BEHAVIOR AND STRENGTH OF WELDED STUD SHEAR CONNECTORS

by

Michelle Deanna Rambo-Roddenberry

Dissertation submitted to the faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY
in
Civil Engineering

W. Samuel Easterling, Chairman
Thomas E. Cousins
Siegfried M. Holzer
Thomas M. Murray
Kamal B. Rojiani

April 8, 2002
Blacksburg, Virginia

Keywords: shear studs, shear connectors, composite beam, push-out test

BEHAVIOR AND STRENGTH OF WELDED STUD SHEAR CONNECTORS

by

Michelle Deanna Rambo-Roddenberry

W. Samuel Easterling, Chairman

Civil Engineering

(ABSTRACT)

The behavior and strength of welded shear studs are subjects of ongoing study. In recent years, research has shown that the American Institute of Steel Construction (AISC) specification equations for shear stud strength are unconservative for studs placed in deck with ribs transverse to the steel beam. Twenty-four solid slab push-out tests, 93 composite slab push-out tests, and bare stud tests were performed to study the effects on stud strength of friction, normal load, position of studs in the ribs of steel deck, concrete strength, and stud properties. Stud diameters ranged from 3/8 in. to 7/8 in., deck heights ranged from 2 in. to 6 in., and both single and pairs of studs were tested. The push-out test results from this study were combined with other studies to propose a new stud strength prediction model. Three new beam tests were performed to study the effect of the stud position in the ribs of the steel deck. The results of these tests, along with 61 other beam tests, were used to verify the new stud strength prediction model. A reliability study was performed to determine resistance factors for stud strength and beam strength.

ACKNOWLEDGMENTS

The author would like to thank Dr. W. Samuel Easterling for his endless support, encouragement, and patience. The completion of this dissertation has been a journey, and Dr. Easterling has been an ideal traveling companion. She would also like to thank Dr. Thomas Murray for his humorous outlook on life and for always giving the best advice. A special thanks goes to Dr. Siegfried Holzer, Dr. Kamal Rojiani, and Dr. Thomas Cousins for serving on her committee and for always welcoming questions. Thanks also to all faculty members in the Structures Division, including Dr. Richard Barker, for sharing their many years of wisdom and providing the best education possible. They have all been an inspiration.

The experimental work and test specimen preparation would not have been possible without the help from Brett Farmer and Dennis Huffman. Thanks to both of them for being so reliable, helpful, and fun to work with. Thanks also to the research assistants who all worked as a team, helping each other in the lab – there are too many to name them all. Thanks to Sarah Carr and Brian Diaz for helping with many of the push-out tests.

The author would also like to thank her parents, Norman and Barbara Rambo, for believing in her and for encouraging her to continue her education. She would also like to thank her husband for his ongoing support and her son for his smiles and unconditional love.

This research has required a great amount of financial support. Thank you to the Via family and the Charles E. Via, Jr. Department of Civil and Environmental Engineering for granting the fellowship that made studying and researching possible. Thank you to the American Institute of Steel Construction, American Iron and Steel Institute, NUCOR Research and Development, Steel Deck Institute, Tru-fit Corporation and TRW Nelson Stud Welding Division for sponsoring this research.

A final thank you to the many researchers at Virginia Tech and around the world who have studied the topic of shear studs over the past few decades. The world is blessed with some truly gifted engineers, whose ideas and methodologies blend to constantly improve the state-of-the-art.

TABLE OF CONTENTS

Abstract ii
Acknowledgments iii
List of Figures ix
List of Tables xii

Chapter 1 Introduction 1
1.1 Background 1
1.2 Literature Review 8
1.3 Scope of Research 41

Chapter 2 Push-Out Specimen Configuration and Test Procedures 43
2.1 Introduction 43
2.2 Test Matrices 43
2.2.1 Solid Slab Push-Out Tests 43
2.2.1.1 Effect of Flange Thickness (Series 1-4) 45
2.2.1.2 Effect of the Steel/Concrete Interface (Series 5-6) 45
2.2.1.3 Effect of Applying Normal Load (Series 7-8) 46
2.2.2 Composite Slab Push-Out Tests 46
2.2.2.1 Effect of Stud Diameter, Concrete Strength, and Deck Height 48
2.2.2.2 Effect of Friction at the Deck/Beam Interface 48
2.2.2.3 Effect of Tension in the Stud Shank 48
2.3 Test Specimen Configuration and Construction 49
2.3.1 General 49
2.3.2 Solid Slab Specimens 49
2.3.3 Composite Slab Specimens 50
2.4 Loading Method and Instrumentation 54
2.5 Test Procedure 60

Chapter 3 Push-Out Test Results 62
3.1 Solid Slab Push-Out Test Results 62
3.2 Composite Slab Push-Out Test Results 64
3.3 Discussion of Solid Slab Push-Out Test Results 64
3.3.1 Effect of Flange Thickness 64
3.3.2 Effect of the Steel/Concrete Interface 68
3.3.3 Effect of Applying Normal Load 69
3.4 Discussion of Composite Slab Push-Out Test Results 70
3.4.1 Strong Position Studs 70
3.4.2 Weak Position Studs 71
3.4.3 Effect of the Stud Head 72
3.4.4 Deep Deck Tests 74
3.4.5 7/8 in. Diameter Studs 75

Chapter 4 Comparison of Push-Out Test Results with Existing Strength Prediction Methods **78**
4.1 General 78
4.2 Solid Slab Ultimate Strength Comparison 79
4.3 Composite Slab Ultimate Strength Comparison 82
4.3.1 AISC Specification Provisions 82
4.3.2 CSA Provisions 83
4.3.3 Eurocode 4 Provisions 88
4.3.4 Johnson and Yuan Model 93

Chapter 5 Experimental Study Using and Results of Bare Stud Tests **104**
5.1 Introduction 104
5.2 Bare Stud Specimens 104
5.3 Test Procedure 106
5.4 Test Results 107

Chapter 6 Evaluation of Push-Out Test Results **110**
6.1 Introduction 110
6.2 Statistics Used in the Analysis of Data 112
6.3 Single Studs in Composite Slabs 113
6.3.1 Strong Position Single Studs in 2 in. and 3 in. Deck 113
6.3.2 Weak Position Single Studs in 2 in. and 3 in. Deck 121
6.3.3 Modification for Different Gauge Deck 126
6.3.4 Middle Position Single Studs in 1 in. and 1 ½ in. Deck 131
6.4 New Definition of Strong and Weak Positions 135
6.5 Multiple Studs per Rib 140
6.5.1 Staggered Position Studs in 2 in. and 3 in. Deck 140
6.5.2 Pairs of Strong Position Studs 142
6.5.3 Pairs of Middle Position Studs 145
6.5.4 Other Tests on Pairs of Studs 146
6.6 Concrete Strength 147
6.6.1 Effect of Concrete Strength on Stud Strength 147
6.6.2 Effect of Concrete Strength on Elastic Stiffness 150
6.7 Deck Height 152
6.8 Stud Height 153
6.9 Normal Load 155
6.9.1 Effect of Normal Load on Stud Strength 155
6.9.2 Effect of Normal Load on Elastic Stiffness 155
6.10 Reduction Factor for $d/t > 2.7$ 158
6.11 Friction in Composite Slabs 161
6.12 Summary of the Evaluation of Push-Out Test Results 164
6.13 New Strength Prediction Model 165
6.14 VT Experimental and New Predicted Strengths 166

6.15 VT Strength Model Compared with Published Data 167

Chapter 7 Experimental Study Using Composite Beam Tests 179
7.1 General 179
7.2 Composite Beam Test Matrix 180
7.3 Composite Beam Test Specimen Configuration and Construction 181
7.4 Instrumentation of Composite Beam Tests 184
7.5 Composite Beam Test Procedure 185
7.6 Results of Composite Beam Tests 186
7.6.1 General 186
7.6.2 Beam Test 1 187
7.6.3 Beam Test 2 192
7.6.4 Beam Test 3 194
7.7 Discussion of VT Composite Beam Test Results 198
7.7.1 General 198
7.7.2 AISC Predictions of Flexural Strength 199
7.7.3 New Predictions for Flexural Strength 201
7.7.4 AISC Predictions for Stud Strength 201
7.7.5 New Predictions for Stud Strength 201
7.7.6 Effects of Deck Height, Stud Position, and Pairing of Studs on Stud Strength 202

Chapter 8 Evaluation of Composite Beam Tests at VT and Elsewhere 204
8.1 General 204
8.2 Composite Beam Test Parameters 206
8.3 Composite Beam Ultimate Strength Comparison 206
8.3.1 General 206
8.3.2 AISC Flexural Theory 215
8.3.3 AISC 217
8.3.3.1 Flexural Strength 217
8.3.3.2 Shear Stud Strength 217
8.3.4 New Strength Prediction Method 224
8.3.4.1 Flexural Strength 224
8.3.4.2 Shear Stud Strength 224

Chapter 9 Resistance Factor for Composite Beams 227
9.1 General 227
9.2 Development of Resistance Factors 227
9.3 Calculation of Resistance Factors 233
9.3.1 Resistance Factor for Stud Strength 233
9.3.1.1 AISC Stud Strength Model 233
9.3.1.2 New Stud Strength Model 233
9.3.2 Resistance Factor for Beam Strength 235

9.3.2.1 Beam Strength Using AISC Stud Strength Model 235
9.3.2.2 Beam Strength Using New Stud Strength Model 237
9.4 Modified Resistance Factor for Composite Beams 238
9.5 New Modified Resistance Factor for Composite Beams 245
9.6 Summary 250

Chapter 10 Summary, Conclusions, and Recommendations 252
10.1 Summary 252
10.2 Conclusions 252
10.3 Recommendations 257

References 259
Appendix A 263
Vita 267

LIST OF FIGURES

Fig.		Page
1.1	Composite Beams Using Shear Stud Connectors (a) Non-Composite Solid Slab (b) Composite Slab Using Cold-Formed Steel Deck	2
1.2	Typical Dimensions and Details of a Push-Out Specimen at Virginia Tech	3
1.3	Push-Out Test of a Composite Slab with Formed Steel Deck	4
1.4(a)	Strong Position Studs in a Composite Beam	5
1.4(b)	Weak Position Studs in a Composite Beam	5
1.5	"Useful Stud Capacity," Q_{uc}, as determined by Chinn (1965)	8
2.1a	Solid Slab Push-Out Specimen with Studs Welded Centrally on Flange	51
2.1b	Solid Slab Push-Out Specimen with Studs Welded Off-Center on Flange	52
2.2	Deck Details	53
2.3a	Composite Slab Push-Out Specimen with Studs in the "Strong" Position	55
2.3b	Composite Slab Push-Out Specimen with Studs in the "2Strong" Position	56
2.3c	Composite Slab Push-Out Specimen with Studs in the "Weak" Position	57
2.3d	Composite Slab Push-Out Specimen with Studs in the "Middle" Position	58
3.1	Stud Strength vs. Flange Thickness (Solid Slab Tests)	68
4.1	Experimental Strength vs. AISC Predicted Strength for Solid Slab Push-Out Tests	81
4.2	Experimental Strengths vs. AISC Predicted Strengths for Composite Slab Push-Out Tests	86
4.3	Experimental Strengths vs. CSA Predicted Strengths for Composite Slab Push-Out Tests	91
4.4	Experimental Strengths vs. Eurocode 4 Predicted Strengths for Composite Slab Push-Out Tests	96
4.5	Experimental Strengths vs. Johnson and Yuan Predicted Strengths for Composite Slab Push-Out Tests	103
5.1	Bare Stud Shear Test Device	105
5.2	Bare Stud Shear and Bending Test Device	106
5.3	Shear Strength, as a Fraction of Tensile Strength, vs. Stud Diameter	107
5.4	Shear Strength vs. Moment Arm	108
6.1	Stud Diameter vs. Slip at Maximum Load for Single Strong Position Studs	116
6.2	Experimental Stud Strength vs. Stud Tensile Strength of Single Strong Position Studs	117
6.3	Effect of Concrete Strength on Stud Strength of Single Strong Position Studs	120
6.4	Experimental Stud Strength at or Before 0.2" Slip vs. Stud Tensile Strength of Single Weak Position Studs	122
6.5	Effect of Concrete Strength on Stud Strength of Single Weak Position Studs	125

LIST OF FIGURES (cont'd.)

Fig.		Page
6.6	Experimental Stud Strength vs. Deck Thickness for Single Weak Position Studs	127
6.7	Ratio of Maximum Strength-to-First Peak Load vs. Deck Thickness for Single Weak Position Studs	128
6.8	Experimental Stud Strength vs. Stud Tensile Strength of Single Middle Position Studs	132
6.9	Experimental Stud Strength vs. Stud Tensile Strength of Single Middle Position Studs (Exponential)	134
6.10	Experimental Stud Strength vs. Stud Position	137
6.11	Experimental Stud Strength vs. Concrete Cover	139
6.12	Stud Strength vs. Concrete Strength	149
6.13	Experimental Stud Strength vs. Ratio of Stud Height-to-Rib Height	154
6.14	Experimental Stud Strength vs. % Normal Load	156
6.15	Experimental Stud Strength vs. d/t	159
6.16	Location of Friction Forces in a Solid Slab and a Composite Slab (after Lyons et al 1994)	162
6.17	Experimental Stud Strength vs. Predicted Stud Strength for VT Tests Using New Model	175
6.18	Experimental Stud Strength vs. Predicted Stud Strength for Other Tests Using New Model	178
7.1	Positions of Studs in Beam Tests	182
7.2	Beam Test Setup	183
7.3	Instrumentation of Beam Tests	185
7.4	Beam Test 1 – Total Load vs. Deflection	189
7.5	Beam Test 1 – Total Load vs. Slip	190
7.6	Beam Test 1 Showing Large Deflections	190
7.7	Beam Test 1 Showing Web Yielding	191
7.8	Beam Test 1 Showing Deformed Stud After Removal of Concrete Slab and Steel Deck	191
7.9	Beam Test 2 – Total Load vs. Deflection	193
7.10	Beam Test 2 – Total Load vs. Slip	194
7.11	Beam Test 3 – Total Load vs. Deflection	195
7.12	Beam Test 3 – Total Load vs. Slip	196
7.13	Beam Test 3 Showing Large Deflections	197
7.14	Beam Test 3 with Large Crack Transverse to the Beam	197
8.1	Flexural Strength vs. Shear Connection Strength	205

LIST OF FIGURES (cont'd.)

Fig.		Page
8.2	Experimental-to-AISC Predicted Moment Capacity vs. Experimental % Composite	220
8.3	Experimental-to-AISC Predicted Shear Stud Strength vs. Experimental % Composite	223
8.4	Experimental-to-New Predicted Moment Capacity vs. Experimental % Composite	225
8.5	Experimental-to-New Predicted Shear Stud Strength vs. Experimental % Composite	226
9.1	Frequency Distribution of Load Effect Q and Resistance R (from Load 1993)	228
9.2	Definition of Reliability Index, β (from Load 1993)	229

LIST OF TABLES

Table		Page
2.1	Solid Slab Test Matrix	44
2.2	Composite Slab Test Matrix	47
3.1	Solid Slab Test Results	63
3.2	Composite Slab Test Results	65-67
3.3	Effect of Stud Head on Stud Strength	73
3.4	Strengths of 7/8 in. Diameter Studs	76
4.1	AISC Ultimate Strength Comparison for Solid Slab Tests	80
4.2	AISC Ultimate Strength Comparison	84-85
4.3	CSA Ultimate Strength Comparison	89-90
4.4	Eurocode 4 Ultimate Strength Comparison	94-95
4.5	Johnson and Yuan Ultimate Strength Comparison	101-102
5.1	Bare Stud Shear Test Results	107
5.2	Bare Stud Shear and Bending Test Results	108
6.1	Number of Push-Out Tests Used in Analysis By Category	111
6.2	Slip at Maximum Load and Loads at 0.2 in. Slip for Single Strong Position Studs	115
6.3	Predicted Stud Strengths of Single Strong Position Studs	118
6.4	Predicted Strengths of Single Weak Position Studs	123
6.5	Effect of Deck Thickness on Ultimate and First Peak Strengths of Single Weak Position Studs	127
6.6	Effect of Deck Thickness on Predicted Strengths of Single Weak Position Studs	129
6.7	Experimental and Predicted Strengths of Single Middle Position Studs	133
6.8	Experimental and Predicted Strengths of Single Middle Position Studs (Exponential)	134
6.9	Effect of Stud Position on Stud Strength	136
6.10	Verification of New “Weak Position” Definition	138
6.11	Staggered Position and Single Strong Position Stud Strengths	141
6.12	Strengths of Single and Pairs of Strong Position Studs (Lyons’ Tests)	143
6.13	Strengths of Single and Pairs of Strong Position Studs	144
6.14	Strengths of Single and Pairs of Middle Position Studs (Diaz’s Tests)	145
6.15	Strengths of Pairs of Studs and Single Studs Using Other Data	146
6.16	Effect of Concrete Strength on Stud Strength	148
6.17	Effect of Concrete Strength on Elastic Stiffness of Studs	151
6.18	Effect of Deck Height on Stud Strength	152
6.19	Effect of Stud Height on Stud Strength (Lyons’ Tests)	153
6.20	Effect of Normal Load on Elastic Stiffness of Studs	157
6.21	Effect of d/t on Stud Strength (Sublett et al 1992)	158

LIST OF TABLES (cont'd.)

Table		Page
6.22	Effect of d/t on Stud Strength (Diaz 1998)	160
6.23	VT Experimental Strengths and New Predicted Strengths	168-174
6.24	VT Strength Model Compared with Published Data	176-177
7.1	Beam Test Parameters	180
7.2	Summary of Bending Strengths in Composite Beam Tests at VT	200
7.3	Summary of Stud Strengths in Composite Beam Tests at VT	200
7.4	Comparison of Stud Strengths in 2" and 3" Deck	203
7.5	Comparison of Stud Strengths in Strong and Weak Positions	203
7.6	Comparison of Strong Position Stud Strengths in Singles and Pairs	203
8.1	Beam Test Parameters	207-210
8.2	Shear Stud Details for Beam Tests	211-214
8.3	Beam Test Results (Flexural Strengths)	218-219
8.4	Beam Test Results (Shear Stud Strengths)	221-222
8.5	Statistics of Stud and Moment Strengths from Beam Tests	226
9.1	Phi Factors for Stud Strength from Push-Out Tests	234
9.2	Stud Strength Phi Factors Using All Push-Out Tests	234
9.3	Phi Factors for Beam Strength Using AISC Stud Strength Model	236
9.4	Phi Factors for Beam Strength Using New Method	238