BOND BEHAVIOR OF GROUTED SPIRAL AND SPLICE CONNECTION UNDER DIRECT AXIAL AND FLEXURAL PULLOUT LOAD

SEYED JAMAL ALDIN HOSSEINI

UNIVERSITI TEKNOLOGI MALAYSIA
BOND BEHAVIOR OF GROUTED SPIRAL AND SPLICE CONNECTION
UNDER DIRECT AXIAL AND FLEXURAL PULLOUT LOAD

SEYED JAMAL ALDIN HOSSEINI

A thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi of Malaysia

AUGUST 2015
“To my beloved parents and my lovely wife, for their encouragement and support”
ACKNOWLEDGEMENT

First of all, gratefulness of thanks to our creator, “ALLAH” for his continuous blessing, which make this work neither the first nor the last.

Special thanks to Assoc. Prof. Dr. Ahmad Baharuddin Abd Rahman for giving this opportunity to work under his supervision and for sharing his great knowledge and experience with me.

I would like to convey my deepest gratitude to Mrs. Zeinab Deriss for her support and encouragement. Appreciation is also extended to all people who gave me heartfelt corporation and shared their knowledge.

Finally, I would like to send my deep appreciations to my family who brought me up with love.
ABSTRACT

The conventional grouted connections with corrugated aluminium sleeves have been used widely in precast concrete construction. The main problem of the conventional grouted sleeve connections is the need for long embedded lengths of reinforcement rebars to achieve full continuity. There is a tendency for the long rebars to touch the sleeve wall and subsequently preventing penetration of grout around the rebar. Since the grout inside the sleeve cannot be inspected after installation, there is doubt that the main rebar is fully bonded. This study proposed a grouted spiral connection which can overcome the use of long embedded length of connected rebars. The main objective of this study was to investigate the effect of spiral confinement on the bond stress-slip relationship. The experimental program was carried out in two phases, Phase I and Phase II. In Phase I, a total of thirty-six spiral connections were subjected to increasing direct axial pullout loads. Then, in Phase II, a total of twelve beams comprising spiral connections were subjected to flexural pullout loads. Parameters considered in this study were pitch distance and diameter of spiral connections. The experimental results showed that the use of smaller pitch distance and spiral diameter resulted in higher bond strength. However, the spiral diameter had more dominant confinement effect such that it increased the bond strength of direct and flexural pullout tests very dramatically by 34.5% and 40%, respectively. In addition, lower bond strength from the beam tests was reported as compared to the axial pullout tests. The bond strengths obtained from the flexural pullout tests were within the range of 0.74 to 0.79 times the bond strengths of the axial pullout tests. Finally, analytical equations were proposed to express the bond stress-slip relationship and bond strength of the grouted spiral connection.
ABSTRAK

Penggunaan sambungan grout konvensional dengan salur aluminium telah digunakan secara meluas dalam pembinaan konkrit pratuang. Masalah utama daripada sambungan grout konvensional adalah keperluan panjang tambatan untuk mencapai kekuatan penuh. Terdapat kecenderungan untuk tetulang bar yang panjang menyentuh dinding salur dan seterusnya menghalang penembusan grout di sekitar bar. Oleh kerana grout di dalam salur tidak boleh diperiksa selepas pemasangan, terdapat keraguan tetulang utama tidak terikat sepenuhnya. Kajian ini mencadangkan satu sambungan gegelung grout yang boleh mengatasi masalah penggunaan tambatan tetulang keluli yang terlalu panjang. Objektif utama kajian ini adalah untuk menyiasat kesan kurungan gegelung ke atas hubungan tegasan ikatan-gelinciran. Program eksperimen telah dijalankan dalam dua fasa, Fasa I dan Fasa II. Dalam Fasa I, sejumlah tiga puluh enam sambungan gegelung dikenaka tindakan beban tegangan paksi. Di dalam Fasa II, sebanyak dua belas rasuk dengan sambungan gegelung dikenakan beban lenturan. Parameter yang dikaji adalah jarak antara gegelung dan diameter gegelung penyambung. Keputusan eksperimen menunjukkan bahawa penggunaan jarak antara gegelung dan diameter gegelung yang kecil dapat meningkatkan kekuatan ikatan. Bagaimanapun, kesan diameter adalah lebih dominan dalam meningkatkan kekuatan ikatan dengan peningkatan sebanyak 34.5% dan 40% masing-masing bagi ujikaji beban paksi dan lenturan. Di samping itu, kekuatan ikatan yang lebih rendah didapati berlaku pada ujian rasuk berbanding dengan ujian tegangan paksi. Kekuatan ikatan yang diperolehi daripada ujian lenturan adalah dalam julat 0.74-0.79 kali ganda kekuatan ikatan tegangan paksi. Akhirnya, persamaan analitik telah dicadangkan untuk menyatakan hubungan tegasan ikatan- gelinciran dan kekuatan ikatan bagi sambungan gegelung grout.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>ii</td>
<td></td>
</tr>
<tr>
<td>DEDICATION</td>
<td>iii</td>
<td></td>
</tr>
<tr>
<td>ACKNOWLEDGMENT</td>
<td>iv</td>
<td></td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>v</td>
<td></td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>vi</td>
<td></td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>vii</td>
<td></td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
<td></td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiv</td>
<td></td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>xx</td>
<td></td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xxii</td>
<td></td>
</tr>
</tbody>
</table>

1  INTRODUCTION  
1.1  Introduction  
1.2  Background of Study  
1.3  Problem Statements  
1.4  Objective  
1.5  Scope of Research  
1.6  Thesis Organization  

2  LITERATURE REVIEW  
2.1  Introduction  
2.2  Bond Mechanisms  
2.3  Bond of Steel Reinforcement Bars  
2.3.1  Mechanical Interlocking
2.3.2 Friction 19
2.3.3 Chemical Adhesion 19

2.4 Factors Influencing Bond Behavior 19
2.4.1 Confinement 20
2.4.1.1 Previous Research on the Confinement 21
2.4.1.2 Effect of Confinement on the Bond Failure 27
2.4.2 Strength of Bonding Material 29

2.5 Previous Research Studies on Grouted Connections 30

2.6 Experimental Investigation on the Bond Force of Splice Bars 35
2.6.1 Comparison with ACI 38

2.7 Bond Stress-Slip 40
2.7.1 Analytical Model of Bond Stress-Slip 40
2.7.1.1 BPE Model 41
2.7.1.2 Haskett et al.’s Model 43
2.7.1.3 Soroushian’s Model 44

2.7.2 Equation of Bond Stress-Slip 46

2.8 Standard Bond Tests 48
2.8.1 Review of Experimental Setups of Direct Pullout Test 49
2.8.1.1 Single Pullout Test 49
2.8.1.2 Double Pullout Test 50

2.8.2 Review of Experimental Setups of Beam Tests (Flexural Pullout Test) 51

2.9 Summary 53

3 RESEARCH METHODOLOGY 55

3.1 Introduction 55

3.2 Preliminary Study 58

3.3 Direct Pullout Tests 61
3.3.1 Details of Specimens 61
3.3.1.1 Trial Specimens 61
3.3.1.2 Grouted Spiral Connections 63

3.3.2 Preparations of Specimens 65
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.3</td>
<td>Experimental Setup of Direct Pullout Load Test</td>
<td>67</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Data Acquisition System</td>
<td>68</td>
</tr>
<tr>
<td>3.4</td>
<td>Experimental Setups of Flexural Pullout Tests</td>
<td>69</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Details of Specimens</td>
<td>70</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Preparations of Specimens</td>
<td>73</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Specifications of Material for the Beam Specimens</td>
<td>81</td>
</tr>
<tr>
<td>3.4.4</td>
<td>Specifications of Material for the Grouted Spiral Connections</td>
<td>82</td>
</tr>
<tr>
<td>3.4.5</td>
<td>Instrumentations</td>
<td>85</td>
</tr>
<tr>
<td>3.4.5.1</td>
<td>Measurement of Load</td>
<td>85</td>
</tr>
<tr>
<td>3.4.5.2</td>
<td>Measurement of Slip</td>
<td>86</td>
</tr>
<tr>
<td>3.4.5.3</td>
<td>Measurement of Steel Strain</td>
<td>87</td>
</tr>
<tr>
<td>3.4.6</td>
<td>Data Acquisition System</td>
<td>88</td>
</tr>
<tr>
<td>3.4.7</td>
<td>Load Control</td>
<td>89</td>
</tr>
<tr>
<td>3.5</td>
<td>Summary</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td><strong>PHASE I: BEHAVIOR OF GROUTED SPIRAL CONNECTIONS SUBJECTED TO DIRECT AXIAL PULLOUT</strong></td>
<td>92</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>92</td>
</tr>
<tr>
<td>4.2</td>
<td>Tensile Test Results of Grouted Spiral Connections</td>
<td>93</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Mechanism of Tensile Force Transfer in Trial Specimens</td>
<td>96</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Mechanism of Tensile Force Transfer in others Series</td>
<td>102</td>
</tr>
<tr>
<td>4.2.2.1</td>
<td>Failure Modes of the Grouted Spirals</td>
<td>104</td>
</tr>
<tr>
<td>4.2.2.2</td>
<td>Behavior of Tensile Strain in the Connected Main Bars</td>
<td>107</td>
</tr>
<tr>
<td>4.3</td>
<td>Structural Behavior</td>
<td>109</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Interlocking Mechanism of Grouted Spiral Connections</td>
<td>111</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Splitting Cracks and Effects</td>
<td>113</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Confinement Effects</td>
<td>115</td>
</tr>
<tr>
<td>4.4</td>
<td>Performance of Grouted Spiral Connections</td>
<td>116</td>
</tr>
</tbody>
</table>
5 PHASE II: BEHAVIOR OF GROUTED SPIRAL CONNECTIONS SUBJECTED TO INCREASING FLEXURAL PULLOUT

5.1 Introduction

5.2 Flexural Test Results of Grouted Spiral Connections
   5.2.1 Mechanism of Force Transfer in Trial Specimens
   5.2.2 Flexural Test Results of other Series
      5.2.2.1 Failure Modes of the Grouted Spiral Connections
      5.2.2.2 Behavior of Tensile Strain in Connected Main Bars

5.3 Comparison of Results between Direct Axial and Flexural Pullout Loads

5.4 Design Recommendation

5.5 Summary

6 ANALYTICAL BEHAVIOR OF GROUTED SPIRAL CONNECTION UNDER AXIAL AND FLEXURAL PULLOUT

6.1 Introduction

6.2 Bond Stress-Slip Behavior of Grouted Spiral Connections
   6.2.1 Analysis of Bond-Slip Relationship by Curve Fitting
   6.2.2 Modelling of the Bond Stress-Slip Relationship

6.3 Evaluating the Confinement Effect by Bond Energy

6.4 Prediction of Bond Strength of Spiral Connections in Deformed Steel Bars

6.5 Comparison with Orangun’s Equation
6.6 Limitations 179
6.7 Summary 180

7 CONCLUSIONS 181
7.1 Summary 181
7.2 Conclusion 182
7.3 Recommendations for Future Research 185

REFERENCES 187
Appendices A-C 193-210
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Comparisons of the commercial and proposed connections of this research</td>
<td>3</td>
</tr>
<tr>
<td>2.1</td>
<td>Application of NMB splice sleeve and Lenton Interlok</td>
<td>32</td>
</tr>
<tr>
<td>2.2</td>
<td>Test-prediction ratios for bars confined by transverse reinforcement [45]</td>
<td>39</td>
</tr>
<tr>
<td>2.3</td>
<td>The value of pitch distance studied by other researchers</td>
<td>45</td>
</tr>
<tr>
<td>2.4</td>
<td>Assessment of the performance of the prediction models</td>
<td>48</td>
</tr>
<tr>
<td>3.1</td>
<td>Preliminary feasibility evaluation of specimens in preliminary study</td>
<td>60</td>
</tr>
<tr>
<td>3.2</td>
<td>Details of trial specimens</td>
<td>62</td>
</tr>
<tr>
<td>3.3</td>
<td>Dimension of all series in Phase I</td>
<td>64</td>
</tr>
<tr>
<td>3.4</td>
<td>Details of grouted spiral connection in Phase II</td>
<td>73</td>
</tr>
<tr>
<td>3.5</td>
<td>Mix proportion of concrete in grade 40</td>
<td>81</td>
</tr>
<tr>
<td>3.6</td>
<td>Description of concrete in grade 40</td>
<td>82</td>
</tr>
<tr>
<td>3.7</td>
<td>Average specifications of Sika Grout-215</td>
<td>84</td>
</tr>
<tr>
<td>3.8</td>
<td>Properties for the rib parameters</td>
<td>84</td>
</tr>
<tr>
<td>3.9</td>
<td>Tensile test results of steel reinforcement bars</td>
<td>84</td>
</tr>
<tr>
<td>3.10</td>
<td>Specifications of strain gauges for deformed steel main bar</td>
<td>87</td>
</tr>
<tr>
<td>3.11</td>
<td>The measured data and accuracies</td>
<td>89</td>
</tr>
<tr>
<td>4.1</td>
<td>Summary of test results of grouted spiral connection</td>
<td>94</td>
</tr>
<tr>
<td>4.2</td>
<td>Average of test results in trial specimens</td>
<td>96</td>
</tr>
<tr>
<td>4.3</td>
<td>Average of test results in Series $D_s$ 25, $D_s$ 35 and $D_s$ 45</td>
<td>103</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.4</td>
<td>Bond stiffness of the grouted spiral connections, MPa/mm</td>
<td>120</td>
</tr>
<tr>
<td>4.5</td>
<td>Strength ratio of specimens</td>
<td>128</td>
</tr>
<tr>
<td>4.6</td>
<td>Bond strength, (MPa) with respect to different spiral diameters</td>
<td>129</td>
</tr>
<tr>
<td>4.7</td>
<td>Bond strength, (MPa) with respect to different pitch distance</td>
<td>129</td>
</tr>
<tr>
<td>5.1</td>
<td>Test results of flexural pullout loads</td>
<td>134</td>
</tr>
<tr>
<td>5.2</td>
<td>Bond strength, (MPa) with respect to different spiral diameter</td>
<td>139</td>
</tr>
<tr>
<td>5.3</td>
<td>Bond strength, (MPa) with respect to different pitch distance</td>
<td>140</td>
</tr>
<tr>
<td>5.4</td>
<td>Comparison of bond strength between axial and flexural pullout tests</td>
<td>148</td>
</tr>
<tr>
<td>5.5</td>
<td>Calculation of required embedded length</td>
<td>151</td>
</tr>
<tr>
<td>6.1</td>
<td>Curve-fitting parameter of $\alpha$ and $\beta$</td>
<td>161</td>
</tr>
<tr>
<td>6.2</td>
<td>Bond energy of grouted spiral connections tested in Phase I</td>
<td>167</td>
</tr>
<tr>
<td>6.3</td>
<td>Bond energy of grouted spiral connections tested in Phase II</td>
<td>168</td>
</tr>
<tr>
<td>6.4</td>
<td>Comparison between test results in Phase I and proposed Equation 6.6</td>
<td>171</td>
</tr>
<tr>
<td>6.5</td>
<td>Comparison between test results in Phase II and proposed Equation 6.7</td>
<td>172</td>
</tr>
<tr>
<td>6.6</td>
<td>Values of parameters used for Equation 6.8</td>
<td>175</td>
</tr>
<tr>
<td>6.7</td>
<td>Comparison between test results in Phase I and Equation 6.9</td>
<td>178</td>
</tr>
<tr>
<td>6.8</td>
<td>Comparison between test results in Phase II and Equation 6.9</td>
<td>179</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>FIGURE NO.</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Grouted splice connection in precast concrete components [13]</td>
<td>4</td>
</tr>
<tr>
<td>1.2</td>
<td>Mechanism of load transfer [17]</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Spiral confinement in splice connections [29]</td>
<td>8</td>
</tr>
<tr>
<td>1.4</td>
<td>Projecting the long embedded length in conventional grouted sleeve [30]</td>
<td>9</td>
</tr>
<tr>
<td>1.5</td>
<td>Cross section through grouted sleeve column splice [31]</td>
<td>10</td>
</tr>
<tr>
<td>2.1</td>
<td>Grouted sleeve connection and connecting elements [33]</td>
<td>15</td>
</tr>
<tr>
<td>2.2</td>
<td>Distribution of bond stress at different levels of pulling force [36]</td>
<td>16</td>
</tr>
<tr>
<td>2.3</td>
<td>(a) Bond force transfer mechanisms [45], (b) typical bond stress-slip relationship [46]</td>
<td>18</td>
</tr>
<tr>
<td>2.4</td>
<td>(a) Plain round bar, (b) lateral pressure parallel to the transverse rib, (c) lateral pressure perpendicular to the transverse rib [54]</td>
<td>22</td>
</tr>
<tr>
<td>2.5</td>
<td>Typical failure pattern (a) without spiral, (b) with spiral [56]</td>
<td>23</td>
</tr>
<tr>
<td>2.6</td>
<td>Grouted spiral connection (a) four splice bars inside the spiral [61], (b) four splice bars outside the spiral</td>
<td>24</td>
</tr>
<tr>
<td>2.7</td>
<td>Anchorage of beam reinforcement at exterior joints [55]</td>
<td>25</td>
</tr>
<tr>
<td>2.8</td>
<td>Stress-slip responses under confinement of transverse reinforcement [55]</td>
<td>26</td>
</tr>
<tr>
<td>2.9</td>
<td>Effect of confinement on the bond failure (a) by splitting in an embedded bar without any confinement, (b) by pullout with present of confinement [66]</td>
<td>28</td>
</tr>
<tr>
<td>2.10</td>
<td>Relationships of bond stress versus displacement [72]</td>
<td>30</td>
</tr>
</tbody>
</table>
Proprietary products tested by Jansson [73]  
Fatigue test setup by Jansson [73]  
Details of test specimens [7]  
Proposed bar splice sleeve [33]  
Configuration of test specimens given by Ling et al. [59]  
Test-prediction ratios for descriptive equations with confinement provided by transverse reinforcement [45]  
Schematic representation of Eligehausen’s tests [42]  
BPE model [42]  
Haskett et al.’s model [84]  
Typical types of pullout tests [91]  
Direct Tension Pullout Bond Test (DTP-BT) [91, 92]  
Experimental setup of tensile load test by Einea et al [7]  
Diagram and reinforcement of RILEM beam test, test pattern for $d_b \geq 16$ mm [95]  
Modification of RILEM beam tests by other researchers [97]  
Flow chart of the research carried out  
Labelling of the specimens  
Series of grouted splices tested in preliminary study [98]  
Configuration of trial specimens T1, T2 and T3  
Configuration spiral with four splice bars in trial specimen T3  
Details of all specimens comprising main bars, spiral, and splice bars  
The arrangement of connections in the PVC before casting  
Preparation of specimens  
Installation of strain gauge  
Experimental setup of tensile load test  
Data acquisition system of tensile load test  
Grouted spiral connections in flexural pullout test
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.13</td>
<td>Details of specimen in Phase II</td>
<td>72</td>
</tr>
<tr>
<td>3.14</td>
<td>Preparation of formwork</td>
<td>74</td>
</tr>
<tr>
<td>3.15</td>
<td>Preparation of reinforcement cage</td>
<td>75</td>
</tr>
<tr>
<td>3.16</td>
<td>Preparing the beam specimen</td>
<td>77</td>
</tr>
<tr>
<td>3.17</td>
<td>Casting of ready-mix concrete</td>
<td>79</td>
</tr>
<tr>
<td>3.18</td>
<td>Compacting of concrete with a hand-held vibrator</td>
<td>80</td>
</tr>
<tr>
<td>3.19</td>
<td>Smoothing the surface of beam specimens</td>
<td>80</td>
</tr>
<tr>
<td>3.20</td>
<td>Demoulding and preparing the specimens in final step</td>
<td>81</td>
</tr>
<tr>
<td>3.21</td>
<td>Position of grouted spiral connection in beam specimen</td>
<td>83</td>
</tr>
<tr>
<td>3.22</td>
<td>The rib geometry of deformed steel bar</td>
<td>83</td>
</tr>
<tr>
<td>3.23</td>
<td>Position of load cell</td>
<td>86</td>
</tr>
<tr>
<td>3.24</td>
<td>Arrangement of LVDTs</td>
<td>87</td>
</tr>
<tr>
<td>3.25</td>
<td>Location of strain gauge attached to the main bar</td>
<td>88</td>
</tr>
<tr>
<td>3.26</td>
<td>Data acquisition system for flexural pullout tests</td>
<td>89</td>
</tr>
<tr>
<td>3.27</td>
<td>Setup of loading frame for flexural pullout tests</td>
<td>90</td>
</tr>
<tr>
<td>4.1</td>
<td>Specimen A-T1-S (a) failure mode, (b) force transfer mechanism</td>
<td>97</td>
</tr>
<tr>
<td>4.2</td>
<td>Specimen A-T2-S (a) failure mode, (b) force transfer mechanism</td>
<td>98</td>
</tr>
<tr>
<td>4.3</td>
<td>Comparison of slip between A-T1-S and A-T2-S</td>
<td>99</td>
</tr>
<tr>
<td>4.4</td>
<td>Confinement effects contributed by the splice bars in A-T3-S</td>
<td>100</td>
</tr>
<tr>
<td>4.5</td>
<td>Comparison of bond strength between A-T2-S and A-T3-S</td>
<td>101</td>
</tr>
<tr>
<td>4.6</td>
<td>Failure mode of specimen A-T3-S</td>
<td>102</td>
</tr>
<tr>
<td>4.7</td>
<td>Pullout failure mode</td>
<td>104</td>
</tr>
<tr>
<td>4.8</td>
<td>Mechanism of bar bond-slip failure</td>
<td>106</td>
</tr>
<tr>
<td>4.9</td>
<td>Bond stress distribution (modified from Ferguson model) [36]</td>
<td>107</td>
</tr>
<tr>
<td>4.10</td>
<td>Stress-strain in the main connected bar</td>
<td>108</td>
</tr>
<tr>
<td>4.11</td>
<td>Failure mode (a) without radial crack, (b) with radial crack</td>
<td>110</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.12</td>
<td>Mechanical interlocking mechanism of bond [108]</td>
<td>112</td>
</tr>
<tr>
<td>4.13</td>
<td>Componential stresses of resultant stress [108]</td>
<td>112</td>
</tr>
<tr>
<td>4.14</td>
<td>Componential stress</td>
<td>112</td>
</tr>
<tr>
<td>4.15</td>
<td>Propagation of splitting cracks and effects [111]</td>
<td>113</td>
</tr>
<tr>
<td>4.16</td>
<td>Componential derivation of resultant bearing stress [108]</td>
<td>114</td>
</tr>
<tr>
<td>4.17</td>
<td>Reduction of shear area due to splitting cracks [108]</td>
<td>115</td>
</tr>
<tr>
<td>4.18</td>
<td>Passive confinement generated by spiral</td>
<td>116</td>
</tr>
<tr>
<td>4.19</td>
<td>Best-fit straight lines to calculate the bond stiffness of connection</td>
<td>117</td>
</tr>
<tr>
<td>4.20</td>
<td>Comparison of average bond stiffness in all series</td>
<td>119</td>
</tr>
<tr>
<td>4.21</td>
<td>Effect of spiral diameter on the average bond stiffness</td>
<td>119</td>
</tr>
<tr>
<td>4.22</td>
<td>Bar slips due to micro-space and compressive deformations of grout [35]</td>
<td>122</td>
</tr>
<tr>
<td>4.23</td>
<td>Bar slips due to micro-space and compressive deformations of grout</td>
<td>122</td>
</tr>
<tr>
<td>4.24</td>
<td>Development of inclined cracks [55]</td>
<td>123</td>
</tr>
<tr>
<td>4.25</td>
<td>Bond strength versus pitch distance</td>
<td>125</td>
</tr>
<tr>
<td>4.26</td>
<td>Stress transfer mechanism</td>
<td>126</td>
</tr>
<tr>
<td>5.1</td>
<td>Flexural pullout experimental (a) beam details showing the spiral connection, unbonded length of rebar, loads and LVDTs positions, (b) actual beam tested in the laboratory</td>
<td>133</td>
</tr>
<tr>
<td>5.2</td>
<td>Grout fracture initiating the bar pullout</td>
<td>135</td>
</tr>
<tr>
<td>5.3</td>
<td>Comparison of bond strength between specimens F-T3-S with splice bars and F-T2-S without splice bars</td>
<td>136</td>
</tr>
<tr>
<td>5.4</td>
<td>Bond strength versus spiral diameter under flexural pullout</td>
<td>138</td>
</tr>
<tr>
<td>5.5</td>
<td>Comparison of confined surface area</td>
<td>138</td>
</tr>
<tr>
<td>5.6</td>
<td>Bond strength versus pitch distance</td>
<td>139</td>
</tr>
<tr>
<td>5.7</td>
<td>The location of the failure in the left side of the beam in connector</td>
<td>141</td>
</tr>
<tr>
<td>5.8</td>
<td>Failure mode (a)-(b) flexural pullout with the grouted connection located inside the left beam, (c) pullout of the main rebar</td>
<td>141</td>
</tr>
</tbody>
</table>
5.9  Stress-strain of specimens under flexural pullout test (a) F-P15-D25-S, (b) F-P35-D25-S

5.10 Comparison of bond strength between direct axial and flexural pullout (a) bond strength versus spiral diameter, (b) bond strength versus pitch distance

5.11 Stress-strain in the main steel bar (a) specimen A-P15-D25-S under direct axial pullout test, (b) specimen F-P15-D25-S under flexural pullout test

5.12 Bond stress-slip relationship (a) specimen A-P15-D25-S under direct axial pullout test, (b) specimen F-P15-D25-S under flexural pullout test

5.13 Level of bond strength of specimens for different series

6.1  Analytical behavior of grouted spiral connection

6.2  Curve fitting of experimental bond stress-slip of grouted spiral connection (a) under direct axial pullout, (b) under flexural pullout

6.3  Comparison of bond stress-slip relationships between experimental results and curve fitting equation of (a) specimen A-P25-D35-S direct axial pullout test, (b) specimen F-P25-D35-S under flexural pullout test

6.4  (a) Configuration of specimen in research of Soroushian model [55], (b) equivalent Soroushian model used in the spiral connections

6.5  Comparison between predicted bond stress-slip relationships with experimental results (a) A-P15-D25-S (I), (b) A-P25-D25-S (I), (c) F-P15-D25-S, (d) F-P25-D25-S

6.6  Bond energy (a) A-P15-D25-S, (b) A-P15-D35-S and (c) A-P15-D35-S in direct axial pullout in Phase I

6.7  Bond energy (a) F-P15-D25-S (b) F-P15-D35-S and (c) F-P15-D35-S in flexural pullout in Phase II

6.8  Statistical approach- logarithmic regression method for predicting parametric response (a) direct axial pullout, (b) flexural pullout

6.9  Grout confined area in grouted spiral connections

6.10 Comparison between direct axial pullout and Equation 6.9

6.11 Comparison between flexural pullout and Equation 6.9
LIST OF SYMBOLS

P - Applied load
\( d_b \) - Diameter of main bar
\( l_d \) - Embedded length
\( \tau \) - Average bond stress
U - Bond strength of concrete
\( f_n \) - Lateral confining pressure
\( f_{cu} \) - Concrete compressive strength
\( f_{bt} \) - Bond stress
\( T_b \) - Bond force
\( A_b \) - Cross sectional area of spliced bars
\( A_{tr} \) - Area of transverse reinforcement normal to the plane of splitting through the anchored bars
\( C_{min} \) - Smaller of minimum concrete cover or \( \frac{1}{2} \) of clear spacing between bars
\( f_{yt} \) - Yield strength of transverse reinforcement
\( s \) - Spacing of transverse reinforcement
\( n \) - Number of bars developed or splice at the same location
\( C_{So} \) - Side cover
\( C_{Si} \) - \( \frac{1}{2} \) of the bar clear spacing
\( C_s \) - Minimum \((C_{So}, C_{Si} + 6.4m)\)
\( C_b \) - Bottom cover
\( C_{max} \) - Maximum \((C_b, C_s)\)
\( \tau_{max} \) - Maximum bond strength
S - Slip
\( s_1 \) - Slip at maximum bond strength of \( \tau_1 \)
\( \alpha \) - A curve-fitting parameter
\( f'_c \) - Tensile strength of concrete
\( f_s \) - Steel stress
\( X \) - Distance from loaded face pullout bond specimen.
\( x \) - Distance from center of embedded bar
\( D \) - Diameter of cylindrical grout
\( D_s \) - Diameter of spiral
\( P_s \) - Pitch distance of spiral
\( L_s \) - Length of grouted spiral connection
\( L_e \) - Embedded length of main connected bar
\( N_c \) - Number of Coil
\( h \) - Rib height
\( c \) - Rib spacing
\( \nu \) - Rib inclination
\( f_{c,g} \) - Compressive strength of grout
\( \sigma \) - Stress
\( K_s \) - Stiffness
\( R_s \) - Strength ratio
\( f_{u,b} \) - Maximum stress at failure
\( P_u \) - Load capacity
\( f_{s,y,b} \) - Specified yield strength
\( T \) - Tensile load in the main bars of beam specimen
\( a \) - Shear span
\( j \) - Distance between the resultant tensile and compressive loads
\( \gamma \) - Ratios between bond strength of axial and flexural pullout
\( \beta \) - A curve-fitting parameter
\( A_g \) - Confined grout, cross sectional area
\( f_{spiral} \) - Tensile stress in spiral
\( A_{spiral} \) - Cross sectional areas of the spiral
\( d_{spiral} \) - Diameter of cross sectional area of spiral
\( d_{sb} \) - Diameter of splice bar
\( P_g \) - Tensile strength of grout in connection
\( P_{spiral} \) - Tensile load endured by the spiral
# LIST OF APPENDICES

<table>
<thead>
<tr>
<th>APPENDIX</th>
<th>TITLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Response of grouted spiral connection with deformed steel bars under direct axial pullout in Phase I</td>
<td>193</td>
</tr>
<tr>
<td>B</td>
<td>Response of grouted spiral connection with deformed steel bars under flexural pullout in Phase II</td>
<td>199</td>
</tr>
<tr>
<td>C</td>
<td>List of publication</td>
<td>210</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Introduction

The construction industry in Malaysia has shifted from conventional reinforced concrete system to industrialized building system (IBS) through the application of precast concrete system. The precast concrete system has led the building market to an extremely competitive environment. Using this system, considerable amount of building components are fabricated in factories in a fully controlled condition by means of proper equipment. The precast concrete system has considerable advantages such as certainty in cost and time, enhancing occupational health and safety, achieving higher construction productivity and quality, reliance on manual foreign labor, and decreasing the cost of construction [1].

In 1960, Ministry of Local Government and Housing visited a number of European countries for evaluation of their housing development program [2], which led to initiating IBS in Malaysia. Then, the government dedicated about 22.7 acres of land along Jalan Pekeliling, Kuala Lumpur to a great project that consisted of seven blocks of 17 stories flat, 3000 units of low-cast flat, and 40 shop lots [3].

In 2006, the Malaysian construction industry re-introduced the IBS system with the expectation the new technologies in precast concrete can be adopted for innovative construction techniques. For instance, the Construction Industry Master
Plan (CIMP) 2006-2015 published in December 2006 was an attempt to plan the direction for future developments of the Malaysian Construction Industry. In the 2005 Budget, the construction of 100,000 units of reasonably-priced houses using IBS was pledged by the government. The Surat Pekeliling Perbendaharaan Bil. 7 Tahun has 2008 strongly asserted that the government’s projects must use IBS in their construction process not less than 70% of the whole structures [1]. These efforts demonstrate the situation of IBS in the construction industry of Malaysia.

One of the major concerns that commonly arise with regard to the use of prefabricated precast concrete components is the need to develop quality connections in a way to maintain the structural integrity through the precast sections [4]. In the precast continuous construction system, both the design and structural details of the precast connections should have the same features of cast-in-place connection [5]. In this regard, the America Concrete Institute (ACI) has published different details on how to emulate cast-in-places in the precast construction sites [6]. On the other hand, still there is not enough supplementary information in the ACI code regarding the design of precast connections in particular the knowledge related to continuity and bond in reinforcement bars.

In order to achieve full continuity of reinforcement bars for joining precast concrete components, grouted splice connectors are preferred and employed (see Figure 1.1). Grouted splice connectors have shown the capability of being used as connections in the precast concrete structures. These connectors reduced the splice length for ensuring the continuity of steel bars considerably [7]. The splice connectors make the installation process simpler and solve the problems of bar congestion and detailing, especially in structures that are heavily reinforced[8]. For the first time, in the late 1960s [9, 10], this splice method was introduced by Dr. Alfred A. Yee upon the invention of NMB splice sleeve® [10]. From that time, different types of mechanical couplers such as BarSplice Double Barrel Zap Screwlok®, Lenton Interlok® [11, 12] Lenton QuickWedge®, etc. have been developed and commercialised. Most of the splice connectors have been invented by private individuals and are difficult to obtain the technical details due to the proprietorship rights. Due to limited literature regarding the behavior of grouted
splices connections, researchers prefer to investigate the non-proprietary splice that is inexpensive. Table 1.1 shows the differences between the commercial connections and non-proprietary splice connections which were studied in this research. The commercial splice connections normally required special mould to fabricate and are made from cast iron. On the other hand, the proposed non-proprietary connectors required steel pipe, spiral and splice bars only. Concerning the performance, an adequate splice connector should be capable of providing high quality assurance in bond strength even with short spliced lengths. In this splices technique, the strength of the splice joint relies heavily on the anchorage bond.

**Table 1.1:** Comparisons of the commercial and proposed connections of this research

<table>
<thead>
<tr>
<th>Commercial splice connector</th>
<th>Proposed splice connector in this research</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMB splice sleeve</td>
<td>Steel pipe with spiral confinement</td>
</tr>
<tr>
<td>Double Barrel Zap Screwlok</td>
<td>Spiral confinement with four splice bars</td>
</tr>
<tr>
<td>Lenton Interlok</td>
<td></td>
</tr>
</tbody>
</table>

Characteristics of commercial splice connectors:
1. Need special moulds to fabricate the thread and splice which is expensive
2. Cast iron is used for the splice which is brittle
3. Proprietary

Characteristics of proposed non-proprietary splice connectors:
1. Steel pipe spiral and splice bars of connections are easily available in the market with inexpensive materials
2. These types of connections can be fabricated easily without any special mould.
3. Non-proprietary
Figure 1.1 Grouted splice connection in precast concrete components [13]

Usually the bond development has strong effect on the interaction between the grout and splice bar for the grouted splice connections, that are usually used in connecting precast concrete components. In fact, the mechanism of load transfer between the precast concrete components depends on the quality of adequate bond provided by the grouted splice (Figure 1.2) [14]. Investigation works on the factors that affect the bond were studied greatly over the last 40 years and as a result, considerable modifications have been introduced to bond clauses in design codes worldwide [15]. Detailed evaluations of bond strength and bond behavior are complicated, as the magnitude of bond strength is influenced by a wide range of factors. For example, the CEB-FIP Model Code 90 [16] includes not less than 10 parameters which influence the anchorage bond behavior.
In the bond aspect, one of the key factors that can improve the value of bond stress is the present of confinement between the steel bar and grout. The confinement can influence the anchorage bond and reduces the required embedment length of the spliced steel bars [7, 18-20]. The application of confinement delays early development of the splitting cracks either by expansion resistance or bridging of surrounding materials of the steel bars.

This study concentrates on the behavior of proposed grouted splice connections with spiral confinement. To investigate the behavior of new splice connections, it is very essential to know the interactions and also internal stress distribution among the deformed steel spliced bars and its surrounding materials.

1.2 Background of Study

In reinforced concrete structures, the reinforcement bars attain continuity through lapping full anchorage lengths of the steel bars [21]. On the other hand, the long bar lapping lengths may be impractical in cases where there is not adequate space for the accommodation of the required bar development lengths, especially in structures that are heavily reinforced and in cases where larger bar sizes are used,
leading to impractical lapping lengths, or it may be not permissible to be lap spliced by codes [8].

In precast concrete structures, prefabricated components such as wall to wall and column to column need to be jointed together by ensuring the continuity of rebars from the lower component to upper components. To join the prefabricated elements of the precast concrete systems, the lengthy lapping system have not been shown quite appropriate. For example, long extruding starter bars provided for embedment in the adjoining structural elements in the installation process often cause problems of transportation and handling. As a result, for ensuring the ease of the installation and maximizing the speed of construction process, there is a need for short bar anchorage length.

The grouted splice offers a feasible solution to connect the prefabricated elements during erections. During the assembly process, prior to pouring or pumping the grout in the sleeves, the short extruding steel bars could be inserted to the pre-embedded sleeves in the targeted elements. Using this technique, the problem of long embedded lengths can be solved and the process of handling and installation can be performed more easily.

In general, using grouted splices, discontinued bars can be spliced at short embedded bar lengths. Though, the bond performance may be different because of variations existing in the grouted splice configurations. Knowing these issues, the grouted splices responses should be investigated, particularly regarding the bond behavior, for identification of the major factor like confinement that has impact on the bond mechanism in grouted splices.

The influence of confinement on the ductility and compressive strength of compression members has been reported by many researchers [22-26]. Their work was based on the confinement of members along their full length. The confinement effect using spirals or ties on lap splice lengths and development of the longitudinal
reinforcement was investigated in their work. Based on the shape of confinement, circular spirals provide a continuous confining pressure around their axial axis [27].

The concept of spirally confined lap splices of deformed bar comes from the above theory to generate the strength required for connecting the reinforcement bars together (see Figure 1.3). So, In order to employ spiral confinement in grouted connections, more investigations are required rather than relying on speculated predictions. Thus, it is essential to understand the responses of the grouted splices when subjected to the load cases of direct axial and flexural pullout loads. Other forces that may occur in the splice are axial force-moment and axial compression-moment. the work by Kuttab and Dougill [28] has shown that most of the grouted connections in precast column components experienced axial force–moment interaction characteristics. Hence, multi-phases of experimental studies are carried out to study the behavior of proposed connections caused by the bond stress-slip relationship of individual short deformed steel by spiral reinforcement. The confinement provided by the spirals is part of the proposed short splicing method which increases the bond strength. The spirals characteristics and properties are applied in Industrial Building Systems (IBS) where other types of mechanical spliced connections could be substituted by this connection.
1.3 Problem Statements

The problems that need to be addressed in grouted splice connections are:

1. The conventional grouted sleeve connector is one of the famous methods for joining precast concrete components (see Figure 1.4). According to the finding of Kuttab [28], the combination of axial and flexural loads interaction characteristics of grouted sleeve connectors has to be equal to the parent column. Due to this axial and flexural load interaction, long embedded length of 35 times bar diameter based on BS 8110 [21] is needed to achieve the full continuity of reinforcement bars. The main problem in using this connection is the installation process of the grouted sleeve connectors which is quite difficult and it is not easy to achieve with any accuracy. The main bars in the sleeve may not always be perfectly located at the centre of sleeve (See Figure 1.3 Spiral confinement in splice connections [29])
1. There is a tendency for the long bars to touch the wall of the sleeve in the precast component, so preventing penetration of grout around the bar and it is not allowing the grout to fill all the voids inside of the sleeve completely. Since the grout inside the sleeve cannot be inspected after installation, there is doubt that the main bar is fully bonded. So, it is necessary to provide the system which can be assembled by prefilling [8].

2. There is not much research works on the effect of spiral confinement on the bond behavior of grouted splices. Therefore, there is a need to study the confinement effects in the grouted splice connectors.

**Figure 1.4** Projecting the long embedded length in conventional grouted sleeve [30]
1.4 Objectives

Owing to these important characteristics, the bond behavior of reinforcement embedded in grout needs to be investigated accordingly. The key factor governing the anchored-bar behavior in confined grout is the local bond stress-slip relationship. Consequently, to develop new splice connections, it is important to understand the internal stress and the local bond stress-slip relationship between various main connected bars and their surrounding materials. Failure of bond leads to slippage in reinforcement bars and consequently failure of structural members.

To achieve the task of solving the problems stated above, this research is outlined with several main objectives as follows:

i. To investigate the performance of spiral confinement and splice bars to the behavior of connected deformed steel bars in grouted connections under direct axial and flexural loads.

ii. To study the effect of spiral configurations on the bond stress-slip behavior of the deformed steel bars under direct axial and flexural loads.
iii. To study the comparison of direct axial and flexural pullout loads on the bond behavior of deformed steel bars in grouted spiral connection.

iv. To propose equations for predicting the bond strength and bond stress-slip relationship of the grouted spiral connections under direct axial and flexural loads.

1.5 Scope of Research

The scope of the research program includes:

a. The experimental tests of grouted spiral connections with different configurations of spiral confinement.

b. The investigation of the performance of the proposed grouted spirals when subjected to load cases of direct axial and flexural pullout.

c. The study of responses of the grouted spirals towards three considered parameters, pitch distance of spiral, diameter of spiral and type of main bars.

d. The development of simplified equations for predicting the responses of the connections under mentioned load cases.

e. Additionally, two major phases of experimental tests involves

i) Testing of thirty-six grouted spiral specimens under monotonic direct axial pullout to study the behavior of the connections under tension.

ii) Experimental testing of twelve full-scale beam specimens, connected with grouted spirals, under flexural pullout loads to acquire the response of the steel deformed bars in grouted spiral connections.
Furthermore, the scope of the test results for each phase comprises:

a. Phase I – Direct tensile axial pullout test of grouted spiral connections
   i. Failure load capacity
   ii. Bond strength
   iii. Bond stress-slip behavior
   iv. Stress-strain response
   v. Failure mode

b. Phase II – Flexural pullout test of the steel deformed bars in grouted spiral connections
   i. Failure load capacity
   ii. Bond strength
   iii. Bond stress-slip behavior
   iv. Stress-strain response
   v. Failure mode

Lastly, the scope of analytical research consists of:

a. Analysing the bond stress-slip relationship of the grouted splices under direct axial and flexural pullout loads from the experimental results in Phases I and II.

b. Deriving equations to predict the bond strength of the grouted spiral connections under tensile and flexural pullout loads.

c. Evaluating the effect of spiral confinement on the bond stress-slip relationship by calculating the bond energy

d. Comparison of the experimental test results to other researcher to validate the data.
1.6 Thesis Organization

Chapter 2 presents a review of the available literature and the present state of knowledge regarding grouted connections and mechanism of bond stress.

Chapter 3 describes the experimental program, including the details of test specimens, connection configurations, material specifications, instrumentations, test setup and procedures.

Chapter 4 presents the results and discusses the responses of grouted spiral specimens when subjected to increasing direct axial pullout loads.

Chapter 5 displays and discusses the test results and response of full-scale beam specimens, connected with steel deformed bars in grouted spiral connections, under flexural pullout loads.

Chapter 6 presents the analytical derivations for predicting the bond strength response and bond stress-slip relationship of the proposed grouted spiral connections under direct axial and flexural pullout loads.

Chapter 7 summarizes and concludes the entire research carried out.
REFERENCES


82. Zuo, J. Bond strength of high relative rib area reinforcing bars. University of Kansas, Civil and Environmental Engineering; 1998.


104. Tran, B.H., Y. Berthuad, and F. Ragueneau. Essais PIAF: Pour Identifier l’Adhérence et le Frottement. 18ème Congrès Français de Mécanique. 2007.


