BEHAVIOUR OF WELDED WIRE FABRIC AS SHEAR REINFORCEMENT
UNDER CYCLIC LOADING CONDITIONS

X. Xuan and S.H. Rizkalla

ABSTRACT

A total of four pretensioned prestressed single T-beams with identical flexural reinforcements and shear span-to-depth ratio were tested to investigate the behaviour of welded wire fabric as shear reinforcements under cyclic loading conditions. Three beams reinforced with different types of shear reinforcement, including a conventional single-legged stirrup, and a commercially available deformed welded wire fabric, WWF, were subjected to cyclic loading conditions. A beam without shear reinforcement was tested under static loading conditions.

Test results indicated that the effectiveness of WWF as shear reinforcement is the same as that of conventional single-legged stirrups under cyclic loading conditions. Anchorage of WWF by means of two horizontal wires at the top and bottom of the vertical wires was found to be sufficient. The deterioration of the shear capacity of the prestressed concrete beams due to cyclic loading is much faster than the deterioration of the flexural capacity.

KEYWORDS: beams; cracking; cracking patterns; crack widths; cyclic loads; fatigue; failure; prestressed concrete; reinforcing steel; shear strength; shear reinforcement; stirrups; strains; stresses; T-beams; welded wire fabric.
INTRODUCTION

The use of welded wire fabric as shear reinforcement has become popular among precast concrete manufacturers because of its relative ease of placement and saving of time and money due to reduction of cutting, bending, and labor. It has also the additional advantage of controlling the crack width. Few research papers are available regarding the use of welded wire fabric (WWF) as shear reinforcement (3,5,6,7,9). However, until now, no information has been published related to the behaviour of welded wire fabric as shear reinforcement under cyclic loading conditions.

Reinforced and prestressed concrete beams could fail in shear under cyclic loading due to fracture of the shear reinforcement, even if the applied shear load is significantly smaller than the ultimate shear strength of the member (2,4,8). The fatigue fracture of the web reinforcement depends on the stress range as much as the material properties of the web reinforcement. A typical stress range-fatigue life curve for reinforcing bars (2) is shown in Figure 1.

Welded wire fabric is manufactured from cold-drawn steel wires and generally tack-welded in an orthogonal mesh. The cold drawing process significantly decreases the ductility of WWF. The ultimate strain of the WWF is usually less than 2 percent while that of conventional stirrups is generally greater than 15 percent. The anchorage of WWF is provided by the bond of the vertical wires and the dowel action of the longitudinal wires welded to the vertical wires. The welding process creates significant stress concentration, which could be critical under cyclic loading conditions.

The effectiveness of WWF as shear reinforcement using two horizontal wires at the top and bottom of the vertical wires was found to be compatible to the conventional stirrups under static loading conditions (3,5,6,7,9).
RESEARCH SIGNIFICANCE

This research program was undertaken to investigate the behaviour of welded wire fabric as shear reinforcement for pretensioned prestressed concrete T-beams under cyclic loading conditions. Since the fatigue fracture of web reinforcement depends on the stress range, the characteristics of the induced stress under cyclic loading conditions were considered in this study. The overall ductility of the beam, the shear behaviour including shear crack initiation, crack patterns, crack widths and failure nodes were also investigated.

EXPERIMENTAL PROGRAM

Test Specimens

A total of four pretensioned prestressed single T-beams with identical flexural reinforcement and shear span-to-depth ratio were tested in this program. Two beams reinforced with deformed welded wire fabric as shear reinforcement, and one beam with single-legged stirrups were subjected to cyclic loading conditions. The fourth beam, without shear reinforcement, was tested statically up to failure in order to evaluate the shear strength corresponding to the shear crack initiation as well as the effect of cyclic loading on the failure mode.

The dimensions and the cross-section details of a typical beam are shown in Figure 2. All beams were reinforced with two 15M-300 MPa longitudinal deformed bars and two 13 mm 7-wire stress-relieved prestressed strands with a specified minimum tensile strength of 1860 MPa. Two 9.5 mm (#3)-400 MPa deformed bars were used as longitudinal compressive reinforcements. The beam flange was reinforced with a 4x4-W4-W4 welded wire mesh. Detailed description of the specimens tested in this program is given in Table 1. The
configuration of the welded wire fabric used in this program is shown in
Figure 3. The material properties of the welded wire fabric and single-
legged stirrups used in this program are given in Figure 4. It should be
noted that the lack of ductility of the vertical wires of the deformed welded
wire fabric is based on results of independent test results of nine speci-
mens.

Concrete was obtained from a local ready-mixed concrete supplier. The
mix contained normal portland cement and local river aggregates. The con­
crete mix, by weight, per cubic meter were: cement, 325 kg; sand, 925 kg;
gravel, 1000 kg; water, 170 kg; maximum aggregate size, 15 mm; and 100 mm
slump. The average concrete strength, based on 150 x 300 mm cylinders casted
and tested simultaneously with the beams was 43.1 MPa. All beams were
sprinkled with water and covered with plastic sheets for seven days. The
prestressed force was released at the eighth day. The age of the beams at
testing varied from 53 to 177 days.

Testing Apparatus and Procedure

Each beam was loaded with two equal concentrated loads with a span of
3000 mm, which provides shear span-to-depth ratio of 2.69. The test set-up
for a typical beam during testing is shown in Figure 5. The average concrete
strains were measured using demec points which were attached to the concrete
surface to cover areas of possible diagonal cracks. Crack widths and the
slides along the diagonal cracks were measured at different locations using
three sets of demec points as shown in Figure 6.

The steel strains were measured using electrical resistance strain gages
attached to the prestressed and non-prestressed longitudinal reinforcements
as well as the stirrups. Strain gages were also used to monitor forces in
the prestressed strands, anchorage, and slippage of the web reinforcement.

The beam without shear reinforcement was subjected to static loading up to failure in small load increments varied between 10 kN to 15 kN. At each increment, while the displacement was held constant, readings of load, stroke, strain gages and deflections were measured and recorded using a Hewlett-Packard Data Acquisition System. Lengths of cracks were marked and readings of demec points were taken.

The other three beams, with shear reinforcements, were subjected to cyclic loading conditions. However, all beams were initially loaded statically, to a total load of 180 kN. At this stage, flexural-shear cracks were initiated in each of the shear-span of the beams, at an angle of 45 to 65 degrees to the horizontal axis of the beam. The beams were subjected to cyclic loading with a lower and upper load levels of 40 kN and 180 kN, respectively. The frequency of the applied repetitive load was 1.5 Hz. The cyclic loading was stopped at logarithmic intervals, where the beams were subjected to static cycle with increments of 30 kN, to measure and record the response.

TEST RESULTS AND DISCUSSION

Static Loading Test

Material properties and measured test results of all tested beams are summarized in Table 2. The load-deflection curve of beam PS1-0 without web reinforcement, subjected to monotonic load, is shown in Figure 7. Slight reduction of the beam stiffness was observed at a total load level of 120 kN, due to the formation of the flexural cracks. However, significant reduction of the stiffness was recorded after the initiation of the flexural-shear cracks at a total load level of 180 kN as shown in Figure 7. Stresses in the
bottom longitudinal reinforcements, based on the measured strains, shown in Figure 8, indicate that the bottom longitudinal reinforcements yielded at a total applied load of 240 kN.

The crack pattern of beam PSI-0 is shown in Figure 9. The failure mode of beam PS1-0 was typical shear-tension failure as conformed by the formation of secondary cracks along the bottom longitudinal reinforcement propagated from the flexural-shear cracks due to yielding of the longitudinal reinforcement (1).

Cyclic Loading Tests

The crack patterns of all tested beams are shown in Figure 9. Typical load-deflection hysteresis behaviour for beams subjected to cyclic loading conditions is shown in Figure 10. The load-deflection hysteresis loop between the two load levels $P_{\text{min}}$ and $P_{\text{max}}$ was measured through static loading at the designated number of cycles. It can be observed that the permanent deflection in the first cycle was significant in comparison to the relatively stable residual deflection under the other cycles. As expected, the stiffness of the beam decreased with increasing the number of cycles. The behaviour was typical for beams with single-legged stirrups and welded wire fabric.

The measured deflections at the maximum applied load, $P_{\text{max}}$, versus the number of cycles for the three beams subjected to cyclic loading, shown in Figure 11, indicate that the flexural behaviours of the three beams were also similar. In general, the measured deflections increased slightly with increasing the number of cycles. However, significant increase was measured following the formation of additional critical diagonal shear cracks due to cyclic loading conditions. The slight increase of the fatigue life of beam
PC3-6SM could be attributed to the ductility of the single-legged stirrups in comparison to the welded wire fabric.

Induced stresses in the bottom longitudinal reinforcement for all the beams under cyclic loading at $P_{\text{max}}$ are shown in Figure 12. The increments of the stresses in the longitudinal reinforcements due to the cyclic loading were very small and all the longitudinal reinforcements did not yield before failure of the beams. This behaviour suggests that the deterioration of the flexural capacity of the pretensioned prestressed concrete beam was insignificant, and the failure was mainly due to the deterioration of the shear mechanism in the beam due to cyclic loading conditions.

**Stirrup Stresses**

Typical measured stress ranges in stirrups between the upper load level and lower load level for the three beams subjected to cyclic loading conditions are shown in Figure 13. In this discussion, the stress range, which is directly related to the fatigue strength, was used rather than the strain to account for the variation of the material properties and the sizes used in this investigation. The stress in the stirrups at the initial cyclic loading was negligible. However, the stress ranges increased proportionally to the logarithm of the number of cycles which certainly reduced the fatigue life of the stirrups. This behaviour confirms that the reduction of the fatigue life of the prestressed concrete beam is mainly due to the deterioration of the shear mechanism of the beam.

**Failure Mechanism**

For beams PCI-WD and PC2-WD with deformed welded wire fabric, additional diagonal cracks were developed at the tension zone in both shear span zones.
The existing flexural-shear cracks were also extended toward the compression zone within the first 1000 cycles as shown in Figure 9. However, Beam PC1-WD was stable, without any additional cracks, up to 40,000 cycles, at which a major large diagonal crack was developed on the left shear span with an angle of 25 degrees, as shown in Figure 9. As the number of cycles increased, the diagonal crack widened and the stress range in the vertical wires of WWF crossed by the crack increased rapidly. At 49,745 cycles, three vertical wires fractured and failure occurred suddenly. For beam PC2-WD, large diagonal cracks formed on the right shear span after 1100 cycles. At about 5050 cycles, a large diagonal crack formed on left shear span with an angle of 28 degrees. Failure occurred due to fracture of three vertical wires crossed by the diagonal shear cracks at 25490 cycles. The above mechanism indicated that the anchorage of WWF by using two horizontal wires was sufficient for cyclic loading conditions.

For beam PC3-S6M with single-legged stirrups, two diagonal cracks on the right shear span and one on the left shear span were formed with angles of 45 to 55 degrees at 1000 cycles. Small diagonal cracks were formed at the tension zone of the left shear span. At about 100,000 cycles. A large diagonal crack developed on the left shear span close to the supports with an angle of 25 degrees. As the number of cycles increased, this crack widened and propagated along the transition of the web and flange. The stresses in the stirrups crossed by the crack increased rapidly. Because of the small concrete cover used for the single-legged stirrups at the bottom, hooks of the stirrups were straightened before failure of the beam at 132,833 cycles.

**Crack Patterns and Crack Widths**

Crack patterns of all the tested beams in this program are shown in
Figure 9. For beam PS1-0 without web reinforcement subjected to static loading conditions, no further diagonal cracks were developed after the formation of the first flexural-shear cracks, and failure occurred due to formation of secondary cracks along the bottom longitudinal reinforcement propagated from the flexural shear cracks. For the other three beams, subjected to cyclic loading, additional diagonal cracks were developed by increasing the number of cycles. The observed crack patterns of the tested beams with different shear reinforcement configuration tested under cyclic loading conditions were similar, as shown in Figure 9.

The maximum crack width at maximum load level, $W_{\text{max}}$, was calculated using the measured concrete surface deformations in three directions at different locations of the beam. The crack width was determined by the movement perpendicular to the crack. The maximum crack widths of the beams under cyclic loading versus the number of cycles are shown in Figure 14. The total crack widths, based on the summation of the crack widths of the entire beam, were found to have the same behaviour of the maximum crack widths shown in Figure 14.

In general, crack widths were found to be increased with the increase of number of loading cycles. The rate of increase was approximately proportional to the logarithm of the number of cycles at the early stage. After the formation of the large diagonal cracks, the crack widths increased rapidly prior to the failure of the beam due to the formation of the major diagonal crack in one of the shear spans of the beam.

Both maximum crack widths and total crack widths were similar for all the beams tested under cyclic loading. At failure, there was no significant difference between beams with WWF as shear reinforcement and conventional single-legged stirrups in terms of crack patterns and crack widths.
CONCLUSIONS

Based on the test results, the following conclusions could be drawn:

1. For this type of pretensioned prestressed concrete T-beam, failure occurred due to the yielding of the longitudinal reinforcement under static loading conditions. While under cyclic loading conditions, failure was mainly due to the fracture of shear reinforcement or deterioration of the anchorages of single-legged stirrups.

2. The deterioration of the shear capacity of the prestressed concrete beams due to cyclic loading is much faster than the deterioration of the flexural capacity.

3. Anchorage of WWF by means of two horizontal wires at the top and bottom of the vertical wires were sufficient under cyclic loading conditions.

4. The effectiveness of WWF as shear reinforcement is the same as that of conventional single-legged stirrups in the overall behaviour of the beam under cyclic loading conditions.

ACKNOWLEDGEMENTS

This study was performed in the Structures Laboratory at the University of Manitoba. The assistance given by Messrs. Moray McVey, Ed. Lemke, and Dave Fedorowich during the experimental program is sincerely appreciated. The research project was financed by the National Science and Engineering Research Council, Canada. Donation of the welded wire fabric provided by DUR-O-WALL Ltd., Chicago, Illinois, and the steel forms and material provided by Con-force Ltd., Manitoba, are greatly appreciated.
APPENDIX. - REFERENCES


FIGURE LEGENDS

Fig. 1 Typical stress range-fatigue life curve for reinforcing bars
Fig. 2 Dimensions and cross-section details of the specimens
Fig. 3 Typical configuration of welded wire fabric
Fig. 4 Load-elongation curves for shear reinforcements
Fig. 5 Test set-up
Fig. 6 Demec gage points configuration
Fig. 7 Load-deflection curve for Beam PSI-0 under static loading
Fig. 8 Stress in the longitudinal reinforcement of beam PSI-0
Fig. 9 Crack patterns
Fig. 10 Typical load-deflection curve for tested Beams subjected to cyclic loading
Fig. 11 Deflections at the maximum applied load versus number of cycles
Fig. 12 Stresses in the bottom longitudinal reinforcements at the maximum applied load
Fig. 13 Typical stress ranges in stirrups
Fig. 14 Maximum crack width at the maximum applied load level
<table>
<thead>
<tr>
<th>Beam</th>
<th>Type of Shear Reinforcement</th>
<th>Size (Area) (mm²)</th>
<th>Yield Strength f_y (MPa)</th>
<th>Ultimate Strength f_u (MPa)</th>
<th>Concrete Comp. Str. f'_c (MPa)</th>
<th>Shear Reinforcement Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1-O</td>
<td>None</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>41.4</td>
<td>-</td>
</tr>
<tr>
<td>PC1-WD</td>
<td>WWF</td>
<td>D4.7 Deformed (28.4)</td>
<td>587</td>
<td>587</td>
<td>43.7</td>
<td>0.0291</td>
</tr>
<tr>
<td>PC2-WD</td>
<td>WWF</td>
<td>D4.7 Deformed (28.4)</td>
<td>587</td>
<td>587</td>
<td>44.4</td>
<td>0.0291</td>
</tr>
<tr>
<td>PC3-S6M</td>
<td>Single-legged stirrup</td>
<td>6 mm Deformed (31.17)</td>
<td>483</td>
<td>693</td>
<td>43.1</td>
<td>0.0266</td>
</tr>
</tbody>
</table>
Table 2. Test results

<table>
<thead>
<tr>
<th>Beam</th>
<th>Flexural Crack (2P) (kN)</th>
<th>Shear Crack (2P) (kN)</th>
<th>Ultimate load (2P) (kN)</th>
<th>Fatigue Life (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1-0</td>
<td>140</td>
<td>175</td>
<td>318</td>
<td>-</td>
</tr>
<tr>
<td>PC1-WD</td>
<td>140</td>
<td>175</td>
<td>-</td>
<td>49,745</td>
</tr>
<tr>
<td>PC2-WD</td>
<td>140</td>
<td>168</td>
<td>-</td>
<td>25,497</td>
</tr>
<tr>
<td>PC3-S6M</td>
<td>140</td>
<td>180</td>
<td>-</td>
<td>132,833</td>
</tr>
</tbody>
</table>
Xiaoyi Xuan is a graduate student in the Department of Civil Engineering at the University of Manitoba. He received his B.Sc. from Zhejiang Engineering College, China, and his M.Sc. from the University of Manitoba, Canada.

ACI Member Sami H. Rizkalla is an associate professor and Head of the Structures Division of the Civil Engineering Department at the University of Manitoba, Canada. He received his B.Sc. degree from Alexandria University, Egypt, and his M.Sc. and Ph.D. degrees from North Carolina State University. He is a member of ASCE, PCI, and CSCE. He is also a member of the Executive Committee of the Structures Division of the Canadian Society for Civil Engineers. His research activities are in the area of reinforced and prestressed concrete structures.
Fig (1)
Sec. A - A

15 M Bars

2 - #3 Bars

2 - Ø13 P/S Strands

Wire Mesh

Fig (c)
$P_u = 20\, \text{KN (686 MPa)}$

$P_u = 16.7\, \text{KN (592 MPa)}$

Load (KN)

% Strain

Single Legged Stirrup

Welded Wire Fabric

Fig (4)
W: Crack Width
S: Slide

Fig (6)
Figure 14.1

No. of Cycles (log)

Maximum Crack Width (mm)

PC3 - 56M
PC2 - WD
PCI - WD