitting crack appeared within the lap splice region due to lap splice failure for both beams.

Fig.8, Cracks Pattern of the RPC Beam (B-L.R.2)

Fig.9 shows the crack patterns of the beams that were suffered bar tension failure. It is can be seen from this figure that the flexural cracks were distributed within the constant moment region and there was major crack occurred outside the lap splice towards the applied load location.

Figure 9. Cracks Pattern of the RPC Beams: a) B-L.R.1,
b) B-Ls030db, c) B-Cov.40 and d) B-.W.T.R.

## 7. Conclusions

Based on the results of tests on seven reactive powder concrete beams of the present research which were reinforced with high tensile steel bars lap spliced at mid-span, the following conclusions may be drawn:

1. The lap splice length of 20 bar diameter is sufficient to develop a full bond strength between the high strength steel bars and concrete in the lap spliced RPC beam when subjected to monotonic load
2. The minimum critical lap splice length of high tensile steel bars was 20 bar diameter in RPC beams when exposed to repeated load as this length causes the beam to collapse by splice failure when subjected to larger number of load cycles.
3. Increasing the lap splice length by order of 10 times bar diameter strengthened the lap splice region and preventing slippage to be occurred between high strength steel bars and reactive powder concrete under larger number of cycles of repeated load exposure. Despite of the large number of repeated load action that this beam was exposed to but it was achieve increasing in ductility ratio by 19% compared with the beam with lesser splice length and tested under monotonic load.
4. Lap splicing high tensile steel bars in RPC beams exposed to repeated loading of large number of cycles requires providing adequate confinement in the beams. A confinement by providing adequate concrete cover achieved good strengthening to the lap splice by preventing the concrete splitting within the lap splice region and increased ductility ratio by 5% even when the beam exposed to repeated load action.
5. The most efficient method to obtain higher splice capacity is to provide transverse reinforcement (stirrups) within the lap splice region. This method increased the ductility ratio by 28% even after the beam was exposed to repeated load compared with the beam which was without this reinforcement and tested under monotonic load.

## 8. References

1. Richard, P., Cheyrezy, M., (1994), "*Reactive Powder Concretes with High Ductility and 200-800 MPa Compressive Strength"* Concrete Technology: Past, Present, and Future, Proceedings of the V. Mohan Malhotra Symposium, ACI SP144-24, pp.507-518.
2. Sun, M., Gao, R., Li, A., and Wang, Y., (2016), *" Bond of Reinforcement in Reactive Powder Concrete: Experimental Study",* VII European Congress on Computational Methods in Applied Sciences and Engineering, M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.), Crete Island, Greece, 5–10 June.
3. Shahrooz B. M., Miller R. A., Harries K. A. and Russell H. G., (2011). NCHRP Report 679, " *Design of Concrete Structures Using High -Strength Steel Reinforcement*", NCHRP Report 679, Transportation Research Board, pp. 3-4.
4. Deng Zong -Cai, D., Daud, J.R., and Yuan Chang-Xing, (2013) "Bonding between high strength rebar and reactive powder concrete", The World Congress

on Advanced in Structural Engineering and Mechanism, pp.489-504, Korea, September 8-12.

5. El-Hacha, R., El-Agroudy, H., and Rizkalla, S., (2006), “Bond Characteristics of High-Strength Steel Reinforcement,” ACI Structural Journal, Vol. 103, No. 6, Nov-Dec, pp 771–782.
6. Seliem, H.M., Hosny, A., Rizkalla, S., Zia, P., Briggs, M., Miller, S., Darwin, D., Browning, J., Glass, G.M., Hoyt, K., Donnelly, K., and Jirsa, J.O., (2009), “*Bond Characteristics of ASTM A1035 Steel Reinforcing Bars,” ACI Structural Journal*", Vol. 106, No. 4, pp 530–539.
7. Ferguson, P.M. and Briceno, A., (1969), *"Tensile Lap Splices, Part 1: Retaining Wall Type, Varying Moment Zone"*, Research Report No.113-2, Center For High Way Research, the University of Texas at Austen, July.
8. Rezansoff T,1978" *Performance of lapped splices in reinforced concrete loaded beyond yielding of the steel*", Canadian Journal of Civil Engineering, Vol.5, pp.489-496.
9. Lee J, , (2015)" Bonding Behavior of Lap-spliced Reinforcing Bars Embedded in Ultra-High Strength Concrete with Steel Fibers", KSCE Journal of Civil Engineering , PP.9, DOI: 10.1007/12205-015-1396-7.