SHEAR TESTS OF HOLLOWCORE FLOOR SLABS WITH STEEL FIBRES

Technical Report Prepared on Request from
Stahlton Engineered Concrete, a Division of Fulton Hogan Ltd.

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1. PROBLEM STATEMENT

Pre-stressed hollow core slabs are light weight flooring elements that can cover long span lengths. Even though these elements have adequate bending capacity, site observations showed that without careful consideration to initial concrete strength and the high levels of pre-stress during design, these units may be susceptible to web shear failures as observed in Figure 1. New Zealand code (NZS3101 2006) requires nominal transverse shear reinforcement for pre-stressed double-T beams (Al-Ani et al. 2008), but such a requirement is not given for hollow-core flooring units. To address the lack of shear resistance in the web, the required shear capacity can be provided by: i) filled cores with stirrups cast in with topping concrete or ii) addition of steel fibres into the concrete mix during the casting. In this report, the test results of shear tests with different levels of steel fibres are assessed and reported. The results showed that steel fibres provide a reasonable amount of extra shear capacity provided that they are designed according to the procedures given in NZS3101 (Explained in Section 2).

![Figure 1 Shear failure observations from a site in Christchurch](image)

Summary of Contents:

1. Problem statement:
   The introduction to the problem being investigated
2. Background theory on shear capacity calculations:
   The overview of tools to be utilized in the report
3. Test setup:
   The testing apparatus is explained along with its limitation.
4. Test specimens:
   The details of the tested specimens are summarized.
5. Test results:
   The results of the tests have been listed, plotted along with the damage observations taken during the tests.
6. Analysis of Results:
   The results of the tests have been inspected for clarifying the overall effects caused by the steel fibres.
7. Conclusions:
   The summary of outcomes and challenges for future reference.

Appendix A:
Manufacturer’s data for steel fibres (Dramix 3D 80/60BG)

Appendix B:
Strand certificate provided for the test specimens.
2. BACKGROUND THEORY ON SHEAR CAPACITY CALCULATIONS

The total shear capacity, \( V_T \), of a pre-stressed hollow core unit with steel fibres can be calculated by the shear contribution from concrete \( (V_c) \), shear reinforcement \( (V_s) \) and steel fibers \( (V_f) \). In the reported specimens, there were no shear reinforcement so its contribution is taken as zero \( (V_s=0) \). Accordingly, the shear capacity of a pre-stressed hollow core unit can be calculated as given below (NZS3101 2006):

\[
V_T = V_c + V_f
\]  

(1)

Concrete shear contribution can be calculated using equations 2 and 3:

\[
V_c = \left(1 + \frac{K \cdot N_{pt}}{b_w h \cdot f_c'}\right) v_b \cdot b_w d
\]  

(2)

\[
v_b = (0.07 + 10 \frac{\sum A_{pt}}{b_w d}) \cdot \sqrt{f_c'} , \quad 0.08 \sqrt{f_c'} \leq v_b \leq 0.2 \sqrt{f_c'}
\]  

(3)

where, \( K \) = 3 for \( N > 0 \) (compression), 12 for \( N < 0 \) (tension)  
\( N_{pt} \) = Axial force imposed by pre-stressing -in \( N \) (allow for losses)  
\( b_w \) = The total width of the web  
\( h \) = The section height  
\( d \) = The effective depth of the strand  
\( A_{pt} \) = Area of the strand (accounting for dowel action)  
\( f_c' \) = Concrete compressive strength

Shear contribution given by the steel fibres can be calculated as outlined in Part 2 appendix C5A of NZS 3101 (NZS3101 2006):

\[
V_f = 0.7 k_f k_1 \tau_{fd} b_w d \quad \text{(in \( mm \) and \( MPa \))}
\]  

(4)

\[
k_f = 1 + n \left(\frac{h_f}{b_w}\right) \cdot \left(\frac{h_f}{d}\right) \leq 1.5 \quad \text{(in \( mm \))}
\]  

(5)

\[
n = \frac{b_f - b_w}{h_f}, \quad n \leq 3 \text{ and } n \leq \frac{3b_w}{h_f} \quad \text{(in \( mm \))}
\]  

(6)

where, \( b_f \) = Width of the flange  
\( h_f \) = Thickness of the flange

\[
k_1 = 1 + \sqrt{\frac{200}{d}} \leq 2 \quad \text{(in \( mm \))}
\]  

(7)

\[
\tau_{fd} = 0.12 f_{Rk,4} \quad \text{(Design value)}
\]  

(8)

where, \( f_{Rk,4} = \) The characteristic residual tensile strength of the steel fibre reinforced concrete at crack mouth opening level 4, i.e. at \( CMOD_4 = 3.5 \ mm \). (For ultimate shear strength analysis, \( f_{Rk,1} \) was used in this report since it gives the highest contribution)
The mean values of \( f_{Rk,i} \) for each level of \( CMOD_i \) are given by the manufacturer specifications (Appendix A) and are summarized for the used steel fibre type is given in Table 1 (Values are for 15 kg/m\(^3\)).

<table>
<thead>
<tr>
<th>( CMOD_i )</th>
<th>( f_{Rk,i} ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CMOD_1 ) = 0.5 mm</td>
<td>2.4</td>
</tr>
<tr>
<td>( CMOD_2 ) = 1.5 mm</td>
<td>2.3</td>
</tr>
<tr>
<td>( CMOD_3 ) = 2.5 mm</td>
<td>2.1</td>
</tr>
<tr>
<td>( CMOD_4 ) = 3.5 mm</td>
<td>2.0</td>
</tr>
</tbody>
</table>

\( CMOD \): Crack mouth opening displacement

The values given above are for Dramix 3D 80/60BG type steel fibres with 15kg/m\(^3\) fibre dosage.

### 3. TEST SETUP

In the tests, the one point loading test setup at Stahlton was used. The loading distance from the nearest simple support was arranged such that the specimen could fail in shear. The load was applied monotonically using a powered hydraulic pump. The loads were measured using a 250kN capacity load cell placed between the loading jack and spreader beam. The readings were taken by using a digital load display showing the kg values of the loading. The detailed schematics and photo of the test setup is shown in Figure 2 and Figure 3c respectively.

#### 3.1. Limitations of the Test Setup

The test setup was good enough to observe the load carrying capacity, but it limited the possible observations and data that could have been made in a laboratory condition:

- The reaction frame formed by top and bottom steel beams connected by high strength steel bars were not rigid and confined enough to prevent out of plane deformations. This might have affected the expected experimental response of the specimen to a degree.
- The load was applied by using a powered hydraulic pump and the loading rate could not be controlled slowly enough to observe displacements. Because of this, no displacement measurements could be taken in the setup.
- All readings, measurements were taken manually. No real time data logging was used in this on-site test setup. As a result of this, the measurements are not as accurate as a test carried out in laboratory conditions.
- There were no concrete cylinder specimens present in the testing grounds. Therefore, the concrete strength measurements were taken using a digital Schmidt hammer. 10 measurements per specimen were taken and averaged. Resulting measurements are only rough approximations for concrete strength, which will be given for each test specimen.
4. TEST SPECIMENS

Each specimen was pre-stressed with 5 high strength strands of 100 mm² nominal area. The yield force of each strand is given as 184 kN in the Mill Test Certificate provided by the manufacturer (Appendix B). The specimens were pre-stressed at 67% of their yielding force (123 kN). Potential pre-stressing losses were in the order of 15% for these specimens. The cross sectional detail for each specimen is as shown in Figure 3a with the only difference being the amount of steel fibres put into each specimen (Steel fibre type: Dramix 3D 80/60BG)

![Figure 3a Cross section for the test specimens and pre-stress information](image)

In total, there were only six test specimens. 2 of these specimens were as built control specimens without any steel fibres (Specimens A1, A2). On the other hand specimens S1, S2 had 13.33 kg/m³ steel fibres while specimens S3, S4 contained 26.67 kg/m³ steel fibres. Both ends of each specimen (end a, end b) were tested till shear failure, summing up to 12 tests in total. Due to the lack of concrete cylinder samples, the concrete compressive strength, \( f'_c \), was measured using a digital Schmidt hammer (Figure 3b) by averaging 10 hammer readings at each end of the specimens. The properties of the test specimens are summarized in Table 2.

![Figure 3b Digital Schmidt hammer](image)

![Figure 3c Test specimen placed within the setup](image)

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Specimen Detail</th>
<th>Concrete Strength ( f'_c ) (MPa)</th>
<th>Steel Fibre Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As built specimens</td>
<td>A1a As built specimen 1 end a</td>
<td>70.5</td>
<td>0</td>
</tr>
<tr>
<td>A1b As built specimen 1 end b</td>
<td>62.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A2a As built specimen 2 end a</td>
<td>63.0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>A2b As built specimen 2 end b</td>
<td>63.5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Steel fibre dosage 13.33</td>
<td>S1a Steel fibre specimen 1 end a</td>
<td>64.5</td>
<td>13.33</td>
</tr>
<tr>
<td>S1b Steel fibre specimen 1 end b</td>
<td>58.5</td>
<td>13.33</td>
<td></td>
</tr>
<tr>
<td>S2a Steel fibre specimen 2 end a</td>
<td>70.0</td>
<td>13.33</td>
<td></td>
</tr>
<tr>
<td>S2b Steel fibre specimen 2 end b</td>
<td>60.0</td>
<td>13.33</td>
<td></td>
</tr>
<tr>
<td>Steel fibre dosage 26.67</td>
<td>S3a Steel fibre specimen 3 end a</td>
<td>65.0</td>
<td>26.67</td>
</tr>
<tr>
<td>S3b Steel fibre specimen 3 end b</td>
<td>66.0</td>
<td>26.67</td>
<td></td>
</tr>
<tr>
<td>S4a Steel fibre specimen 4 end a</td>
<td>57.0</td>
<td>26.67</td>
<td></td>
</tr>
<tr>
<td>S4b Steel fibre specimen 4 end b</td>
<td>58.5</td>
<td>26.67</td>
<td></td>
</tr>
</tbody>
</table>
5. TEST RESULTS

The specimens were monotonically loaded until shear crack formation occurred, which approximately corresponds to \( CMOD_1 \) (~0.5 mm deflection). After this state, the specimens were pushed further until a level crack widening occurred, which approximately corresponded to \( CMOD_4 \) (~3.5 mm deflection). In all of the tests, brittle shear failure was observed. However, the specimens with steel fibres had slightly higher capacity both at \( CMOD_1 \) (Ultimate capacity point) and \( CMOD_4 \) (Residual capacity point). The results reported here are analyzed further in the analysis of results section. While doing the tests, manual load readings were taken using the digital display connected to the load cell, which gave the load values in terms of mass (i.e. kg). For practicality, the observed force values were written on the test specimens using \( g = 10 \, \text{m/s}^2 \) during the tests. However, as it is given in the following text, these values have been recalculated using \( g = 9.81 \, \text{m/s}^2 \) for a better accuracy in analyses of results.

5.1. Test Results of As Built Specimens: A1a, A1b, A2a and A2b

The summary of the force readings taken during the tests is given in Table 3 and Figure 4. Damage photos for the as built specimens, without any steel fibres, are shown from Figure 5 to Figure 8.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( f'_c ) (MPa)</th>
<th>( F_{CMOD1} ) (kN)</th>
<th>( V_{CMOD1} ) (kN)</th>
<th>( F_{CMOD4} ) (kN)</th>
<th>( V_{CMOD4} ) (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1a</td>
<td>70.5</td>
<td>121.64</td>
<td>107.96</td>
<td>49.05</td>
<td>43.53</td>
</tr>
<tr>
<td>A1b</td>
<td>62.0</td>
<td>101.04</td>
<td>89.68</td>
<td>49.05</td>
<td>43.53</td>
</tr>
<tr>
<td>A2a</td>
<td>63.0</td>
<td>105.95</td>
<td>94.03</td>
<td>49.05</td>
<td>43.53</td>
</tr>
<tr>
<td>A2b</td>
<td>63.5</td>
<td>101.04</td>
<td>89.68</td>
<td>49.05</td>
<td>43.53</td>
</tr>
</tbody>
</table>

\( CMOD_1 \) corresponds to the shear failure value
\( CMOD_4 \) corresponds to the residual capacity after shear crack widens
\( F \): applied load value
\( V \): shear force resulting from the applied load (\( V = 0.8875F \))

As built specimens (Steel fibre = 0 kg/m²)

![Figure 4](image_url)

**Figure 4** Applied force vs. corresponding \( CMOD \) values for as built specimens A1a, A1b, A2a, A2b
Figure 5 Test specimen A1a

Figure 6 Test specimen A1b

Figure 7 Test specimen A2a

Figure 8 Test specimen A2b
5.2. Test Results of Specimens with 13.33 kg/m$^3$ steel fibre density: S1a, S1b, S2a and S2b

The summary of the force readings taken during the tests is given in Table 4 and Figure 9. Damage photos for these specimens with steel fibres, are shown from Figure 10 to Figure 13.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>$f_c$ (MPa)</th>
<th>$F_{CMOD1}$ (kN)</th>
<th>$V_{CMOD1}$ (kN)</th>
<th>$F_{CMOD4}$ (kN)</th>
<th>$V_{CMOD4}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1a</td>
<td>64.5</td>
<td>127.53</td>
<td>113.18</td>
<td>73.58</td>
<td>65.30</td>
</tr>
<tr>
<td>S1b</td>
<td>58.5</td>
<td>129.49</td>
<td>114.92</td>
<td>72.59</td>
<td>64.43</td>
</tr>
<tr>
<td>S2a</td>
<td>70.0</td>
<td>127.53</td>
<td>113.18</td>
<td>77.50</td>
<td>68.78</td>
</tr>
<tr>
<td>S2b</td>
<td>60.0</td>
<td>127.53</td>
<td>113.18</td>
<td>68.67</td>
<td>60.95</td>
</tr>
</tbody>
</table>

$CMOD_1$ corresponds to the shear failure value
$CMOD_4$ corresponds to the residual capacity after shear crack widens
$F$: applied load value
$V$: shear force resulting from the applied load ($V=0.8875F$)

Figure 9 Applied force vs. corresponding $CMOD$ values for specimens with steel fibre density 13.33 kg/m$^3$ S1a, S1b, S2a, S2b

Figure 10 Test specimen S1a with visible steel fibres within cracks (13.33 kg/m$^3$ steel fibre content)
Figure 11 Test specimen S1b with visible steel fibres within the cracks (13.33 kg/m³ steel fibre content)

Figure 12 Test specimen S2a (13.33 kg/m³ steel fibre content)

Figure 13 Test specimen S2b (13.33 kg/m³ steel fibre content)
5.3. **Test Results of Specimens with 26.67 kg/m³ steel fibre density: S3a, S3b, S4a and S4b**

The summary of the force readings taken during the tests is given in Table 5 and Figure 14. Damage photos for these specimens with steel fibres, are shown from Figure 15 to Figure 18. The results of specimen S4b have been neglected since the reaction frame showed significant out-of-plane deflection in this test and the significantly high capacity value observed in this test may not represent the real capacity value. Therefore, the results of S4b are not considered in the analysis of results section.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>f’c (MPa)</th>
<th>F_CMOD1 (kN)</th>
<th>V_CMOD1 (kN)</th>
<th>F_CMOD4 (kN)</th>
<th>V_CMOD4 (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3a</td>
<td>65.0</td>
<td>125.57</td>
<td>111.44</td>
<td>88.29</td>
<td>78.36</td>
</tr>
<tr>
<td>S3b</td>
<td>66.0</td>
<td>151.07</td>
<td>134.08</td>
<td>98.10</td>
<td>87.06</td>
</tr>
<tr>
<td>S4a</td>
<td>57.0</td>
<td>127.53</td>
<td>113.18</td>
<td>94.18</td>
<td>83.58</td>
</tr>
<tr>
<td>S4b</td>
<td>58.5</td>
<td>167.75</td>
<td>148.88</td>
<td>107.91</td>
<td>95.77</td>
</tr>
</tbody>
</table>

CMOD 1 corresponds to the shear failure value
CMOD 4 corresponds to the residual capacity after shear crack widens
F: applied load value
V: shear force resulting from the applied load (V=0.8875F)

**Figure 14** Applied force vs. corresponding CMOD values for specimens with steel fibre density 26.67 kg/m³: S1a, S1b, S2a, S2b

**Figure 15** Test specimen S3a (26.67 kg/m³ steel fibre content)
Figure 16 Test specimen S3b (26.67 kg/m³ steel fibre content)

Figure 17 Test specimen S4a (26.67 kg/m³ steel fibre content)

Figure 18 Test specimen S4b (26.67 kg/m³ steel fibre content)
6. ANALYSIS of RESULTS

Since all specimens had slightly different concrete compression strength due to Schmidt hammer measurements, the comparison of the results may not be very accurate. However, it is possible to average the concrete strength in each respective specimen group and represent each group with a single concrete strength value (i.e. for as built specimen group and steel fibre reinforced specimen group). Since shear strength in concrete elements is directly proportional to the square root of the concrete strength, as given in Equation 3, the observed experimental shear capacity values can be modified accordingly to facilitate a more meaningful comparison. This process is given in Table 6.

<table>
<thead>
<tr>
<th>#</th>
<th>$f'_c$ (MPa)</th>
<th>Observed $F_	ext{CMODi}$ (kN)</th>
<th>$F'_\text{ave,c}$ (MPa)</th>
<th>Modified $F_{M,\text{CMODi}}$ (kN)</th>
<th>$V_{M,\text{CMODi}}$ (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1a</td>
<td>70.5</td>
<td>121.64</td>
<td>49.05</td>
<td>116.58</td>
<td>47.00</td>
</tr>
<tr>
<td>A1b</td>
<td>62.0</td>
<td>101.04</td>
<td>49.05</td>
<td>103.26</td>
<td>50.13</td>
</tr>
<tr>
<td>A2a</td>
<td>63.0</td>
<td>105.95</td>
<td>49.05</td>
<td>107.41</td>
<td>49.73</td>
</tr>
<tr>
<td>A2b</td>
<td>63.5</td>
<td>101.04</td>
<td>49.05</td>
<td>102.03</td>
<td>49.53</td>
</tr>
<tr>
<td>S1a</td>
<td>64.5</td>
<td>127.53</td>
<td>73.58</td>
<td>126.29</td>
<td>72.86</td>
</tr>
<tr>
<td>S1b</td>
<td>58.5</td>
<td>129.49</td>
<td>72.59</td>
<td>134.65</td>
<td>75.48</td>
</tr>
<tr>
<td>S2a</td>
<td>70.0</td>
<td>127.53</td>
<td>77.50</td>
<td>121.23</td>
<td>73.67</td>
</tr>
<tr>
<td>S2b</td>
<td>60.0</td>
<td>127.53</td>
<td>68.67</td>
<td>130.94</td>
<td>70.51</td>
</tr>
<tr>
<td>S3a</td>
<td>65.0</td>
<td>125.57</td>
<td>88.29</td>
<td>122.27</td>
<td>85.97</td>
</tr>
<tr>
<td>S3b</td>
<td>66.0</td>
<td>151.07</td>
<td>98.10</td>
<td>145.98</td>
<td>94.79</td>
</tr>
<tr>
<td>S4a</td>
<td>57.0</td>
<td>127.53</td>
<td>94.18</td>
<td>132.60</td>
<td>97.92</td>
</tr>
<tr>
<td>S4b</td>
<td>58.5</td>
<td>167.75</td>
<td>107.91</td>
<td>172.17</td>
<td>110.75</td>
</tr>
</tbody>
</table>

Note: $F_{M,\text{CMODi}} = \sqrt{\frac{f'_c}{f'_c}} \times F_{\text{CMODi}}$, $V_{\text{CMODi}} = F_{\text{CMODi}} \times 0.8875$ (from equilibrium)

Using these results, the comparison of all the specimens can be made as shown in Figure 19. In this plot, it can be seen that the added doses of steel fibres in concrete causes an increased capacity at both $\text{CMOD1}$ and $\text{CMOD4}$ levels.

![Figure 19](image-url)

**Figure 19** Test results modified using average concrete strength values: a) As built specimens without any steel fibres; b) Specimens with 13.33 kg/m$^3$ steel fibres; c) Specimens with 26.67 kg/m$^3$ steel fibres

On the other hand, the steel fibres seem to be more effectively increasing the residual capacity (i.e. at $\text{CMOD4}$ level) rather than the capacity at shear failure (i.e. $\text{CMOD1}$ level). This can be
clearly seen when percentage of additional capacity over the as built capacity are plotted at $CMOD_1$ and $CMOD_4$ levels (Figure 20). In this figure, it can be seen that addition of 13.33 kg/m$^3$ to the as built specimen resulted in capacity gain of 19.53% and 48.95% at $CMOD_1$ and $CMOD_4$ respectively. Similarly, addition of 26.67 kg/m$^3$ of steel fibres caused capacity gain of 24.5% and 89.2% at $CMOD_1$ and $CMOD_4$ respectively.

![Figure 20 Percentage of shear capacity gain over the as built capacity](image)

Considering the limited number of tests in this particular inspection, it is not possible to conclude a generalized result for the amount of added capacity by different steel fibre dosages. However, it can safely be said that additional steel fibres in concrete is beneficial for increasing the shear capacity of a hollow core section. This also adds much needed residual resistance that can be a lifesaving factor in the case of a shear failure.

6.1. Capacity Check According to NZS 3101

6.1.1. Concrete shear contribution ($V_c$)

Concrete shear contribution can be calculated using equation 2 and 3 as follows ($b_w=260$ mm, $d=155$ mm, $A_{pt}=99$ mm$^2$, $N_{pt}=5×123$ kN):=

$$v_b = (0.07 + 10 \cdot \frac{5 \times 99}{260 \times 155}) \cdot \sqrt{f'_c} = 0.1928 \sqrt{f'_c} \rightarrow 0.08 \sqrt{f'_c} < 0.1928 \sqrt{f'_c} < 0.2 \sqrt{f'_c} \text{ OK}$$

$$V_c = (1 + \frac{3 \cdot 123000 \cdot 5}{260 \cdot 200 \cdot f'_c}) \cdot 0.1928 \sqrt{f'_c} \cdot 260 \cdot 155 = (1 + \frac{35.481}{f'_c}) \cdot 7769.84 \sqrt{f'_c}$$

$$V_c = (7769.84 + \frac{275681.69}{f'_c}) \sqrt{f'_c}$$

Due to the variances in each test, the average concrete strength values, $f'_{ave,c}$, and the observed shear capacities normalized accordingly, $V_{M,CMOD_1}$ (previously given in Table 6), will be used for the comparison with theoretical capacity values. The resulting concrete shear contribution values, $V_c$, are given in Table 7.
6.1.2. Shear contribution due to steel fibres ($V_f$):

Ultimate capacity values due to the additional steel fibre content can be calculated using equations 4-8. For these calculations, $f_{Rk,i}$ values given in the manufacturer’s steel fibre specification (Appendix A) are required. However, it should be noted that the provided values are only valid for steel fibre dosage of 15 kg/m$^3$. In the reported test specimens, the steel fibre dosage levels were 13.33 kg/m$^3$ and 26.67 kg/m$^3$. Therefore, the numerical capacity calculation given by NZS 3101 (equations 4-8) will result in an average shear capacity rather than an exact estimate. This estimation may give reasonable results for the specimens with 13.33 kg/m$^3$ steel fibre content whilst the result may show a degree of deviation for the specimens with 26.67 kg/m$^3$ steel fibres. The shear capacity contribution can be calculated as given below. The results are summarized in Table 7.

Using Eq. 7: $k_1 = 1 + \frac{200}{\sqrt{155}} = 2.14 > 2.0 \Rightarrow k_1 = 2$

Using Eq. 6: $n = \frac{1140 - 260}{30} = 29.33$, $n \leq 3$ and $n \leq \frac{3 \cdot 260}{30} = 26 \Rightarrow n = 3$

Using Eq. 5: $k_f = 1 + 3 \cdot \frac{30}{260} \cdot \frac{155}{260} = 1.067 < 1.5$ OK

Using Eq. 8: $\tau_{f_d, CMOD1} = 0.12 \cdot 2.4 = 0.288$ MPa at $CMOD1$

Using Eq. 4: $V_{f, CMOD1} = 0.7 \cdot 1.067 \cdot 2 \cdot 0.288 \cdot 260 \cdot 155 = 17338N = 17.34kN$

<table>
<thead>
<tr>
<th>#</th>
<th>$f'_{ave,c}$ (MPa)</th>
<th>$V_{M,CMOD1}$ (kN)</th>
<th>$V_c$ (kN)</th>
<th>$V_f$ (kN)</th>
<th>$V_T$ (kN)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1a</td>
<td>64.75</td>
<td>103.46</td>
<td>0</td>
<td>96.78</td>
<td>-6.5</td>
<td></td>
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<tr>
<td>A1b</td>
<td>64.75</td>
<td>91.64</td>
<td>0</td>
<td>96.78</td>
<td>+5.6</td>
<td></td>
</tr>
<tr>
<td>A2a</td>
<td>64.75</td>
<td>95.33</td>
<td>96.78</td>
<td>0</td>
<td>+1.5</td>
<td></td>
</tr>
<tr>
<td>A2b</td>
<td>64.75</td>
<td>90.55</td>
<td>0</td>
<td>96.78</td>
<td>+6.9</td>
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</tr>
<tr>
<td>S1a</td>
<td>63.25</td>
<td>112.08</td>
<td>17.34</td>
<td>113.80</td>
<td>+1.5</td>
<td></td>
</tr>
<tr>
<td>S1b</td>
<td>63.25</td>
<td>119.50</td>
<td>17.34</td>
<td>113.80</td>
<td>-4.8</td>
<td></td>
</tr>
<tr>
<td>S2a</td>
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<td>107.59</td>
<td>17.34</td>
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<td>+5.8</td>
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<tr>
<td>S2b</td>
<td>63.25</td>
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<td>17.34</td>
<td>113.80</td>
<td>-2.1</td>
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<td>108.51</td>
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<td>113.45</td>
<td>+4.6</td>
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<tr>
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<td>129.56</td>
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<td>-12.4</td>
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<td>113.45</td>
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<tr>
<td>S4b*</td>
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<td>113.45</td>
<td>-25.8</td>
<td></td>
</tr>
</tbody>
</table>

* Omitted specimen

$V_T$ values are calculated using the manufacturer’s specifications for 15 kg/m$^3$ steel fibre content

When these capacities are plotted, it can be seen that the calculated shear capacities correlate well with the experimental results. This is also valid for the specimens with steel fibres. Due to the lack of information for high dosages of steel fibres, the results are more accurate for a steel fibre content about 15 kg/m$^3$, as suggested by the manufacturer. Moreover, the capacity gain from 13.33 kg/m$^3$ to 26.67 kg/m$^3$ is negligible in the reported experimental results. However, as
stated previously, increasing doses of steel fibres seem to be increasing the residual capacity more efficiently than the ultimate capacity (Shown in Figure 20), which can be beneficial to ductility and life safety of these elements.

![Figure 20: Observed Shear Capacities](image1)

**Figure 21**: Comparison of experimental shear capacities (normalized to $f'_{ave,c}$) and calculated shear capacities according to NZS 3101

7. CONCLUSIONS

Considering the limited number of tests reported herein, it is not possible to generalize the results. However, it can be stated that addition of steel fibres into concrete, in general, has beneficial effects. Although they add to the ultimate shear capacities of the pre-stressed hollow core elements (~20% in the reported work), this additional strength is not too significant above 15 kg/m³ dosage of steel fibres. On the other hand, higher steel fibre content may contribute more significantly to residual strength of the considered element. This allows some residual force resistance that may be important for life safety during such sudden failures. The quantification of the residual capacity for such scenarios are still an engineering challenge that still needs further research (Al-Ani et al. 2008; NZS3101 2006). Nonetheless, even the low dose of 13.33 kg/m³ steel fibre content resulted in an ultimate capacity gain of approximately 20% while it caused approximately 50% residual strength gain. 26.67 kg/m³ dose of steel fibre caused capacity gains of 25% for ultimate and 90% for residual.

REFERENCES


NZS3101 (2006) The Design of Concrete Structures vol 3101. New Zealand Standard,
APPENDIX A-Steel Fibre Data Sheet

Technical Data Sheet

3D 80/60BG

Customer: Stanlit
Location: National
Project: Double Ts
Remark: Nationwide
Date: 10/12/2013

Residual Flexural Strength
15 kg/m³ Dramix 3D 80/60BG in C40/50

Average residual flexural strength $f_{rel}$, according to EN 14651. Only valid for the mentioned combination of fibre type, dosage and concrete compressive strength.

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Dosage</th>
<th>Concrete</th>
<th>$f_{rel,lm}$</th>
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<tbody>
<tr>
<td>MOD 0.5mm</td>
<td>15 kg/m³</td>
<td>C40/50</td>
<td>2.4 N/mm²</td>
</tr>
<tr>
<td>MOD 1.5mm</td>
<td>15 kg/m³</td>
<td>C40/50</td>
<td>2.3 N/mm²</td>
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<tr>
<td>MOD 2.5mm</td>
<td>15 kg/m³</td>
<td>C40/50</td>
<td>2.1 N/mm²</td>
</tr>
<tr>
<td>MOD 3.5mm</td>
<td>15 kg/m³</td>
<td>C40/50</td>
<td>2.0 N/mm²</td>
</tr>
</tbody>
</table>
# APPENDIX B

**Post Tensioning Certificate**

**MILL TEST CERTIFICATE**

**CERT NO:** JCG2225J060010  
**DATE OF ISSUE:** 29 November 2013  
**Part:** 1 of 1

**CUSTOMER:** RC Macdonald Limited  
**PRODUCT:** AS DESCRIBED IN INVOICE

**PILE:** 12.7mm  
**STANDARD/GRADE:** AS NS 4672 1 AND 2 2007.

**RELAXATION:** LOW RELAXATION  
**LAY:** RIGHT HAND LAY PLAIN ACRS CERTIFIED  
**REFERENCE NO:** MR39270101

**TEST METHOD:**  
**GRADE OF EXTENSOMETER:**

**ENVIRONMENTAL CONDITIONS TEMPERATURE:** 18-28 CELSIUS  
**TEST DATE:** 19 November 2013

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<th>Weight (kg)</th>
<th>WC</th>
<th>DIA (mm)</th>
<th>AREA (mm²)</th>
<th>UW (g/m)</th>
<th>BL (kN)</th>
<th>Y10.1% (kN)</th>
<th>MOE (kN/mm²)</th>
<th>EL (%)</th>
<th>RELAX (%)</th>
<th>EP</th>
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<td>-</td>
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<td>758.5</td>
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<td>150.0</td>
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<td>198.65</td>
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<td>197.20</td>
<td>7.7</td>
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<td><strong>Grand Total</strong></td>
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<td>192.00</td>
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</tr>
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</table>

**Remarks:** RCM14250

---

**APPROVED BY:**

[Signature]

Mr. Chaiwanchai Chiekhakkang/Authorized Signature

---

We hereby certify that material described herein has been manufactured and tested with satisfactory results in accordance with the requirements of the above material specification. This certificate may not be reproduced except in full, unless permission for the reproduction has been obtained in writing from the laboratory.

---

<table>
<thead>
<tr>
<th>Spec.</th>
<th>No.</th>
<th>Description</th>
<th>No.</th>
<th>Unit Weight</th>
<th>No.</th>
<th>Breaking Load</th>
<th>No.</th>
<th>Yield Load</th>
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<td>---</td>
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</tr>
</tbody>
</table>

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**NATA**

[Stamp]

---

**SIW**

[Logo]
**Load-strain Curve of PC STAND**

Conforming To: AS NZS 4972.1 AND 2 2007

Grade 1870  Size 12.7mm

Grade of extensometer: C

Coll No. S3B182K440

Yield Load at 0.1% : 183.31 kN

Modulus of Elasticity : 199.03 kN/mm²

Date (DD/MM/YYYY) 16/11/2013

Remarks: RCM14380

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Checked by [Signature]