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Received on: 04/08/2016
Accepted on: 29/12/2016

# Experimental Research on Tension Lap Splice in Reactive Powder Concrete Beams Exposed to Repeated Loading

***Abstract:*** *This research is a part of an experimental study to examine the effect of lap splicing tension steel bars reactive powder concrete (RPC) beams under repeated loads. Eight RPCbeams whose tension steel bars were spliced at mid-span for a length equals 20 times the bar diameter 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 repeated loads. The studied parameters were: the steel fiber volumetric ratio (1.5%,1.75% and2%), diameter of tension steel bars (12mm, 16mm and 20mm) and the repeated loading regime in which three types of loading were used depending on the minimum to maximum ratio of the applied load. The first loading regime with ratio of 0% with 0 kN for the minimum load while the maximum was the load beyond that causes yielding of steel bars and this is determined from the previous monotonic load test. The second type with 27% ratio (30 kN for the minimum and 105-110 kN for the maximum). The last type was with 20% ratio (the minimum12 kN and the maximum 60 kN).It should be mentioned that 10mm bar diameter was used to the top reinforcement and stirrups for all beams. The mid-span deflection as well as cracks propagation were recorded for each beam throughout the test. The main results showed that the adopted spliced length of tension steel bars was sufficient in monotonic load but insufficient under the action of high number of cycles of the repeated load. In addition, there were beams of splice failure that having low steel fiber ratio or larger diameter of tension steel bars.*

***Keywords:*** *lap Splice, Reactive Powder Concrete, Steel Fibers, Repeated Loading.*

How to cite this article: H.M. AlHassani, Q.A-M. Hassan and F.F. Saleem, "Experimental Research on Tension Lap Splice in Reactive Powder Concrete Beams Exposed to Repeated Loading," *Engineering and Technology Journal*, Vol. 5, Part A, No. 5, pp. 479-484, 2017.

## 1. Introduction

Reactive powder concrete (RPC) represents one of the newest generation of concrete which is produced to give cube compressive strengths reaching 800 MPa, tensile strength up to 150MPa and unit weight up to 3000kg/m$^3$. This concrete type often produced without coarse aggregate by using cement, silica fume, very fine sand (as aggregate), very low water cement ratio, super plasticizer with high tensile strength steel fibers [1,2]. The advantageous of adding steel fibers in RPC, are the high strength, good ductility and durability [3].

1. In spite of these advantages with 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 [4]. This leads to important development of sufficient bond capacity between the bars and matrix, which affect the structural behavior of the RPC members**.** Experimental works to examine the bond of steel bars embedded in RPC by performing pullout test are available in such as work done by Zong et al and Sun et al [4,5]. The present research program was undertaken to provide information about the effect of tensile reinforcement lap splice on the behavior of reinforcement reactive powder concrete beams subjected 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 20db was adopted. This minimum value was expected to be non-adequate to lap splice of steel bar (with minimum diameter 12mm) tested under monotonic load and repeated loads. So with this expectation, different parameters were studied experimentally, which may weaken the lap splice, these are:

1. Decreasing the steel fiber volumetric ratio
2. Increasing the bar diameter and
3. Applying different repeated loading regimes

## 2. 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 mixed materials proportion of RPC beams specimens.

https://doi.org/10.30684/etj.35.5A.7
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**Table 1: Properties of the steel bars**

| | | | | |
|---|---|---|---|---|
| Nominal diameter (mm) | 10 | 12 | 16 | 20 |
| Actual diameter (mm) | 10.03 | 11.98 | 15.88 | 20.07 |
| Yield strength (MPa) | 769 | 655 | 491 | 591 |
| Ultimate strength (MPa) | 887 | 739 | 759 | 731 |
| Total elongation (%) | 10.63 | 11.0 | 10.7 | 10.93 |
| Grade of steel according to ASTM A615M−16 | 80 | 80 | 60 | 80 |

**Table 2: Mixed materials proportion used in the experimental work**

| | | | |
|---|---|---|---|
| Cement kg/m$^3$ | 900 | 900 | 900 |
| Sand kg/m$^3$ | 990 | 990 | 990 |
| Silica fume kg/m$^3$ | 225 | 225 | 225 |
| W/B* | 0.16 | 0.16 | 0.16 |
| Glenium 51% | 6 | 6 | 6 |
| Steel fibers volumetric ratio | 2 | 1.75 | 1.5 |
| Steel fibers content kg/m$^3$ | 156 | 136.5 | 117 |

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

## 3. Preparation of Test Beams Specimens

Nine RPC beams were molded and tested, each with cross section (180*180) mm, 2100 mm length, reinforced with two longitudinal bars (of diameter 12mm,or 16mm or 20mm) as main reinforcement at the bottom which were lap spliced at mid-span for a length equals 20 times the bar diameter, and two 10 mm diameter steel bars as top reinforcement. Bars of 10 mm diameter closed stirrups @ 75mm spacing were provided outside the lap region for all beams. All reinforcement had 30mm side, top and bottom clear covers as shown in Figure 1.

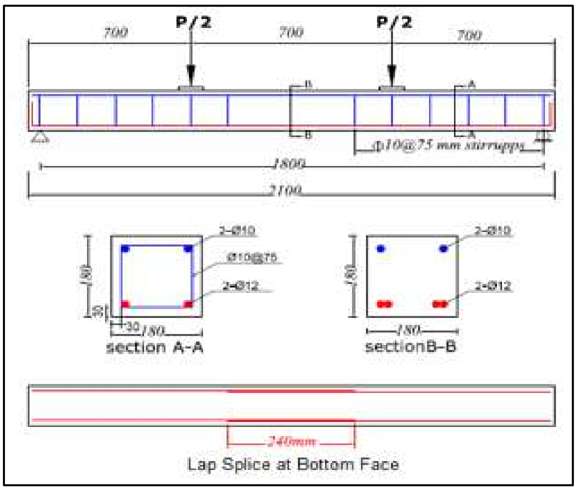

**Figure 1: Geometry details of (B-R.) beam**

All beams loads were simply supported and subjected to two symmetrical point loads to obtain a constant moment zone over 700mm length to study the behavior of lapped splices 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 [6]. The equation that presented by Al-Hassanyet al [7] was used to predict the nominal flexural strength of beam (B-N.L.), which is found to be 38.6 kN.m, and consequently the maximum load carrying capacity of the beam is 140.5 kN.

Three types of repeated loading regimes (L-R.) were applied on the tested beams, namely; L-R.1: This type of loading regime was adopted by Rezans of [8] in which the minimum load was 0 kN while the maximum load was chosen to be beyond the load causes yielding of steel bars and this load was set to be increased in the next cycles. In the present study the load which causes yielding was found to be 105-110 kN for beams with bar diameter 12mm(from the previous test of beam (B-R.), while the minimum load was set to be zero kN. The load causes yielding in beams that contain bars with diameter 16mm or 20mm was determined from the steel strain gauges readings, which were, installed on bars at the lap splice end locations before the beam was casted. It should be mentioned that readings of strain gauges was recorded at every 5kN load step, and the relationship of modulus of elasticity with stress and strain was used in determining the load that causes yielding as shown below:

$$E = \sigma / \varepsilon \qquad (1)$$

The yield strain will be determined using Eq.1 and Table 1 (which listed the yield stress of each bar) with E=200000MPa. When the yield strain was read from the data logger, the load corresponding to this strain was chosen as the maximum load applied according to this loading regime type. These values was found to be 110kN and 190kN for bars with diameter 16mm and 20mm respectively. However, this value of maximum load can be increased in the next cycles since the principle of the maximum load is beyond yielding and because of the limited time allowed for the test.

L-R.(2): In which the minimum to maximum load ratio was 30%.This loading regime was chosen the maximum load to be the same maximum load that was adopted in the first regime while the minimum load equal to 30kN. The maximum load was increased in the next cycles to achieve moderate number of cycles less than the maximum number, which was adopted to be 40 cycles.

L-R.(3): The minimum to maximum load ratio is 20% according to this loading system, where the maximum load equal to 60 kN ,and minimum load equal 12 kN.

It should be mentioned that the maximum number of cycles (40 cycles)was according to lab time and if the beam did not collapse within this range the beam was thereafter exposed to an increasing load (monotonic manner) until failure. The test specimens had different steel fibers volumetric ratio ($V_f$), different diameter ($d_b$) of the bars spliced, and subjected to different repeated loading regimes (L-R.). A designation system was used to identify the variable parameters as follows. The two reference beams, designated as (B-R.) and (B-N.L.) had $V_f$ =2% and $d_b$=12mm and listed as group G0 in Table 3, but the other beam (B-N.L.) had no lap splice. The second group G1 contained the three RPC beams: (B-L.R.1), (B-L.R.2) and (B-L.R.3) having $V_f$ =2% and $d_b$=12mm, lap splice length 240mm. The third group G2 contained the two beams (B-Vf1.5) and (B-Vf1.75) having $V_f$ variable as indicated, $d_b$=12mmand splice length 240mm. The forth group G3 contained the RPC beams (B-db16) and (B-db20) having $V_f$ =2% and db variable as indicated. All beams were tested up to failure. Table 3 gathers the details of the tested beams.

## 4. Test setup, loading and Results

The two reference RPC beams (B-N.L.) and (B-R.) were tested under monotonic loading while the remaining seven RPC beams were tested under repeated loading system where two values of loads (maximum and minimum load) were applied throughout each cycle. Three 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 day of beam test. The average of the three cylinder tests was considered to represent the compressive strength of the beams concrete. Table 4 gives a summary of the experimental results.

**Table 3: Details of all the tested RPC beams**

| Group No. | Beam designation | Flexural steel reinf. | Lap splice length mm | Steel fibers volumetric ratio, Vf | Clear cover mm | Type of loading |
|---|---|---|---|---|---|---|
| G0 | B-N.L. | 2-Ø12 | - | 2% | 30 | Monotonic |
| | B-R. | 2-Ø12 | 240 | 2% | 30 | Monotonic |
| G1 | B-L.R.1 | 2-Ø12 | 240mm | 2% | 30 | L.R.1 |
| | B-L.R.2 | 2-Ø12 | 240mm | 2% | 30 | L.R.2 |
| | B-L.R.3 | 2-Ø12 | 240mm | 2% | 30 | L.R.3 |
| G2 | B -Vf1.5 | 2-Ø12 | 240mm | 1.5% | 30 | L.R.1 |
| | B-Vf1.75 | 2-Ø12 | 240mm | 1.75% | 30 | L.R.2 |
| G3 | B-db16 | 2-Ø16 | 320mm | 2% | 30 | L.R.1 |
| | B-db20 | 2-Ø20 | 400mm | 2% | 30 | L.R.1 |

**Table 4: Summary of experimental results**

| Group No. | Beam identity | Total No. of cycles | Ultimate load kN | Failure deflection mm | Cylinder compressive strength MPa | Loading regime | Failure mode |
|---|---|---|---|---|---|---|---|
| G0 | B-N.L. | - | 138.8 | 24.6 | 139.2 | - | Tension failure |
| | B-R. | - | 136.5 | 23.9 | 129.5 | - | Tension failure |
| G1 | B-L.R.1 | 12 | 105.3 | 23.7 | 128.6 | 1 | Tension failure |
| | B-L.R.2 | 26 | 122.8 | 19.5 | 129.6 | 2 | Tension failure |
| | B-L.R.3 | 41 | 126.1 | 16.1 | 138.5 | 3 | Splice failure |
| G2 | B -Vf1.5 | 14 | 100.3 | 23.7 | 118.4 | 1 | Splice failure |
| | B-Vf1.75 | 18 | 102.3 | 18.4 | 125.6 | 2 | Splice failure |
| G3 | B-db16 | 41 | 161.8 | 29.2 | 135.2 | 1 | Splice failure |
| | B-db20 | 17 | 232.9 | 31 | 130.3 | 1 | Splice failure |

## 5. Discussion of Results

*I. Flexural Response of the beams tested under monotonic load*

Figure 2 shows the load deflection curves of the two reference beams (B-N.L.) and (B-R.). It can be seen from this figure that these two beams reached the same ultimate load capacity strength despite presence of lap splice in the second beam. The only explanation of this response is that the spliced 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.

Figure 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.

*II. Flexural response of the beams tested under repeated load*

The seven remaining beams were subjected to repeated load. As indicated in Table 4 there were four beams tested under loading regime type 1, three of them collapsed by splice failure which were (B-Vf1.5), (B-db16) and (B-db20) and the only one that failed by tensile failure was (B-L.R.1). The beam with lower steel fiber ratio (B-Vf1.5) failed after fourteen load cycles with maximum repeated load less than that of beam (B-L.R.1) which has higher steel fiber ratio. The beams with higher strength due to increasing their flexural reinforcement (B-db16) and (B-db20) achieved greater number of load cycles with higher maximum load applied compared to (B-L.R.1) beam. The beam (B-db16) was forced to collapse after passing the maximum number of cycles (40 cycles) by increasing load until the failure occurred.

The two beams that were tested under repeated loading regime type two were beams (B-L.R.2) and (B-Vf1.75). The first one did not exhibit lap splice failure while the second beam did. Noticing that the only difference between the two beams is the ratio of steel fiber. That difference made beam (B- Vf1.75) to resist lesser number of load cycles than beam (B-L.R.2). It should be mentioned that beam(B-Vf1.75) was forced to collapse by increasing the load after achieving 26 cycles as a result of the limited time at the day of the test.

The last RPC beam (B-L.R.3) that was exposed to the repeated loading regime type 3 managed to withstand the 60 kN maximum load for forty cycles (the adopted maximum number of cycles) and then was forced to collapse by increasing the load on it. It seems that the large numbers of cycles influences lap behavior since the other two beams (B-L.R.1) and (B-L.R.2) with exactly the same properties did not collapse by splice failure. Figures 4 to 10 illustrate the load deflection curves of all RPC beams that were tested under repeated load.

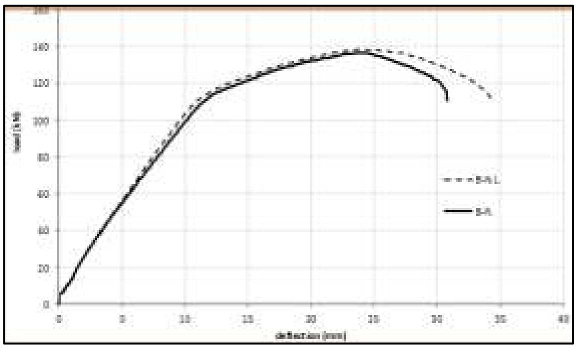

**Figure 2: Load-deflection curves of (B-N.L.) and (B-R.) beams**

**Figure 3: Crack pattern of (B-N.L.) and (B-R.) beams**

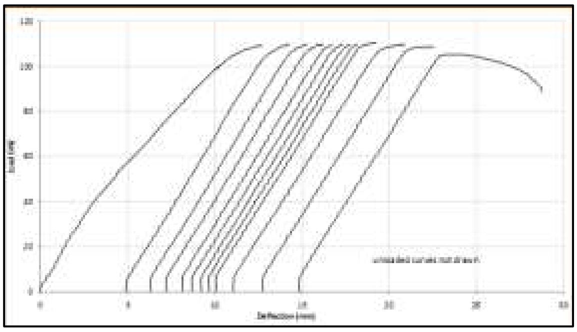

**Figure 4: Load-deflection curve of RPC beam (B-L.R.1)**

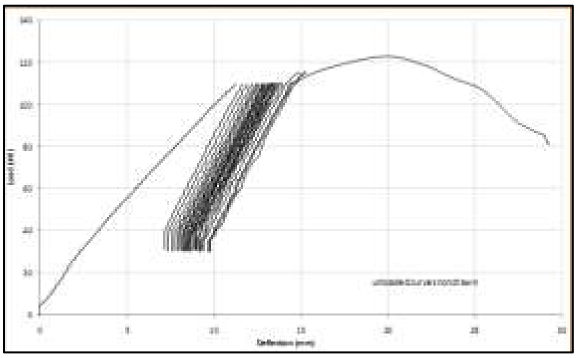

**Figure 5: Load-deflection curve of RPC beam (B-L.R.2)**

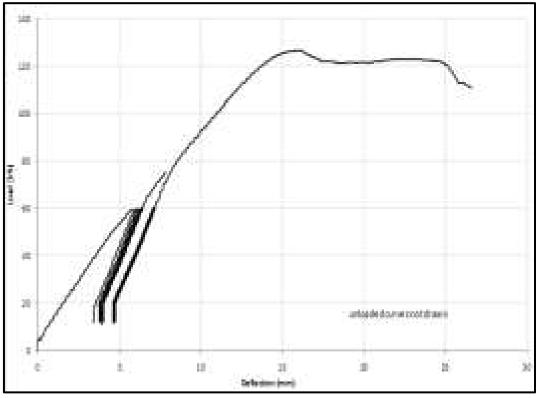

**Figure 6: Load-deflection curves of RPC beam (B-L.R.3)**

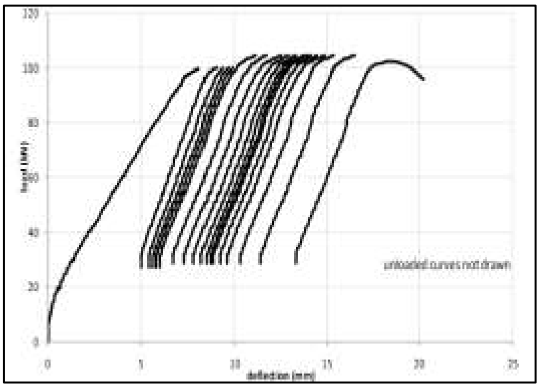

**Figure 7: Load-deflection curves of RPC beam (B-Vf1.75)**

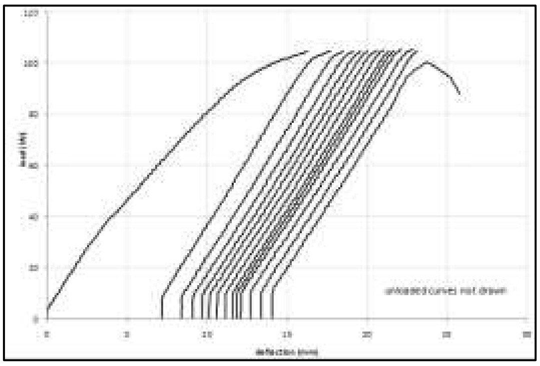

**Figure 8: Load-deflection curves of RPC beam (B-Vf1. 5)**

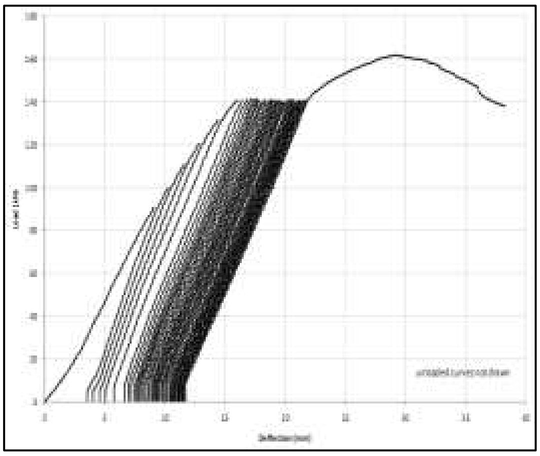

**Figure 9: Load-deflection curves of RPC beam (B-db16)**

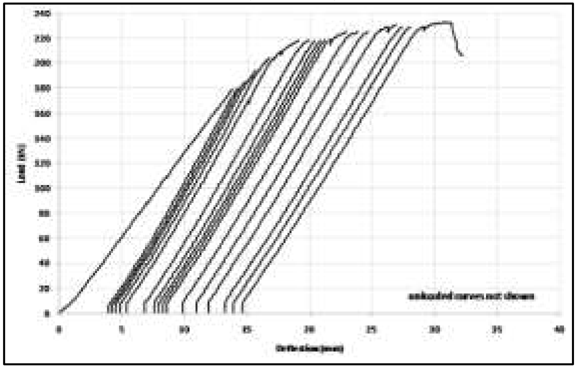

**Figure 10: Load-deflection curves of RPC beam (B-db20)**

Only two beams (B-L.R.1) and (B-L.R.2) failed by bar tensile failure type because the spliced bars- concrete bond was strong and bar slipping was prevented due to the high ratio of steel fibers used and the relatively small number of cycles that were exposed to. The lesser number of repeated load cycles on these two beams as compared with those on beam (B-L.R.3) made the failure mode to be tensile failure rather than splice failure. The cracks patterns of these two beams are shown in Figure.11, and as it is obvious that the major crack lies outside the lap splice region and there are few flexural cracks distributed within the constant moment region.

According to Lee(9)the lap splices failure in ultra-high strength concrete is observed by few splitting cracks which were induced from the flexural cracks and this splitting crack(s) was occurred in the concrete within the lap splice region, as shown in Figure 12.

**Figure 11: Crack patterns of RPC beams that suffered flexural failure**

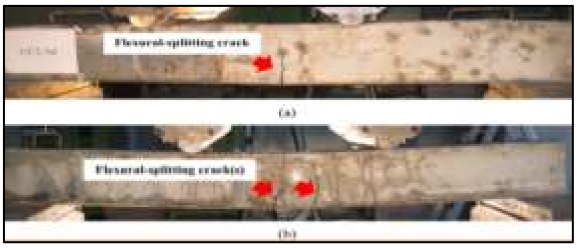

**Figure.12, Propagation of flexural cracks at a splice failure according to Lee [9]. (a) UHSC beam with lap splice length of 70 mm (5 db), (b) UHSC beam with lap splice length of 130 mm (10 db)**

Figure 13 shows the crack patterns of the RPC beams that were suffered splice failure. The same cracks distribution were observed in each of the beams (B-L.R.3), (B-Vf1. 5%), (B-Vf1. 75%), (B-db16) and (B-db20) which all suffered lap splice failure. There were some cracks distributed within the constant moment region with one major crack forming within the lap splice region. The lap splice failure was resulted after the formation and progressing of some splitting cracks in the concrete within the lap splice region. It was noticed that the maximum progress of splitting crack was shown in the RPC beam (B-Vf 1.5%) with a rapid crack and widely opened due to a high brittleness of this beam, which has steel fiber volumetric ratio equal to 1.5% only.

## 6. Conclusions

Based on the tests results the following conclusions may be drawn:

1- The adopted lap splice length of 20 times bar diameter is found sufficient to allow RPC beam to behave flexural similar to an identical non-spliced beam when both beams are exposed to monotonic loading. This means that this length of lap splice is sufficient to develop a full bond between the steel bars and concrete in the lap splice zone of such beams.

2 – This lap splice length of 20 times bar diameter has been found as a critical length in RPC beams exposed to repeated loading, as this length may cause the beam to collapse by splice failure when subjected to a specific type of repeated loading regime with large number of load cycles.

3- This splice length (20db) has also been found insufficient to develop the full bond between the steel bars and the RPC when less steel fiber volumetric ratio is used in RPC beams exposed to repeated loading even with small number of load cycles.

4- Using larger diameter tension steel bars with splice length 20db changes the failure mode repeatedly loaded RPC beams from tensile failure type to lap splice failure.

**Figure 13: Crack patterns of RPC beams that suffered lap splice failure**

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