PERFORMANCE OF GROUTED SLEEVE CONNECTORS SUBJECTED TO INCREMENTAL TENSILE LOADS

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Abstract
Full strength grouted sleeve connectors ensure the integrity of connected precast concrete components. This research investigated the behaviour and the strength performance of the proposed A, B, C and D-series grouted sleeve connectors for joining precast concrete components. The connectors were subjected to increasing tensile loads until failure. The performances of the connectors were also evaluated in terms of stiffness, yield strength, ductility and failure modes. The experimental results show that the C-series grouted splice sleeve connectors successfully achieved the full tensile strength of the connected steel bars. In addition, the confinement provided by the steel sleeve controls and delays the splitting cracks of the surrounding grout and eventually enhances the bond between bar-and-grout significantly. The enhanced bond contributes to a shorter development length of the connected bar as compared to the conventional bar lapping method.

Keywords: bond, connector, grout, precast concrete, splice sleeve

INTRODUCTION

A sleeve combined with grout is a cylindrical connector used to join two discontinuous steel reinforcement bars without complying to the conventional lap length. The use of conventional bar lapping system in precast concrete structures may be uneconomical and unpractical, particularly for large diameter steel bars because they require longer development length and lead to congestion of steel bars, and also difficulties in manufacturing fabrication, and transportation. Alternatively, splice sleeves can be used as a connection system for connecting reinforcement bars extruding from one structural element to other elements. Apart from wall frame systems, splice sleeves can also be used as beam-to-column, column-to-column, and column-to-base connections (Figure 1). This method is widely used in North America since the late 1980’s (Jansson et al., 2008).

![Figure 1. Application of grout-filled splice (source Splice Sleeve North America, Inc.)](image-url)
A splice sleeve connector is a specially designed cylindrical sleeve that utilizes non-shrinkage grout as the bonding material to splice steel bars. The usage of splice sleeves is fairly simple and straightforward, where they are cast together with the precast concrete components, splicing the reinforcement bars protruding from other elements as they are jointed together at site. Then, the grout is pumped or poured into the sleeve, through the splice inlet, to fill the space and to ensure composite action among the components in the splice sleeves. As the grout reaches sufficient compressive strength of about 20N/mm², the temporary bracing that keep the precast elements in position can be removed.

The splice sleeves that are currently available in the market include Lenton Interlok®, NMB Splice Sleeve®, Zap Screwlok®, and Lenton Quick Wedge®. The connectors are proprietary products owned by foreign companies, namely ERICO, Inc., Splice Sleeve North America, Inc. and BarSplice Product, Inc., accordingly. Their designs are complex and require special techniques to mould them into their intended shapes, of which this technique is rather expensive in Malaysia.

The objectives of the study were (a) to develop new splice sleeve connectors by utilizing commercially available steel section as a mean to reduce manufacturing cost and (b) to study their tensile performance and to determine the feasibility of the proposed splice sleeves. Fifteen specimens were tested and their performances were evaluated based on their stiffness, yielding strengths, ultimate tensile capacities, ductility and the failure mode.

**LITERATURE REVIEW**

In order to develop a splice sleeve with the least required development length, general concepts of bond and confinement are studied. It is known that from the literature review, bond performance between a steel bar and concrete can be enhanced through the confining concrete. This behaviour has been studied by several researchers, either experimentally or analytically.

Lutz (1966), Goto (1971) and Thompson (2002) discuss the principle of bond performance. The bond between steel bar and concrete is contributed by three major factors, (a) chemical adhesion, (b) friction, and (c) mechanical interlocking between bar ribs and concrete keys.
Regarding the effects of confinement, Untrauer (1965) found that the bond strength between steel and concrete increases linearly with normal pressure (confinement). He derived an equation that represents the relationship between the compressive strength of concrete, normal pressure and reinforcing bond strength. Soroushian (1989), who investigated the local bond stress behaviour of deformed bars in confined concrete, concluded that the bond strength decreased linearly as the bar diameter increases. Nilson (1975) derived a relationship between bond stress and bar slip in reinforced concrete to study the slip of bar in unconfined concrete. He developed a method to determine the slip from the displacement function by numerical integration of the strain.

Coogler (2006) conducted experimental testing for his master thesis, evaluating the tensile performance of two types of offset splice, namely Lenton Quick Wedge® and Zap ScrewLok®. He employed these splices in full scale simply supported beams to study the loading behaviour.

Jansson (2008) evaluated the performance of two types of in-line splice, Lenton Interlok® and NMB Splice Sleeve® under incremental static and 1 million cycle fatigue loads. The tests were monitored under the Michigan Department of Transportation to determine the suitability of the splices.

Amin Einea (1995) developed new splices by utilizing commercially available pipe sections for field connections. A total of 15 grout-filled pipe splices were tested. He claimed that adequate bond strength could be achieved with the embedded length of seven times the bar diameter, provided that appropriate grout compressive strength and confinement are provided.

DESCRIPTION OF SAMPLES AND TESTING

In this paper, the discussions emphasize on the tensile test results of 15 specimens selected from several different series of splice sleeve connections. Figure 3 illustrates the details of the sleeve specimens. Only Y16 high strength steel bars were investigated, as this bar size is commonly used in the construction sites. High early strength non-shrinkage Sika Grout-215 was used for the bonding material. The embedded length of the reinforcement bars in the sleeves was fixed at less than 150mm. Therefore, most of the overall length of the sleeve was limited to 300mm.

![Figure 3. Detail of the test specimens](image-url)
Table 1 shows the material properties and dimension of the test specimens. Detail descriptions of the specimens are as follows:

- **A-Series**: In specimens A-1 and A-3, each sleeve consists of two semi-circular steel pipes complete with two steel plates welded onto the pipes at 75mm from both ends, while each steel bars were threaded at the end to fix the nut. The nut-headed steel bars were joined head to head in the sleeve by grouting. As for A-2, no modification was made onto the pipe sleeves to receive the insertion of deformed steel bars.

- **B-Series**: The deformed steel bars and nut-headed steel bars were inserted into the 300mm corrugated aluminium sleeves from both ends to meet at mid length of B-1 and B-2, respectively. As for B-1, steel bars were lapped adjacent throughout the length of the sleeve.

- **C-Series**: Four Y10 steel bars were welded to the inner surface of the 65mm-diameter steel pipes from both ends, providing interlocking mechanism for the grout. As for C-3, C-4 and C-5, 2@2mm height rings were welded onto the pipes from both ends to interlock with the grout. Connector C-5 had additional aluminium sleeve placed between the steel bars and the mild steel pipe. The hexagonal tapered nuts were welded onto the Y16 high strength steel bars (Figure 4) before the nut-headed steel bars were being spliced in C-1, C-3 and C-5. Meanwhile, the deformed steel bars were spliced in C-2 and C-4 with 150mm to be embedded in the sleeves.

- **D-Series**: In these connectors, 4@300mm long Y10 steel bars were welded to the short pipes, of 50mm and 25mm at mid span and both end, respectively, to form a cylindrical sleeve. The short pipes of 65mm inner diameter were used for D-1, D-2 and D-3, while 38mm inner diameter short pipes were used for D-4. D-1 and D-2 had their Y10 steel bars welded onto the inner surface of the short pipes, while Y10 steel bars were welded on the outer surface of the short pipes.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Material for the sleeve</th>
<th>Length of sleeve (mm)</th>
<th>Diameter of sleeve (mm)</th>
<th>Effective thickness of sleeve (mm)</th>
<th>Grout strength $f_{ceq}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-Series</td>
<td>Mild steel pipe</td>
<td>200</td>
<td>50</td>
<td>4.05</td>
<td>43.32</td>
</tr>
<tr>
<td>B-Series</td>
<td>Corrugated aluminium sleeve</td>
<td>300</td>
<td>43</td>
<td>≈1.0</td>
<td>58.10</td>
</tr>
<tr>
<td>C-Series</td>
<td>Mild steel pipe</td>
<td>300</td>
<td>65</td>
<td>4.5</td>
<td>62.97</td>
</tr>
<tr>
<td>D-Series</td>
<td>Mild steel pipe</td>
<td>300</td>
<td>65</td>
<td>4.5</td>
<td>51.47</td>
</tr>
</tbody>
</table>

Figure 5 shows the preparations and casting of the specimens. Wooden frames were used to hold the specimens in position before the grout was poured into the sleeve. The Y16 steel bars were inserted into the sleeve from both ends, meeting at mid length before they were tied to the frame. As the grout hardened and achieved the targeted strength of at least 40N/mm², the specimens were tested under incremental tensile load until failure (Figure 3), to obtain their ultimate loading capacity.
Figure 4. Tapered nut welded on steel bar  

Figure 5. Casting of the specimens

Direct tensile tests were conducted in accordance with BS EN 10002-1 2001 “Metallic materials – Tensile Testing – Part 1: Method of test at ambient temperature”. Series A, B and C were tested using 250kN capacity actuator (Figure 6a). They were placed vertically and gripped to the actuator at about 11MPa pressure. Then, the actuator’s arm moved upward gradually, inducing tensile force at a rate of 0.5kN/s. The relationship between incremental load and displacement were recorded during the test. As for D-series specimens, they were tested using the 1000kN capacity actuator (Figure 6b).

Figure 6. Direct tensile test using Dartec actuator

RESULTS AND DISCUSSION

Table 2 summarizes the tensile performance of the specimens, in terms of ultimate loading capacities, P (kN), the corresponding displacement, ΔL (mm), load at yield, Pₚ (kN), ductility ratios, δL/ΔL₀, and also the failure modes of each specimen. Figure 7 shows the relationship of load-displacement of the test specimens. The displacement readings obtained during the testing were the superimposition of: (a) elongation of steel bars, (b) elongation of splice sleeve, (c) bond-slip of the steel bars in the grout, and (d) bond-slip of the grout in the sleeve.
Table 2. Tensile performance of the specimens

<table>
<thead>
<tr>
<th>Sample</th>
<th>Failure load $P_o$ (kN)</th>
<th>Displacement $\Delta L$ (mm)</th>
<th>Load at yield $P_y$ (kN)</th>
<th>$f_{yu}$</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>87.0</td>
<td>8.72</td>
<td>77</td>
<td>1.06</td>
<td>2.18 Bar slipped</td>
</tr>
<tr>
<td>A-2</td>
<td>40.9</td>
<td>1.00</td>
<td>40</td>
<td>0.50</td>
<td>0.8 Bar slipped</td>
</tr>
<tr>
<td>A-3</td>
<td>101.8</td>
<td>5.56</td>
<td>100</td>
<td>1.24</td>
<td>4.7 Bar slipped</td>
</tr>
<tr>
<td>B-1</td>
<td>11.9</td>
<td>2.65</td>
<td>10</td>
<td>0.14</td>
<td>1.9 Sleeve fractured</td>
</tr>
<tr>
<td>B-2</td>
<td>8.7</td>
<td>1.45</td>
<td>8</td>
<td>0.11</td>
<td>1.4 Sleeve fractured</td>
</tr>
<tr>
<td>B-3</td>
<td>136.6</td>
<td>35.51</td>
<td>108</td>
<td>1.65</td>
<td>3.4 Bar slipped</td>
</tr>
<tr>
<td>C-1</td>
<td>122.2</td>
<td>35.51</td>
<td>105</td>
<td>1.48</td>
<td>2.6 Bar fractured</td>
</tr>
<tr>
<td>C-2</td>
<td>134.8</td>
<td>25.45</td>
<td>116</td>
<td>1.84</td>
<td>4.4 5.78 Bar fractured</td>
</tr>
<tr>
<td>C-3</td>
<td>125.1</td>
<td>38.14</td>
<td>117</td>
<td>1.52</td>
<td>3.1 12.3 Bar fractured</td>
</tr>
<tr>
<td>C-4</td>
<td>135.4</td>
<td>29.48</td>
<td>117</td>
<td>1.64</td>
<td>3.2 9.21 Bar fractured</td>
</tr>
<tr>
<td>C-5</td>
<td>123.0</td>
<td>20.94</td>
<td>106</td>
<td>1.49</td>
<td>2.8 7.48 Bar fractured</td>
</tr>
<tr>
<td>D-1</td>
<td>96.0</td>
<td>27.19</td>
<td>76</td>
<td>1.17</td>
<td>7.6 3.58 Bar slipped</td>
</tr>
<tr>
<td>D-2</td>
<td>86.8</td>
<td>11.81</td>
<td>84</td>
<td>1.05</td>
<td>9.3 1.27 Bar slipped</td>
</tr>
<tr>
<td>D-3</td>
<td>94.9</td>
<td>13.94</td>
<td>90</td>
<td>1.15</td>
<td>9.8 1.42 Bar slipped</td>
</tr>
<tr>
<td>D-4</td>
<td>70.9</td>
<td>8.31</td>
<td>70</td>
<td>0.86</td>
<td>8.2 1.01 Bar slipped</td>
</tr>
</tbody>
</table>

The performance of the splice sleeves was evaluated based on their ultimate tensile capacities, stiffness, yielding strengths, ductility and also failure modes. An adequate splice sleeve should have its bond strength equal or greater than the tensile capacity of the connected reinforcing bars. This is to (a) prevent splice failure before the connected reinforcing bars yield, for optimum usage of the capacity of precast elements, and (b) to ensure the ductile behaviour of the splice connection, for survival consideration. Thus, the test specimen will be considered adequate when the steel bars fractured outside the sleeve.
Figure 7. Load-displacement relationship up to 20mm

Failure modes

It is essential to study the failure modes, as they demonstrate the manner of defects and describe the causes of failure so that remedy and improvement can be made. Basically, the failure modes can be categorized into 4 types as shown in Figure 8. These include (a) sleeve fracture, (b) bar fracture, (c) bar slippage, and (d) grout slippage.

Figure 8. Classifications of failure modes
Sleeve fracture

B-1 and B-2 connectors, which utilized the corrugated aluminium sleeve as the sleeve body, fractured at mid length at the discontinuity of steel bars. The sleeve fractured as soon as the grout that bridged the reinforcement bars underwent tensile fracture. The corrugated aluminium sleeves were made of a long deformed aluminium sheet (approximately 1mm in thickness). They were rolled and attached together spirally with internal diameter of approximately 43mm, forming corrugated cylindrical sleeve to encourage grout-sleeve bond. At failure, together with the fracture of the grout, the aluminium sleeve of B-2 underwent tensile failure, while B-1 tore apart at mid length, approximately (see Figure 8(a)).

Bar fracture

All C-Series connectors had their spliced steel bars fractured outside the sleeve, indicating adequacy of bond strength. Either one of the upper or the lower bars, of which was relatively weaker in tension, fractured after enduring severe deformation. The malleable property of steel bar had caused the steel bar to reduce its cross sectional area as it elongated after yielding. This may be caused by higher stress concentration due to the smaller effective area. This occurred at several locations along the steel bars, where plastic deformation was observed. The failure mode of bar fracture was accompanied with a ductile load-displacement response that is preferable for construction, as shown in the C-Series curves of Figure 7.

Bar slippage

A-Series, C-Series and B-3 connectors failed as their steel bars slipped from the surrounding grout. Before the slippage, it was expected that the bar-grout bond relies mainly on the mechanical interlocking effect between the bar ribs and the grout keys, with minor contribution by friction and chemical adhesion, as observed by Lutz (1966) and Goto (1971). In this case, the interlocking mechanism relied on the shear area of the grout keys to resist the slipping force that was derived from the resultant acting perpendicularly to the inclined rib surface (see Figure 9a). The distribution of bond stress along the embedded length is illustrated in Figure 10, which is modified from the bond stress distribution diagram by Ferguson (1988). Initially, at small tension force, higher stress was found near the ends of the bars where the loading was applied, engaging the grout keys at the region to resist the force. Slip occurred as the adhesion between the bar and the grout in this region broke down and the bar ribs began to crush some parts of the grout keys. Then, further loading increment had shifted the bond stress deeper along the bars from both ends of the sleeves, engaging additional ribs to resist the load. The slip of steel bars accumulated as the load increased. Then, as the incremental load was approaching the bond limit, shifting of the bond stress continued as bond stress peaks moved deeper along the bar. Eventually, this triggered ultimate slip of steel bar, because there was no capacity left provided by the interlocking of the steel ribs and the concrete. For most of the A-Series and D-Series specimens, the slip failure occurred suddenly. This failure mode is not preferable in construction, as it indicates that the connectors lack the characteristic of ductility.
Grout slippage

Grout slippage is defined as the slippage occurred between the grout and the sleeve. The typical failure mode of the grout slippage is shown in Figure 8d. As seen in specimen A-2, it failed as the grout slipped together with the reinforcement bar. It was due to the inexistence of the interlocking mechanism between the steel pipe (sleeve) and the grout. The tensile resistance relied on the surface friction between the grout and the steel pipe, of which, according to the theory of friction, increases proportionally as the splitting force (the component force derived from the resultants acting perpendicularly to the inclined surface of bar ribs) acting on the sleeve wall increases (Figure 11). Eventually, at ultimate load, the grout fractured at the discontinuity of the steel bars and subsequently slipped at 40.9kN load.
Tensile Resistance

The tensile resistance of each connector is defined as the maximum load that can be carried and is indicated by the highest failure load obtained from the tensile tests. In this study, the tensile resistance of the connectors ranges between 8.7kN and 135.6kN. Based on the failure modes, the tensile capacities of these connectors are governed by; (a) the tensile strength of the sleeve, (b) the rebar-grout bond strength (c) the grout-sleeve bond strength, and (d) the ultimate tensile strength of the connected reinforcement bars. These factors are discussed in details as follows.

Tensile strength of sleeve

The results show that the sleeve made from mild steel pipe (A and C-series) provides higher tensile resistance compared to the corrugated aluminium sleeve (B-1 and B-2). In the case of the mild steel pipe, the designed yield strength was 250N/mm², and the thickness of the pipes was at least 4mm. The tensile resistance of the splice sleeve can be acquired by multiplying the yield strength with the effective cross sectional area of the sleeve. In this case, it was about twice higher than the tensile capacity of the connected reinforcing bars and as a result A and C series remained unfractured at ultimate load (Figure 12a).

As for B-1 and B-2 series, the end-to-end arrangement of steel bars had caused the aluminium sleeve and the grout that bridged the discontinuity of the steel bars to carry the tensile load (Figure 12b). It is fairly assumed that the tensile strength of the grout was approximately 10% of its compressive strength, which was 5.81N/mm². Therefore, by multiplying the tensile resistance stress with the effective grout area (sleeve area - bar area), the tensile resistance of the grout in the sleeve was 6.9kN. As for the corrugated aluminium sleeves, only limited effective area took part in the tensile resistance since the thickness was approximately 1mm. The tensile stress of the aluminium sleeve was only 90N/mm², which was 36% of the mild steel metal. Multiplication of 90N/mm² with the effective cross sectional area is equal to 6.0kN. The combination of the tensile resistance contributed by the grout and the aluminium sleeve equals to 12.9kN, which is fairly reasonable as compared to the 11.9kN ultimate load of specimen B-1, of which both the grout and the aluminium sleeve fractured at ultimate.
Tensile strength contributed by the bar-grout anchorage bond

It is known from the literature review that the anchorage length of the steel bar, the compressive strength of the bonding material, and the degree of confinement influence the bar-to-concrete bond performance (Soroushian et al., 1991, Hayashi et al., 1993, Amin Elna et al., 1995). In this study, the influence of these factors was rather not obvious and not measurable. This is because the embedded length and the grout strength were not varied, and also the degree of confinement in the sleeve was rather difficult to quantify.

However, it can be seen that, the higher bond strength of C-Series was partially contributed by higher grout strength of 62.97N/mm² compared with the other specimens as listed in Table 1. Besides that, the confinement effect also contributed to the higher bond performance in the sleeves. For A-2, C-3 and C-4 series, the confinement forces were generated due to peripheral tensile resistance of the sleeves, responding to the splitting forces derived from the resultant of the mechanical interlocking mechanism between the Y16 bar ribs and the grout keys. These passive confinement forces resisted the splitting failure of the grout that may decrease the effective shear area of the grout keys in resisting the pull-out force (Figure 13).

A similar principle applies in B-3, where the steel bars were spliced adjacently throughout the length of the corrugated aluminium sleeve. Connector B-3 presented higher bond strength of 135.6kN, although it eventually slipped after a certain degree of elongation.
The 300mm confined lap length is approximately 46% shorter than the required conventional lap length by BS-8110 (which is 35 x bar diameter = 560mm).

C-1 and C-2 provides more efficient confinement to the spliced bars. They generated additional confinement forces instead of relying solely on the passive forces that control the splitting cracks. The active confinement forces were generated by the Y10 bars that were welded onto the sleeve upon movement of the grout together with the Y16 bar towards the direction of the pulling force. These confinement forces were derived from the resultant acting perpendicularly to the Y10 bar ribs and towards the centroid of the sleeve (Figure 14). These confinement forces had efficiently enhanced the bar-grout bond performance by (a) controlling the splitting cracks that leads to the degradation of bonding strength, and (b) inducing additional normal forces to reinforcement bar to increase the friction resistance with the grout.

![Figure 14. Confinement forces generated in C-1 and C-2 connectors](image)

The comparison between C and D-series proved that confinement should be provided throughout the splice length in order to acquire more efficient bond performance. However, the provision of the confinement was inconsistency throughout the length of D-series. Only several portions of the grout (50mm at mid length and 25mm from both ends of the sleeve) were confined using steel pipes. Although D-Series were cast and tested in Polyvinyl Chloride (PVC) pipe, its confinement effects was assumed negligible because of (a) large diameter (110mm) which led to less significant confinement effect to the bond performance, and (b) its plasticity behaviour, which is hardly predictable in the study. The result shows that the D-series provided an averagely about 31% lower tensile capacities compared to the C-Series.

![Figure 15. Bearing area versus shear area on reinforcement bars](image)

Besides that, the surface conditions of the steel bars, which include the rib patterns and the distance between bar ribs, affect the bar-grout bond performance. This is evidence from
specimens A-3 and A-1 that utilized deformed and threaded steel bars respectively. The tensile capacity of A-3 was 14.8% higher as compared to A-1. This result was contributed by the 0.1 relative rib areas of the deformed steel bars used in A-3, which was recognized by many researches as the optimum rib design, due to the optimization between the bond performance and cost-benefit (Abram et al., 1913, Clark et al., 1946, 1949, Darwin et al., 1993, Hamad et al., 1995). The deformed steel bar in A-3 provides higher bond strength compared to the threaded steel bar in A-1. This higher bond strength was contributed by the higher shear/bearing area, thus, engaging larger shear area to resist the slipping force as compared to the threaded steel bars (Figure 15). Since the bond strength was not equally distributed along the embedded length (Goto et al., 1971, Mains et al., 1951), higher relative shear area would provide better resistance towards progressive failure of the grout keys. Hence, the deformed steel bars provide better bond performance compared with the threaded steel bars.

**Tensile strength contributed by the grout-sleeve anchorage bond**

The grout-sleeve bond is an essential requirement to resist the grout from slipping out of the sleeve. Specimen A-2 failed at 40.9kN due to inexistence of interlocking mechanism between the grout and the sleeve. However, by welding the steel plate on the semi-circular pipes as in specimens A-1 and A-3, or by welding Y10 bars that have deformed ribs as in C-1 and C-2, or even by providing welded rings onto the sleeve as in C-3, C-4 and C-5, improved the tensile performance drastically. Figure 12 shows the grout-sleeve bond mechanism for different configurations of the sleeves. Specimen A-2 relied on the surface friction resistance between the grout and the sleeve. Specimen A-3 had an additional sleeve end resistance despite of relying solely to the friction-slip resistance. In C-2 specimen, the grout-sleeve bond was contributed by the surface friction-slip resistance and also the interlock-slip mechanism to the Y10 bars on the sleeve. Finally, C-5 relied on the effective shear area on the grout to resist the slipping force.

**Figure 12. Grout-sleeve bond mechanisms comparison among specimens**

**Tensile strength of steel bars**

All C-Series specimens had their steel bars fractured outside the sleeve, with the fracture loads ranging from 122.2kN to 135.5kN (equivalent to 607.7N/mm² and
672.4N/mm² of bar fracture stress). Excellent bond performance was generated in the sleeves. Although the fractured strengths were inconsistent, the quality of the steel bars were still reliable, as they fractured beyond the yield strength of 410N/mm², of which was 48% to 64% higher. In common practices, the reinforcement bars in reinforced concrete are designed to endure stress less than yielding stress of 410N/mm² (Y-type high strength steel bars), to ensure continuous elastic behaviour of the global structural system for maximum performance. The C-series specimens produced much higher bonding than the yield strength. Therefore, the C-series connectors are suitable to be used in construction industry, provided that sufficient grout strength is provided.

Stiffness

Stiffness is the ratio of the tensile load divided by the corresponding displacement. The specimen with high stiffness ratio endures relatively smaller displacement with correspondence to large tensile force. In load-displacement curve, the stiffness is represented by the slope of the curves.

Due to excellent bar-grout bond, specimens C-1, C-2, C-3, C-4 and C-5 presented higher stiffness as compared to others (interpreted from the slope of load-displacement curve of Figure 4). Then, the stiffness decreased drastically, followed by severe elongation of steel bars before they eventually fractured at 122.2kN, 134.8kN, 125.1kN, 135.4kN, 123.0kN load, accordingly. On the other hand, specimens D-1, D-2, D-3 and D-4 presented relatively lower stiffness due to the (a) inconsistency confinement along the splice length of the specimens, where only 50mm at mid length and 25mm at both ends were confined by using mild steel pipes.

Yield Strength

The yield strength is identified as the steel begins to behave plastically, where some fraction of deformation becomes permanent and non-reversible. The yield strength of the steel is commonly determined by finding the intersection of the load-displacement curve with the parallel 0.2% offset strain line to the initial slope of the curve. However, in this case, the tensile resistance of the splice sleeves is governed by the composite action between the steel bars, the grout and the sleeve. Perfect elastic behaviour is impossible, as the stiffness of the specimens degrades progressively throughout the testing due to propagation of minor internal cracks as a result of interlocking reaction between bar ribs and the grout keys (Figure 14). Therefore, the yield strength obtained from the offset strain line method may not be representative to indicate the significant decrease in stiffness or the beginning of the plastic behaviour. Thus, the yield strengths of the splice sleeves are estimated upon the occurrence of drastic decrease in stiffness (the slope of load-displacement curve).

![Figure 14. Internal crack propagation in grout (modified from Yankelevsky (1985))](image-url)
The yield strength of the specimens, approximated from the load-displacement curves of the specimens, ranged from 8.4kN and 118.8kN. The occurrence of sudden decrease in stiffness of the specimens was governed by (a) bar-grout bond capacity, in the case of specimens A-1, A-3, B-3, D-1, D-2, D-3 and D-4, (b) grout-sleeve bond capacity, in the case of A-2, (c) sleeve tensile capacity, in the case of B-1 and B-2, and also (d) bar yielding strength, of which was weaker.

**Ductility**

Ductility is the property of steel that permits it to reduce in the cross sectional area under tension, before it fails ultimately. An adequate splice sleeve to be utilized as connections in precast concrete structures should provide ductile behaviour. It should endure considerable elongation before it eventually fails by necking, with consequent rapid increase in local stresses. In this study, the ductility ratio is obtained by dividing the corresponding displacement at ultimate state (ΔL) with the initial yield displacement (ΔL₀) of the specimen. The specimens with low ductility ratio (A-series, C-series, B-1 and B-2) are not preferable for use in construction, because they may experience sudden failure.

The grout-filled splice sleeve is formed with two different materials of different behaviour. Slippage of bars from high strength grout gives brittle failure, while fracture of high strength steel bars gives ductile failure. In order to obtain ductile behaviour, the bond should not fail before the steel bars yield, and the steel bars should undergo a certain degree of elongations before fracture. The C-Series presented satisfactory results as they fulfilled the requirements. In terms of loading behaviour (interpreted from the load-displacement curves in Figure 4), they also follow closely to the typical load-displacement pattern of a steel material, enduring through the stages of elasticity, strain-hardening, rupture and also necking.

As for specimen B-3, the reinforcement bars slipped out of the sleeve before reaching the ultimate tensile capacity. Judging on the failure mode, it may not be an adequate splice sleeve requirement. However, the fractured load of 135.6kN is about the capacity of a Y16 steel bar. It also presented the ductility ratio of 10.44, signifying satisfactory elongation before reaching the ultimate state. Hence, B-1 may also be acceptable for construction.

**CONCLUSION**

In this study, a total of fifteen proposed splice sleeves were experimentally tested under incremental static tensile load and were evaluated for feasibilities, based on their stiffness, yielding strength, ultimate tensile capacities, ductility ratios and failure modes. The study concluded that:

i) An adequate splice sleeve connectors should have the following criteria:
   a. undergoes failure mode of bar fractured instead of slippage
   b. presents high stiffness behaviour, where small displacement with correspondence of large pulling force takes place
c. presents high bond strength, which is comparable to the tensile resistance of the spliced steel bars, and also high ductility ratio for survival considerations in real practice.

ii) Based on the failure modes observed, the tensile capacities of a splice sleeve are governed by the following factors which are to be considered in the design of splice sleeve:
   a. tensile strength of the sleeve,
   b. the rebar-grout bond strength,
   c. the grout-sleeve bond strength, and
   d. the tensile strength of reinforcement bars.

iii) Specimens C-1, C-2, C-3, C-4 and C-5 are considered acceptable and feasible to function as a connection system to carry full tensile load.

iv) As for specimen B-3, although the connected reinforcement bars slipped, it produced high bonding strength and high ductility ratio. Thus, it is also considered acceptable.

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