SIZE EFFECT ON SHEAR STRENGTH OF GFRP-RC CONTINUOUS BEAMS WITHOUT STIRRUPS

Karam Mahmoud¹ and Ehab El-Salakawy²

¹ Ph.D. Candidate, Dept. of Civil Eng., University of Manitoba, Winnipeg, MB, Canada
E-mail: karam_mahmoud83@yahoo.com

² Professor and Canada Research Chair in Durability and Modernization of Civil Structures, Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada R3T 5V6,
Phone: (204) 474-8319, Fax: (204) 474-7513
E-mail: ehab.el-salakawy@umanitoba.ca

KEYWORDS: Size effect, Shear strength, Continuous beams, Moment redistribution, GFRP bars.

ABSTRACT

The use of the non-corrodible fiber reinforced polymer (FRP) bars as main reinforcement for concrete structures to overcome the steel corrosion problem is exponentially increasing. The relatively low modulus of elasticity of FRP bars caused the size effect on shear strength to be more pronounced than that in steel-reinforced concrete (RC) beams. Also, this effect was more significant in beams with small longitudinal reinforcement ratios. Currently, there is no research data related to the size effect on shear strength in GFRP-RC indeterminate structures. As such, this study aims to evaluate the size effect on the shear strength of continuous beams without stirrups. The experimental results of six large-scale continuous GFRP-RC beams are presented in this paper. The test beams had a rectangular cross section of 200 mm width and a depth ranged from 250 to 750 mm. The beams were continuously supported over two equal spans of 2,800, 3,750 and 5,250 mm for beams with an effective depth of 250, 500 and 750 mm, respectively. The longitudinal reinforcement ratio was 0.8% in three beams and 1.2% in the other three beams. The test results showed that significant size effect was observed with increasing the effective depth in beams failed in the exterior shear span. The opposite was observed in beams failed in the interior shear span where the shear strength increased when the depth increased.

1 INTRODUCTION

The size effect on shear strength of steel-reinforced concrete (RC) beams has been always a major concern. It was reported that the shear stress at failure decreased as the member depth increased (Kani 1967; Shioya et al. 1989; Collins and Kuchma 1999; Bentz 2005). This effect is more sever in the case of large members made of high strength concrete (HSC) beams (Collins and Kuchma 1999). Similarly, size effect was observed in FRP-RC simply-supported beams tested recently; however, the size effect was more pronounced when GFRP bars were used as longitudinal reinforcement for both normal (NSC) and high (HSC) strength concrete (Alam and Hussein 2012 and 2013; Matta et al. 2013). Also, Bentz et al. (2010) concluded that the same size and strain effects on the shear strength in steel-RC beams were observed in FRP-RC beams.

The shear behaviour of continuous beams reinforced with steel bars has been widely investigated. It was found that because of the established moment and shear redistribution in such members, the diagonal tension cracking analysis used in simple beams can be applied to continuous beams (Ernst1958; Rodrigues et al. 1959). Moreover, the size effect on steel-RC continuous beams was investigated by Collins and Kuchma (1999). It was reported that the shear stress at failure decreased with increasing the member size. Also, the decrease in the shear strength of beams made of HSC was slightly greater than that in NSC beams.

On the other hand, for FRP-RC continuous beams, research has shown that moment redistribution does occur in such members (El-Mogy et al. 2010; Kara and Ashour 2013). Following this effort, an
extensive research program has started at the University of Manitoba to study the shear behavior of GFRP-RC continuous beams (Mahmoud and El-Salakawy 2014). This paper represents, up to the authors’ knowledge, the first attempt to understand the size effect on the shear strength of GFRP-RC continuous beams and to examine whether the current design equations can predict safely the shear strength of such beams.

2 EXPERIMENTAL PROGRAM

Six large-scale, two-span continuous NSC beams reinforced with GFRP bars were tested to failure. None of the specimens had transverse reinforcement. The variables were the effective depth of the beam and longitudinal reinforcement ratio (0.8% and 1.2%). The test beams had a rectangular cross section of 200 mm width and three different effective depths of 250, 500 and 750 mm. The longitudinal reinforcement was arranged to satisfy an assumed 20% moment redistribution from the hogging to the sagging regions. The specimen designation can be explained as follows. The letter “G” refers to GFRP bars as reinforcing materials while “N” refers to the concrete grade, NSC. The number is for the longitudinal reinforcement ratio and the last letter refers to the size of the beam where “S, M and L” are for beams with 250, 500 and 750-mm depth, respectively. Details of the test specimens are shown in Fig. 1 and Table 1.

2.1 Test Setup and Instrumentations

All test beams were supported on two roller supports at both ends and one hinged support at the middle. The beams were tested under a two-point loading system in each span. A load-controlled rate of 10 kN/min was used to apply equal loads to the two spans. The loading was occasionally paused for visual inspection of the beam and marking the cracks. Two load cells were used to measure the reactions at the two exterior supports. Moreover, deflection was measured, using linear variable displacement transducers (LVDTs), at three different locations in each span, at mid-span and at each loading point in the span. The strains in both longitudinal reinforcement and concrete were measured at three critical sections, over the middle support and under the exterior load in each span. Readings of all instrumentation and load cells were collected using a data acquisition system and stored on a personal computer. Details of instrumentations are shown in Figs. 1 and 2.
Table 1 – Concrete Strength and Reinforcement Details of Test Specimens

<table>
<thead>
<tr>
<th>BEAM</th>
<th>( f_c' ) (MPa)</th>
<th>Longitudinal reinforcement at top and bottom</th>
<th>Details of reinforcement</th>
<th>Reinforcement rigidity, ( E_{\rho_r} ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN-0.8-S</td>
<td>39</td>
<td>0.79</td>
<td>2 No.16</td>
<td>536</td>
</tr>
<tr>
<td>GN-0.8-M</td>
<td>39</td>
<td>0.79</td>
<td>4 No.16</td>
<td>536</td>
</tr>
<tr>
<td>GN-0.8-L</td>
<td>39</td>
<td>0.76</td>
<td>4 No.19</td>
<td>496</td>
</tr>
<tr>
<td>GN-1.2-S</td>
<td>39</td>
<td>1.18</td>
<td>3 No.16</td>
<td>799</td>
</tr>
<tr>
<td>GN-1.2-M</td>
<td>44</td>
<td>1.18</td>
<td>6 No.16</td>
<td>799</td>
</tr>
<tr>
<td>GN-1.2-L</td>
<td>39</td>
<td>1.14</td>
<td>6 No.19</td>
<td>744</td>
</tr>
</tbody>
</table>

Figure 2: Test Setup and External Instrumentations of Test Beams

2.2 Test Setup and Instrumentations

All beams were cast from a ready-mixed concrete with a target 28-day concrete strength of 35 MPa. The average concrete strength for different beams, obtained on the day of beam testing, is listed in Table 1. Sand-coated GFRP bars were used as longitudinal reinforcement. The properties of the used bars are given in Table 2.

Table 2 – Properties of GFRP bars

<table>
<thead>
<tr>
<th>Bar size</th>
<th>Nominal Area (mm²)</th>
<th>Tensile strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Ultimate strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.16</td>
<td>197.8</td>
<td>1440</td>
<td>67.7</td>
<td>2.1</td>
</tr>
<tr>
<td>No.19</td>
<td>285.0</td>
<td>1480</td>
<td>65.3</td>
<td>2.3</td>
</tr>
</tbody>
</table>

3 TEST RESULTS AND DISCUSSION

3.1 Mode of Failure and Cracking Pattern

All test beams failed in shear due to a diagonal tension crack formed whether in the interior shear span, in the exterior shear span or simultaneously in both shear spans. Beams GN-1.2-S and GN-0.8-M failed in the interior shear span. On the other hand, beam GN-1.2-L failed in the exterior shear span. The failure of beam GN-0.8-S, GN-1.2-M and GN-0.8-L was due to two diagonal tension cracks, one in the interior shear span while the other one in the exterior shear span. In beams GN-0.8-S and GN-1.2-S, the majority of cracks were vertical flexural cracks concentrated in the maximum moment regions (over the middle support and under the exterior loading points). Also, there were few diagonal cracks formed near failure of the beams. Similar cracking pattern was observed in medium and large size beams (GN-0.8-M, GN-1.2-M, GN-0.8-L and GN-1.2-L); however, flexural cracks formed near the interior loading point and diagonal cracks were observed in the interior shear spans. Also, as the effective depth increases, secondary flexural cracks were formed in both the hogging and sagging moment regions. Furthermore, with increasing the effective depth, the cracking pattern became similar...
to that of a simply-supported beam where more flexural and diagonal cracks were observed near the interior loading point.

### 3.2 Mid-Span Deflection

Figure 3 shows the load-deflection relationship at mid-span of all test beams. Generally, the typical load-deflection curve can be divided, similar to GFRP-RC simply-supported beams, into two distinct stages, pre-cracking and post-cracking. In the pre-cracking stage, the measured deflection was insignificant in all beams; however, the deflection increased after the formation of the first flexural crack in the beam. It can be seen that the size of the beam did not affect significantly the slope of the load-deflection relationship in the post-cracking stage which was very similar for beams having approximately the same longitudinal reinforcement ratio, until failure. Also, as expected, increasing the longitudinal reinforcement ratio/rigidity increased the post-cracking flexural stiffness.

![Figure 3: Load-Deflection Relationship at Mid-Span of Test Beams](image)

### 3.3 Reactions and Moment Redistribution

In beams having a 250 or 500-mm depth, the exterior reaction followed the elastic distribution until cracking. After the formation of flexural cracks at the middle support region, the measured reactions had higher values than those obtained by the elastic theory. This trend continued until failure of the beam, as can be seen in Fig. 4, resulting in normal redistribution of bending moment from hogging to sagging moment regions. The percentage of moment redistribution at failure in beams GN-0.8-S, GN-0.8-M, GN-1.2-S and GN-1.2-M, from hogging to sagging moment regions, was approximately 31, 6.6, 29.4 and 8.1%, respectively. The opposite behavior was observed after cracking of the large size beams where the exterior reactions were of smaller values than those calculated by the elastic theory, all the way up to failure, resulting in reversed moment redistribution from sagging to hogging moment regions. The percentage of moment redistribution at failure was reversed to -7.0% and -9.0% in beams GN-0.8-L and GN-1.2-L, respectively. The reversed moment redistribution in these beams can be attributed to the extensive flexural cracking in the sagging moment regions while no more cracks formed in the hogging moment region in these beams (GH-0.8-L and GH-1.2-L).

It can be noted that increasing the beam depth changed the magnitude and direction of moment redistribution. The moment redistribution reached 31% in beam GN-0.8-S, decreased slightly to 6.6% in beam GN-0.8-M, and then decreased to -7.0% in beam GN-0.8-L. Similarly, the moment redistribution was 29.4%, 8.1% and -9.0% in beams GN-1.2-S, GN-1.2-M and GN-1.2-L, respectively. As discussed above, this could be attributed to the wider and additional cracks developed in the sagging moment regions compared to those in the hogging moment region. This resulted in a relatively weaker sagging moment region which caused the internal forces redirected to the relatively stronger zone (the hogging moment zone).
3.4 Shear Strength

The experimental shear stress and normalized shear stress at failure in both interior and exterior shear spans are listed in Table 3. Beams failed in the interior shear span exhibited adverse size effect where the shear strength increased as the effective depth increased. In beams with longitudinal reinforcement ratio of 0.8%, the shear strength increased by 20% (from 1.1 to 1.32 MPa) and 10% (from 1.32 to 1.45 MPa) when the effective depth increased from 250 to 500 mm and from 500 to 750 mm, respectively. Also, in beams with a higher longitudinal reinforcement ratio (1.2%), increasing the shear strength from 250 to 500 mm resulted in an increase in the shear strength by 16% (from 1.57 to 1.82 MPa). On the other hand, the shear strength of beams failed in the exterior shear span was strongly affected by the size of the beam. In beams GN-0.8-S and GN-0.8-L, the shear strength in the exterior shear span decreased by 13% (from 0.71 to 0.62 MPa) when the depth increased from 250 to 750 mm. This ratio was 27% (form 0.91 to 0.66 MPa) when the depth increased from 500 mm in GN-1.2-M to 750 mm in beam GN-1.2-L.

Table 3: Summary of Test Results

<table>
<thead>
<tr>
<th>Beam</th>
<th>( V_{\text{test}} ) (MPa)</th>
<th>( \frac{V_{\text{test}}}{\sqrt{f_{c}b_{s}d}} ) (MPa)</th>
<th>Failure location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Int.</td>
<td>Ext.</td>
<td>Int.</td>
<td>Ext.</td>
</tr>
<tr>
<td>GN-0.8-S</td>
<td>1.10</td>
<td>0.71</td>
<td>0.176</td>
</tr>
<tr>
<td>GN-0.8-M</td>
<td>1.32</td>
<td>0.64</td>
<td>0.211</td>
</tr>
<tr>
<td>GN-0.8-L</td>
<td>1.45</td>
<td>0.62</td>
<td>0.232</td>
</tr>
<tr>
<td>GN-1.2-S</td>
<td>1.57</td>
<td>1.03</td>
<td>0.251</td>
</tr>
<tr>
<td>GN-1.2-M</td>
<td>1.82</td>
<td>0.91</td>
<td>0.274</td>
</tr>
<tr>
<td>GN-1.2-L</td>
<td>1.55</td>
<td>0.66</td>
<td>0.248</td>
</tr>
</tbody>
</table>

To investigate the continuity effect on the different size beams, test results were compared to simply-supported GFRP-RC beams reported in literature. Matta et al. (2013) tested beams having depths of 292 and 883 mm. It was reported that the shear strength, in beams having 0.59% longitudinal reinforcement ratio, reduced by 30% when the depth increased from 292 to 883 mm. Also, Alam and Hussien (2012 & 2013) reported similar decrease in the shear strength (20%) when the depth increased from 291 to 578 mm in NSC beams with a reinforcement ratio ranging from 0.86 to 0.91%. Higher reduction in the shear strength (38%) occurred when the depth increased from 305 to 734 mm in HSC beams with a reinforcement ratio ranging from 0.87 to 1.37%. It can be noted that GFRP-RC continuous beams failed in the interior shear span showed opposite behavior and high shear strength when compared to that of simply-supported ones. On the other hand, beams failed in the exterior shear span showed a decrease in shear strength with increasing depth.
span have a trend similar to that of the simply-supported beams. Moreover, the decrease in the shear strength of such simple beams is higher than that in continuous beams failed in the exterior shear span (13%). This might be attributed to the higher reinforcement ratio and modulus of elasticity of the bars used in this study.

4 CONCLUSIONS

Based on the test results presented and discussed above, the following conclusions can be drawn.

1. The moment redistribution, from the hogging to the sagging moment regions, decreased or changed direction (form the sagging to the hogging moment region) with increasing the effective depth. This could be attributed to the wider and additional cracks developed in the sagging moment regions compared to those in the hogging moment region. This resulted in a relatively weaker sagging moment region which caused the internal forces redirected to the relatively stronger zone (the hogging moment zone).

2. The GFRP-RC continuous beams that failed in the interior shear span showed adverse size effect on the shear strength. The shear strength of NSC beams increased as the effective depth increased.

3. Similar to simply-supported beams, size effect on the shear strength of continuous beams was observed in beams failed in the exterior shear span where the shear strength decreased significantly as the effective depth increased.

5 ACKNOWLEDGMENTS

The authors wish to express their sincere appreciation to the Natural Sciences and Engineering Research Council of Canada (NSERC) through the Canada Research Chairs Program. The assistance received from the technical staff of the MaQuade structures laboratory at the University of Manitoba is acknowledged.

6 REFERENCES