INVESTIGATION OF THE BEHAVIOR OF OFFSET MECHANICAL SPLICES

by

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OFFSET MECHANICAL SPLICES

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An experimental study of two commercially available offset mechanical reinforcement bar splice systems is presented. The two splice systems, the BarSplice Double Barrel Zap Screwlok© and the Lenton QuickWedge©, were evaluated in four series of tests with reinforcement bar sizes ranging from #4 to #6. The tests were as follows: Direct Tension which tested the splice in open-air tension and allowed the splice to rotate freely; Restrained Tension which tested the reinforcement splice in a manner that inhibited the splice from rotating; Fatigue testing cycled the specimens through a 20 ksi (172 MPa) stress range for 10,000 cycles; In situ beam tests embedded the splices in concrete beams. The beams were subjected to monotonic testing to failure with and without initial fatigue conditioning.

Observations from the tension tests indicate current test methods do not effectively evaluate offset splices. Current practice assumes direct tension testing to be a conservative method for evaluating the ultimate load carrying capacity, and the slip through the splice. Due to rotation produced by the self aligning loads, there is an increase in load carrying capacity caused by large frictional forces at the face of the coupler. The restrained tension tests show promise as an effective test method for mitigating these large friction forces, and more accurately predicting in situ behavior of these types of splices, particular expected slip performance.

Fatigue testing for offset mechanical splices proved to be an impractical test method for this type of splice. Results from this program correlate with the limiting stress restrictions

contained in current design provisions. Flexural beam tests demonstrated that there was little degradation from fatigue conditioning on the performance of the splice. In situ tests also demonstrated that concrete was unable to confine the splice and prevent rotation near ultimate load levels.

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NOMENCLATURE

Abbreviations

ACI	American Concrete Institute
CEB	Comité Euro-International du Beton
FIRR	fatigue-induced reinforcing steel rupture
LVDT	linear variable displacement transducer
LVR	linear variable resistor
UTM	universal testing machine

Notation

A	steel reinforcement cross-sectional area
e	eccentricity of the splice measured between centers of the spliced bars
f_c'	28 day concrete compressive strength
f_u	ultimate strength of steel reinforcement
f_y	yield strength of steel reinforcement
L	length of mechanical splice
N	fatigue cycle number
P	total applied load in flexural beam tests
R	reaction force required to restrain rotation

This thesis was completed using US units throughout except where noted. The following “hard” conversion factors were used:

1 inch = 25.4 mm

1 kip = 4.448 kN

1 ksi = 6.895 MPa

Reinforcing bar sizes are given using the designation cited in the appropriate reference. In the report, a bar designated with a “#” followed by a number refers to a standard inch-pound designation used in the United States (e.g.: #7). The number refers to the diameter of the bar in eighths of an inch. A bar designated with an “M” after the number refers to the standard metric designation. The number refers to the nominal bar diameter in mm (e.g.: 20M).

1.0 INTRODUCTION AND LITERATURE REVIEW

This chapter presents a review of previous related research, test methods, technical literature and findings of a review of State Departments of Transportation guidelines for the use of offset mechanical reinforcing bar splice systems.

1.1 BACKGROUND AND PREAMBLE

The objective of this project is to identify and develop a generic testing protocol and test method for the evaluation of offset reinforcing bar splice systems. This protocol/test is intended to ensure the conformance of such offset splice systems with PennDOT Publication 408, Section 1002.2(c). The resulting generic specification will describe a test method suitable for the future qualification and verification of offset mechanical splice systems.

PennDOT currently evaluates the performance of in-line (connections where the bar centerlines are coincident) mechanical splice systems for reinforcing steel in accordance with Publication 408, Section 1002.2(c) as shown in Table 1-1. This specification refers to CalTrans Test Method CT670 (CalTrans 2004) for determining the specified requirements (PennDOT 2003).

Table 1-1 Mechanical reinforcing bar splice requirements.

I	Ultimate tensile strength of mechanical coupler	greater than	0.90 specified ultimate tensile strength of reinforcing bars
II	Allowable slip (resulting from applied stress of 29 ksi (200 MPa))	less than	0.01 in. (0.25 mm)
III	Yield strength of mechanical coupler	greater than	1.25 specified yield strength of reinforcing bars
IV	Fatigue resistance allowable slip (25 to -25 ksi (172 to -172 MPa) for 10000 cycles)	less than	0.05 in. (1.25 mm)

AASHTO LRFD (2004) Clause 5.11.5.2.2 requires mechanical splice systems to conform to only the second and third criteria given in Table 1-1. ACI 318 (2005) Clause 12.14 only imposes the third criteria given in Table 1-1.

CalTrans Method CT670 and other similar specifications, such as ASTM A1034 (ASTM 2005), were developed to test in-line mechanical splices in direct tension and fatigue. Additionally, provided bar buckling is prevented, these methods can be used to assess splice compression capacity.

Offset splices are analogous to lap splices but utilize a mechanical connection, or coupler, between the spliced bars. Offset mechanical splices allow splices to be made over very short lap lengths and are well suited to creating hoop bars or maintaining the continuity of spiral reinforcement. Offset splices are also practical for connecting bars over closure pours and in repair and retrofit applications to connect new reinforcing steel to existing bars in a relatively small area. Two common offset mechanical splice systems, the BarSplice Double Barrel Zap Screwlok© and the Lenton QuickWedge© are shown in Figure 1-1. Both systems are available for splicing #4, #5 or #6 reinforcing bars. BarSplice has recently introduced a splice for #7 bars. Additionally, the BarSplice product may be used to splice bars of different diameters up to #7.

(a) BarSplice Double Barrel Zap Screwlok©

(b) Lenton Quick Wedge©

Figure 1-1 Offset mechanical reinforcing bar splice systems.

Assessing the performance of offset mechanical bar splices is difficult and there is no available specification for doing so. Manufacturers (BarSplice 2005; Erico 2005) report their products as conforming to the third criteria given in Table 1-1 only. Thus, these couplers are compliant with ACI 318. The manufacturers report obtaining this compliance through direct tension testing of their product in the manner promulgated by CalTrans Method CT670. However, direct tension testing of the spliced bar system results in a moment being generated at the mechanical splice resulting from the eccentricity of the bars. This moment will place complex stresses on the coupler and result in the reinforcing steel kinking at the coupler face as the applied tension loads try to align themselves to satisfy equilibrium. Manufacturers report that they conduct direct tension tests and assume them to be conservative. Thus if the coupler capacity exceeds $1.25f_y$ (where f_y is the specified yield strength of the reinforcing steel) in the tested configuration, it will certainly be adequate with the coupler restrained from rotating as it is when placed in concrete.

The remaining three criteria (Table 1-1) cannot be adequately assessed for an offset mechanical splice because the rotation of the coupler and kinking of the reinforcing steel effects both the ultimate capacity (the kinked reinforcing steel will fail prematurely as compared to straight reinforcing steel) and the slip (the kinking results in additional lateral forces likely to mask the actual slip affects).

ACI 439.3R (1999) reports that offset couplers are only rated for tension. The fourth criteria required by Publication 408 (Table 1-1) requires an assessment of slip under fatigue loading that cycles between equal values of tension and compression. CalTrans Method CT670 is wholly unsuited to such a test. The test-induced kinking of the reinforcing bars combined with the stress reversals over 10000 cycles will likely result in a low cycle fatigue failure of the reinforcing bar near the face of the coupler.

For the reasons discussed above, CalTrans Method CT670 or similar direct tension tests are generally unsuited to evaluating the capacity and performance of an offset mechanical reinforcing bar splice. An alternate test method is required if all four Publication 408 1002.2(c) criteria are to be assessed.

1.2 MECHANICAL REINFORCING BAR SPLICES

Reinforcing bars are spliced *in situ* using lap splices. Lap splices place two bars adjacent to each other over a sufficient length to affect full development of either bar through stress transferred through the surrounding concrete. The typical required length for a tension lap splice is on the order of 50 to 70 times the diameter of the bars being spliced (ACI 318 2005). The splice length is additionally adjusted to account for a number of parameters. Lap splices are not permitted for bars larger than #11 (ACI 318 2005) and are often impractical, regardless of the bar size, in many applications. Alternatives to lap splices include welded connections (requiring weldable, A706 grade, reinforcing bar) or mechanical connections.

Mechanical connections are divided into two categories based on the expected physical loading applied to the splice. Type 1 splices are used when there is no expectation of inelastic deformation or elevated tensile stress due to seismic loading. Type 2 splices are those that have been demonstrated through accepted testing procedures to be able to develop the specified tensile strength of the reinforcing bars for resistance to increased tensile forces that may be expected from seismic loading. Thus, a Type 2 splice may be considered a "seismic splice". Table 1-2 provides the performance requirements recommended by ACI 439.3R (2005) for Type 1 and 2 splices.

Table 1-2 Performance requirements for Type 1 and 2 splices.

	relevant sections in ACI 318-05	**reinforcing bar grade**		
		A706	**A615**	
			Grade 40	Grade 60
Type 1 Splice	12.14.3	$1.25f_y > 80$ ksi (550 MPa)	$1.25f_y$	$1.25f_y$
Type 2 Splice	21.2.6	$1.25f_y$	60 ksi (420 MPa)	90 ksi (620 MPa)

The use of Type 2 mechanical splices is referred to only in the seismic provisions of ACI 318 (2005) while Type 1 mechanical splices are addressed in the body of the code. Proposed revisions of the ACI 493.3R (2005) document: *Types of Mechanical Splices for Reinforcing Bars*[1] recommends the use of Type 2 mechanical splices over conventional laps splices where

[1] ACI 439.3R is presently undergoing major revisions. The new document has been through its first round of TAC comments and has been returned to the committee for further revision. It is not anticipated that the revised document will be approved and published before 2007. As a member of Committee 439, Dr. Harries has access to the draft version of the new document and is the source of these references in this thesis.

inelastic yielding may be experienced. This recommendation is based on the observation that lap splices typically do not perform well under these conditions.

1.2.1 Use of Mechanical Splices

There are many situations that require the use of mechanical splices over the use of conventional lap splices. Mechanical splices are an attractive alternative for providing continuity and anchorage to “hoop” or continuous spiral reinforcement used to provide confinement in columns. Other applications include relieving congestion and reducing the reinforcement ratio in splice regions and in splicing new reinforcing steel to existing steel in patches, closure pours and structural additions. Current codes do not allow #14 or #18 bars to be spliced using a lap splice requiring mechanical splices for these bar sizes. Other uses of mechanical splices are in portions of a structure effected by seismic loads as recommended by new revisions to ACI 439.3R (2005). Finally, in the case of epoxy coated or lower tensile strength reinforcing bars, mechanical splices may represent a practical alternative to the relatively long lap splices required in these cases.

Cagley and Apple (1998) compared two structures: the PNI Garage, in Harrisburg, PA and the NIST Chemistry Lab, in Washington, D.C. For each building, a cost analysis was conducted that compared the specification of in-line mechanical splices to conventional lap splices. It was found that there was less than 0.2% reduction in cost when using lap splices. The study focused solely on column splices, but demonstrated that there was little cost difference in splicing methods. Thus, it may be argued, if quality control can be improved using efficient mechanical splices, there is some advantage in doing so.

Hulshizer et al. (1994) investigated the use of swaged mechanical connectors, in a concrete reactor containment vessel. In this type of structure the complex reinforcing design made it impractical to use conventional lap splices. It was noted that all of the more than 3800 couplings performed within the specifications. There was no noticeable slippage in the non-staggered coupling zones.

1.2.2 Considerations in Using Mechanical Splices

There are a number of considerations to be accounted for in specifying mechanical splices:

Spacing and cover requirements – Minimum cover and spacing requirements for reinforcing steel and conventional lap splices apply equally to mechanical splices. Some splicing systems require additional clearances for installation, particularly if the splice requires special tools for installation. Concrete cover must also be considered when mechanical splices (or formwork inserts serving as mechanical splices) have flanges protruding from the splice. It was recently observed at an ACI Committee 439B meeting[2] that "minimum cover requirements are not respected in 80% of mechanical splices." Additionally, it was noted that it is rare when pultruding flanges are ground off.

The importance of respecting cover requirements must be understood in context. One of the primary purposes of cover is to protect the underlying reinforcing from corrosion. Reduced cover, in this case, translates to reduced life, as the path length for chloride ion ingress is reduced. Thus for highway structures, maintenance of adequate cover is critical.

Concrete cover also serves to inhibit splitting associated with stress transfer from the reinforcing bar to the surrounding concrete. Reduced cover increases the likelihood of splitting

[2] November 6, 2005, Kansas City MO.

cracks parallel to the reinforcing steel. These cracks also accelerate the development of corrosion.

Spacing requirements serve similar purposes with respect to inhibiting splitting along a weak plane formed by adjacent reinforcing bars. Additionally, minimum spacing requirements are required to ensure adequate consolidation of placed concrete. Both may be affected using mechanical splices having dimensions larger than the spliced reinforcing bars.

Bar end preparation – Many mechanical splice systems require special preparation of the bar ends to be spliced. Tapered and threaded connections are common. End bearing splices must be cut square with a tolerance of less than 1½ degrees to ensure proper load transfer. Other end preparations include the cleaning of loose dirt, mill scale and rust particles to ensure an adequate connection with the splice or the removal of any epoxy or zinc coating. Most swaged or sleeve mechanical splices and all offset mechanical splices require no bar end preparation.

Zinc or epoxy coated reinforcing bar – The epoxy coating on reinforcing steel is important for providing resistance to corrosion. Many types of splices require that the coating be removed to ensure a proper splice. The epoxy coating can then be reapplied again over the top of the splice but this increases time and labor. Galvanized (zinc) coating may require removal and reapplication as well. In either case, ensuring a uniform reapplication is critical. Any exposed "black" steel in the vicinity of otherwise protected steel has the enhanced potential to develop a localized corrosion cell. Additionally, a galvanic cell may develop between zinc and exposed "black" steel.

1.3 TYPES OF MECHANICAL SPLICES

There are many types of mechanical splicing products available. In this discussion, they have been categorized as in-line splices, in which the centerline of each spliced bar coincides; and offset splices, where the centerlines have an eccentricity. The latter splice type is alternately referred to as an offset mechanical splice or a mechanical lap splice. Examples of mechanical splice types are described in Table 1-3; the two entries at the right end of Table 1-3 are mechanical lap splices, the remainder are mechanical in-line splices.

Table 1-3 Available mechanical connections types (adapted from ACI 439.3R 1999)

	cold swaged steel couplin g sleeve	**cold swaged coupling sleeve with threaded ends**	**extruded steel coupling sleeve**	**hot-forged steel coupling splice**	**grout-filled coupling sleeve**	**coupler for thread-deformed rebar**	**steel-filled coupling sleeve**	**taper-threaded steel coupler**	**integrally forged coupler with upset NC thread**	**three-piece coupler with NC thread**	**shear screw and double wedge coupling sleeve**	**steel coupling sleeve with wedge**
bar size range	#3-#18	#3-#18	#5-#18	#5-#18	#5-#18	#6-#18	#4-#18	#4-#18	#4-#11	#4-#18	#4-#7	#3-#6
special bar-end preparation	none	none	none	remove loose particles and rust	none	cut square within 1½ degree	remove loose particles and rust	ends must be threaded	none	ends must be threaded	none	None
installations tools	special tools required	hand-held	special tools required	special tools required	grout pump	yes: <#11 no: >#11	hand-held	hand-held	hand-held	hand-held	hand-held	Special tools required
weather restrictions	none	none	none	bars must be dry	none	none	bars must be dry	none	none	none	none	None
special precautions	none	none	none	fire hazard during installation	none	none	fire hazard during installation and proper ventilation required	none	none	none	none	None

1.4 MECHANICAL LAP SPLICE PRODUCTS

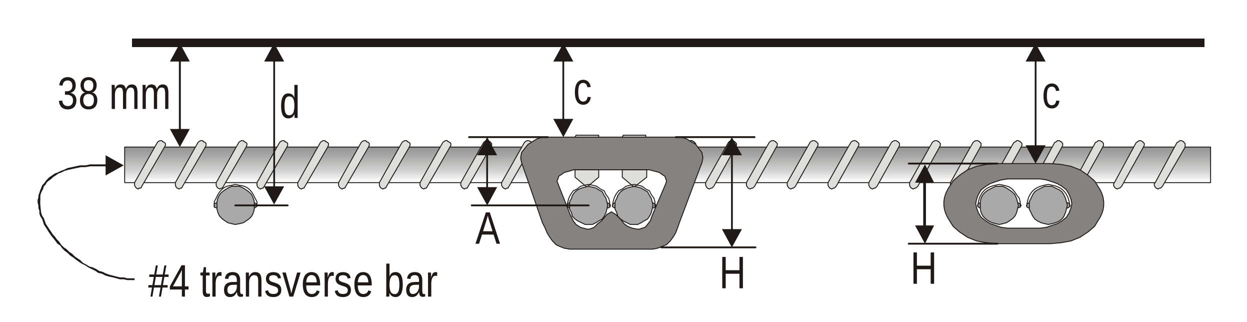
Currently there are only two mechanical lap splicing products available; they are described in the following paragraphs.

The ***BarSplice Double Barrel ZAP Screwlok***©, shown in Figure 1-1(a), is a sleeve that allows two bars to be placed side by side. Allowing at least one bar diameter to protrude from each end, the hardened, pointed set screws are tightened through the top of the sleeve securing the bars in place. The connection is a combination of mechanical (screws penetrating into reinforcing bar) and friction (far side of bar bearing against sleeve). When tightened to approximately 50 ft-lb (68 N-m) of torque, the screw head will shear off indicating appropriate and uniform tightening of all screws. This splice is designed to carry tension and compressive forces but is currently only recommended for tension use. The BarSplice system is available for bars ranging from #4 to #7 and may be ordered in black steel, epoxy coated or galvanized versions. Additionally, it may be used to splice bars of different sizes provided the bars are only one standard size removed (#3/#4, #4/#5, #5/#6 and #6/#7). The manufacture's product literature is presented in Appendix A. A potential concern, to be addressed in this study, is that the hardened screws will penetrate the reinforcing bar introducing a stress raisor. It is not clear whether this stress raisor is more critical than that of the bar deformations (ribs) and thus whether it may adversely affect fatigue performance.

The ***Erico QuickWedge***©, shown in Figure 1-1(b), is an oval shaped sleeve with a wedge shaped pin inserted into it. The reinforcing bars to be spliced are positioned inside the sleeve and the wedge is inserted using a proprietary hydraulic pin driver. The wedge drives the bars against the outer walls of the sleeve effecting a friction connection to hold the bars in place. Additionally, the hardened wedge deforms the bar as it is driven resulting in a further mechanical connection. The QuickWedge is available for bar sizes #4 to #6 and may also be used to join epoxy coated bars. This splice is currently only recommended for tension use. The manufacture’s product literature is presented in Appendix B.

A concern with both the BarSplice and QuickWedge are the dimensions of the product. Table 1-4 shows a generic scenario where longitudinal reinforcing bars are spliced with each product. In each case, the primary steel is assumed to be confined with #4 stirrups (or is located below a transverse mat of #4 bars) and the clear cover is 1½ in. (38 mm). In the case presented, the QuickWedge does not encroach on the clear cover while the BarSplice results in a reduced clear cover of approximately 1⅛ in. (30 mm). Without the confining #4 bar, the 1½ in. (38 mm) cover may be reduced to ⅔ in. (17 mm) and 1⅛ in. (30 mm) for the BarSplice and QuickWedge, respectively.

Table 1-4 Resulting clear cover over offset mechanical splices (dimensions in inches (mm)).



no splice			BarSplice Screwlok				Erico QuickWedge		
Bar Size	**d** with transverse #4 bar	**d** without transverse #4 bar	**H**	**A**	**c** with transverse #4 bar	**c** without transverse #4 bar	**H**	**c** with transverse #4 bar	**c** without transverse #4 bar
#4	2.3 (58)	1.8 (45)	1.7 (42)	1.1 (27)	1.2 (31)	0.7 (18)	1.1 (27)	1.7 (44)	1.3 (32)
#5	2.3 (59)	1.8 (46)	1.8 (45)	1.1 (29)	1.2 (31)	0.7 (17)	1.3 (33)	1.7 (43)	1.2 (30)
#6	2.4 (61)	1.9 (48)	1.9 (48)	1.2 (31)	1.2 (30)	0.7 (17)	1.7 (44)	1.5 (39)	1.1 (29)

shaded values do not respect 1.5 in (38 mm) cover requirement

1.5 PERFORMANCE SPECIFICATIONS

Performance of mechanical splice systems is evaluated with different testing procedures and requirements varying by specifying agency. Typical requirements are listed in Table 1-5. Some jurisdictions have other related requirements; for example, Oregon requires a mechanical splice to achieve a capacity of $1.35f_y$ rather than the typical $1.25f_y$ required by others. It is noted that California Test CT670 (2004) is a test *method* and does not specifically recommend acceptance criteria. The performance criteria associated with CT670 are those applied by CalTrans.

Table 1-5 Mechanical reinforcing bar splice performance criteria for each applicable specification.

PennDOT 408 (2003)	CalTrans CT670 (2004)	AASHTO LRFD (2004)	AASHTO ASD (1996)	ACI 318-05 (2005)	CSA S6-00 (2000)	**parameter**		**performance**
X	**X**	**X**	**X**	**X**		yield strength of mechanical coupler	greater than	125% specified yield strength of reinforcing bars ($1.25f_y$)
					X	yield strength of mechanical coupler	greater than	120% of the specified yield strength of reinforcing bars ($1.20f_y$)
X	**X**	**X**			**X**	allowable slip (resulting from applied stress of $0.50f_y$ then relaxed to $0.05f_y$)	less than	0.01 in. (0.25 mm)
X	**X**					ultimate tensile strength of mechanical coupler	greater than	90% specified ultimate tensile strength of reinforcing bars ($0.90f_u$)
X	**X**					allowable slip resulting from +25 ksi to -25 ksi (+172 MPa to -172 MPa) for 10,000 cycles	less than	0.05 in. (1.25 mm)
	X					allowable slip resulting from cycling between $0.90f_y$ and $0.05f_y$ for 100 cycles	less than	0.05 in. (1.25 mm)

1.5.1 Test Methods for Mechanical Splices

Assessing the performance of mechanical bar splices is difficult and only recently has there been a uniform specification governing these tests. ASTM A1034 (2005) is a new ASTM standard to address testing of mechanical splices. ASTM A1034 provides only general testing methodologies. ASTM A1034 does not provide specific parameters (such as the load at which to measure slip or the stresses appropriate for cyclic testing) and does not quantify any testing acceptance criteria. ASTM A1034 includes an additional parameter – low temperature testing – where any of the standard tests are additionally conducted at a reduced ambient temperature (not specified). Generally, in the continental United States the operating temperature of reinforcing bar systems will not fall below a value where temperature effects (brittle fracture, etc.) may become apparent. ASTM A1034 provides guidance for test methods but leaves the parameters to the specifying jurisdiction.

Before the A1034 specification was released in late 2004, the CalTrans CT670 Test Method (CalTrans 2004) was the only specification to specifically address the testing of mechanical splices. The CT670 test methods are outlined in Table 1-5 along with the acceptance criteria typically associated with each test. Both manufacturers of offset mechanical lap splices (Erico and BarSplice) reported having conducted direct tension testing of their product in the manner directed by CT670. Both products are approved for use by CalTrans for Type 1 splices only. In their technical literature, both manufacturers only make claims to be compliant with the first criteria listed in Table 1-5; thus these couplers are compliant with only ACI 318.

Direct tension testing of offset spliced bar systems results in a moment being generated at the mechanical splice resulting from the eccentricity of the bars. This moment will place complex stresses on the coupler and result in the reinforcing steel kinking at or near the coupler face as the applied tension loads try to align. This effect is shown schematically in Figure 1-2. A key objective of the present work is to quantify the effect of eccentric versus concentric testing and any underestimation of performance or mechanical properties inherent in the conventional concentric loading arrangement.

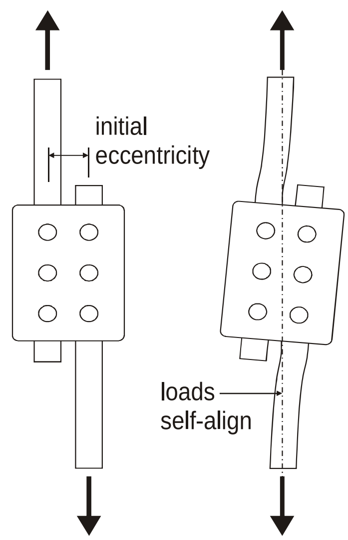


Figure 1-2 Effects of Eccentric loading.

1.6 REVIEW OF AVAILABLE LITERATURE

The body of work addressing mechanical lap splices is very limited with the only published work conducted by Paulson and Hanson.

Paulson and Hanson (1989) provided a summary and review of fatigue data of welded and mechanically spliced reinforcing bars. This survey of existing research focused solely on fatigue data. It was noted that at the time there was no specification that contained provisions for the evaluation of fatigue of reinforcing bar splices. Comparisons were made to AASHTO design specifications for fatigue of straight un-spliced bars. Paulson and Hanson showed that mechanically spliced reinforcing bars may have a shorter fatigue life, although the fatigue life varies greatly based on the type of splice considered. Nonetheless, Paulson and Hanson concluded that for the splice systems tested a fatigue fracture would occur in the bar near the spliced region not in the splice itself. Thus the splicing hardware was sufficiently strong although it affected the spliced bars in a manner affecting fatigue resistance.

National Cooperative Highway Research Program (NCHRP) Project 10-35 (Paulson and Hanson 1991) reports an extensive study of the fatigue behavior of welded and mechanical splices. This study tested mechanical lap splices using *in situ* beam tests and in open air axial tension tests. The authors report two open air tension tests conducted on a #5 QuickWedge product. The specimens were tested in axial tension; the ultimate stress values observed are reported as 63.5 ksi (438 MPa) and 89.0 ksi (614 MPa). The reinforcing bar fracture of the first specimen occurred inside the splice at the wedge, the second specimen fractured just outside the splice. The first specimen did not achieve an ultimate capacity of $1.25f_y$, failing Criteria 3 of Table 1-1. The authors state that due to the offset of the spliced reinforcing bars, axial open air tension tests may not reflect the behavior of the splice embedded in concrete.

Open air fatigue tests were only conducted on in-line spliced bars. Additionally, some modifications were made to a single lap welded splice to allow this splice to also be tested in open air tension. A #8 bar was spliced using 2 #5 bars welded to each main bar; the authors anticipated that the resulting fracture would occur through the #5 bar in a manner similar to a #5 single lap splice tested in embedded in the beams.

Fatigue tests of offset splices were performed on bars embedded in concrete beams. The beams were 84 in. (2133 mm) long, 6 in. (152 mm) wide, 8 in. (203 mm) deep and had a nominal effective depth of 6 in.(152 mm) to the reinforcement steel. Each beam had a single #5 bar as the primary flexural reinforcement and each specimen was tested in third point flexure. There was heavy shear reinforcement located in the shear span but none in the constant moment region where the splice was located. The beams also included crack formers to induce flexural cracking at each end of the coupler.

Test results are given in Table 1-6. Fracture type A was described as a fracture that initiated at the junction of the wedge and the bar, and fracture type B was located immediately outside the splice. FIRR refers to a "fatigue-induced reinforcing bar rupture" occurring during the fatigue load history at the cycle number indicated. After the specimens attained 5 million cycles, the specimens were labeled as "runout" and the stress range was then increased to cause a FIRR and the failure type was noted.

Table 1-6 Key results from Paulson and Hanson (1991)

Specimen	Stress Range, ksi	Number of Cycles to Failure	Result	Fracture Type	Following Stress Range Increase	Failure Location
5L-047-WEDG	24.1	5,000,000	runout		A	
5L-011-WEDG	25.2	3,588,000	FIRR	A		
5L-019-WEDG	24.5	5,000,000	runout			
5L-050-WEDG	23.5	1,617,000	FIRR	B		
5L-001-WEDG	22.5	2,702,000	FIRR	B		at strain gage
5L-027-WEDG	22.4	3,332,000	FIRR	B		at bar mark
5L-029-WEDG	22.2	5,000,000	runout		A	at base of lug
5L-021-WEDG	22.1	4,261,000	FIRR	B		
5L-042-WEDG	19.8	5,000,000	runout		A	at base of lug
5L-002-WEDG	31.3	317,000	FIRR	A		

In Figure 1-3 the data from Table 1-6 is presented. Included in the figure are predictive S-N relationships for straight reinforcing bars tested in air (Helgason and Hanson 1974) and for straight #5 (16 mm dia.) reinforcing bars and smaller tested in beam flexure (CEB 1990). Data from the unspliced in-air tests from Paulson and Hanson (1991) are also included in the figure. It is clearly seen in Figure 1-3 that the QuickWedge splices subject to beam flexure fatigue exhibited a degraded S-N behavior as compared to the bare bars tested in direct tension fatigue.

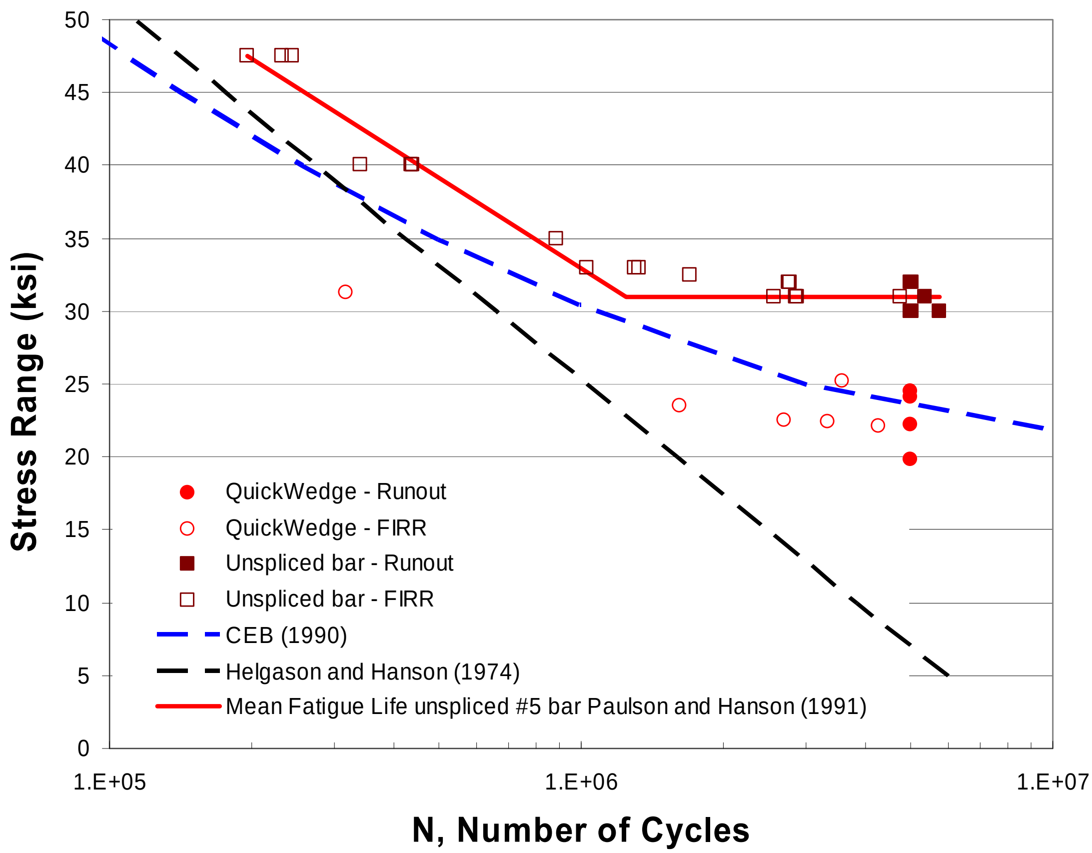


Figure 1-3 S-N Plot from Paulson and Hanson (1991) and limiting equations.

From this study, the authors attempted to establish limits for design stress ranges appropriate for different classes of splices. The AASHTO specified limits for the fatigue stress range on straight reinforcing bars for service loads was 20 ksi (140 MPa). The authors classified mechanical connections into three categories assigning maximum allowable stress ranges of 4 ksi (28 MPa), 12 ksi (83 MPa), and 18 ksi (124 MPa) as indicated in Table 1-7.

Table 1-7 Splice categories according to Paulson and Hanson (1991)

Maximum stress levels	4 ksi (28 MPa)	12 ksi (83 MPa)	18 ksi (124 MPa)	20 ksi (140 MPa)
Splice type	all welded splices	cold swaged steel coupling sleeves; taper- and straight-threaded steel couplers; steel coupling with sleeve with wedge (Quick Wedge)	grout- and steel-filled coupling sleeves;	straight bar (no splice)

It is important to note that all coupling methods were assumed to reduce the fatigue limit of the reinforcing bars to some degree. Based on the limited testing (Table 1-6), the QuickWedge offset mechanical couplers were assigned the same category as swaged and threaded in-line couplers, having a maximum allowable fatigue stress range of 12 ksi (83 MPa). Couplers in this group are characterized as requiring a reduction in area of the spliced bar as results from machining threads, swaging the bar or installing the wedge. The results obtained by Paulson and Hanson, although limited, point to a significant difference in behavior between offset mechanical couplers tested in air and those tested *in situ* in concrete beams.

1.7 EXISTING STATE OF PRACTICE

As part of the PennDOT-funded study supporting this work, a survey of current practice relating to the use of offset mechanical splices was sent to all US State DOTs through the PennDOT Resource Center. Only seven states responded. A summary of the survey responses received is provided in Coogler and Harries (2006). Issues identified with the use of offset mechanical splices primarily involve perceived poor performance attributed to inadequate installation practices. In particular, one state reported the use of offset mechanical splices in repairs of continuous reinforced pavement on I-95 in the late 1990's. They report "too much elongation/movement when coupler was subjected to tension" Additionally, they reported that "installers [were] not keeping offset horizontal and parallel to [the] bridge deck surface, thus infringing on minimum concrete cover." The survey results appear to indicate that offset mechanical splices are only considered in Type 1 splice applications.

1.7.1 Review of DOT Approved Product Listings

Due to the poor response to the survey, a review of US State DOTs' Approved Product Lists (APL) was conducted. The review utilized only that material available on each of the DOT websites. The results of this review are shown in the Table 1-8. In Table 1-8, a "Y" entry indicates that the APL was checked and/or that the splice indicated appears on the APL; a "N" entry indicates that the APL was not found. No entry in Table 1-8 indicates that no APL listing was found, this does not necessarily mean that there are no approved splice products, simply that these were not found on the available APLs. In conducting this review, it was clear that many state APLs are not all-inclusive, and in some cases use of a product is permitted regardless of its inclusion on the APL.

In this review, it was determined that the QuickWedge product is more commonly approved, likely because it has been more widely available for a longer period of time. For example, the QuickWedge product has been recognized in the ACI 439.3R guide for mechanical splices since 1991. The BarSplice product has yet to appear in the 439.3R guide but is included in the current draft revisions.

It is clear that not all approvals properly recognize the nature of the offset mechanical splice products. Often the QuickWedge is included in a list of in-line splice products. In at least one case (Louisiana), the offset mechanical product is approved under a category designated "mechanical butt-splicing devices."

Table 1-8 Review of state DOT Approved Product Lists

State	APL checked	splices on APL			State	APL checked	splices on APL		
		inline	BarSplice	QuickWedge			inline	BarSplice	QuickWedge
Alabama	N				**Montana**	N			
Alaska	N				**Nebraska**	Y			
Arizona	N				**Nevada**	Y			
Arkansas	Y	Y		Y[1]	**New Hampshire**	N			
California	Y	Y	Y	Y	**New Jersey**	N			
Colorado	Y				**New Mexico**	N			
Connecticut	Y				**New York**	Y	Y		
Delaware	none				**North Carolina**	N			
Florida	Y	Y	Y	Y	**North Dakota**	N			
Georgia	Y				**Ohio**	Y	Y		
Hawaii	N				**Oklahoma**	N			
Idaho	Y				**Oregon**	Y	Y		Y[3]
Illinois	N				**Pennsylvania**	Y	Y		
Indiana	Y	Y		Y[2]	**Rhode Island**	N			
Iowa	Y	Y			**South Carolina**	Y			
Kansas	Y	Y		Y	**South Dakota**	Y			
Kentucky	Y				**Tennessee**	Y	Y	Y	Y
Louisiana	Y	Y		Y	**Texas**	Y	Y		Y
Maine	Y				**Utah**	Y			
Maryland	Y				**Vermont**	Y			
Massachusetts	Y	Y		Y	**Virginia**	Y			
Michigan	Y	Y			**Washington**	Y			
Minnesota	Y				**West Virginia**	Y	Y		
Mississippi	Y				**Wisconsin**	Y			
Missouri	Y	Y			**Wyoming**	N			

[1]non-seismic only
[2]not approved for bridge decks
[3] requires two couplers installed at each splice location

1.8 SCOPE OF THESIS

This thesis presents the experimental evaluation of two offset mechanical splice products: the Lenton QuickWedge and BarSplice Screwlok splices. This thesis is organized as follows:

- Chapter 1 presents a review of previous related research, test methods, technical literature and findings of a review of State Departments of Transportation guidelines for the use of offset mechanical reinforcing bar splice systems.
- Chapter 2 presents the details and results of direct tension tests (DT), which were conducted in open air and allowed the splice to rotate freely.
- Chapter 3 presents the details and results of restrained tension tests (RT), similar to the tension tests but inhibited the splice from rotating.
- Chapter 4 presents the details and results of fatigue tests (FT) which again are similar to the direct tension tests but consider the load cycled between tension and compression.
- Chapter 5 presents the details and results of the flexural beam tests (B and BF) which involved placing the spliced bars in concrete beams and testing these under both monotonic and “fatigue conditioned” circumstances.
- Chapter 6 presents recommendations, a summary, conclusion, and further research needs.

2.0 DIRECT TENSION TESTING

This chapter presents a discussion of the direct tension tests conducted as part of the procedure for evaluating the mechanical splice systems. Subsequent chapters address the other test methods considered. Sections 2.1 through 2.3 present specimen designation, material properties and a definition of failure modes common to each of the next chapters. This material is presented here for clarity and will be referenced in the coming chapters of this thesis.

2.1 SPECIMEN DESIGNATION

The results presented in this thesis used to the following designation to label each specimen:

X-Y-Z-N

Where the X stands for the test series:

DT = direct tension

RT = restrained tension

FT = fatigue tension

Where the Y stands for the splicing system:

B = BarSplice

Q = QuickWedge

C = control (single bar having no splice)

L = AASHTO-prescribed lap splice

Where the Z stands for bar size:

4 = #4 reinforcement bar

5 = #5 reinforcement bar

6 = #6 reinforcement bar

Where N is the specimen number ranging from 1-5.

For example, specimen RT-Q5-3 is the third QuickWedge specimen having a #5 bar tested under rotation restrained conditions. Beam test specimen designations are given in Chapter 5.

2.2 MATERIAL PROPERTIES

The reinforcement steel for this project was ordered from a PennDOT approved supplier. The experimentally determined material properties for the reinforcement steel are listed in Table 2-1. It should be noted that although the steel came from one supplier, the different bar sizes each came from different manufacturers, however all the specimens tested for a particular bar size came from the same heat of steel.

Table 2-1 Reinforcing bar material properties.

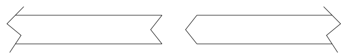
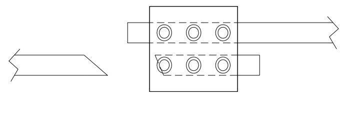
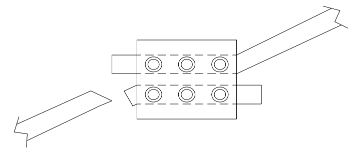
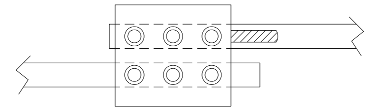
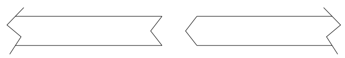
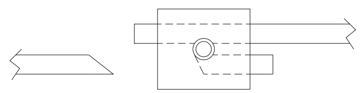
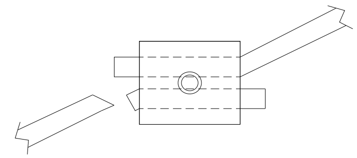
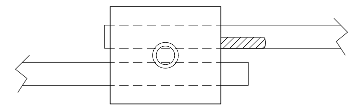
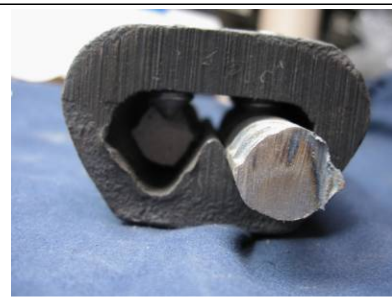
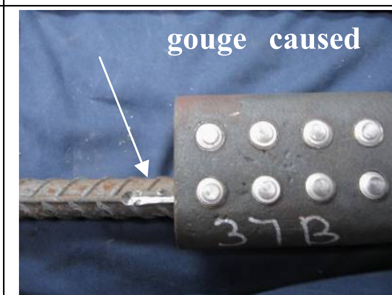
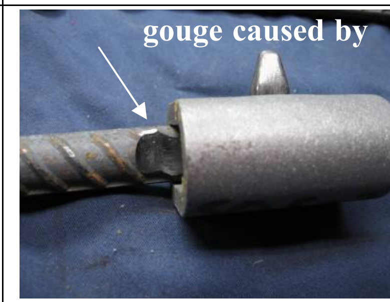
	nominal value (AASHTO M31 (1996))	#4	#5	#6
yield strength, f_y	60 ksi (414 MPa)	65 ksi (448 MPa)	60 ksi (414 MPa)	60 ksi (414 MPa)
yield strain, ε_y	0.002	0.003	0.003	0.0035
tensile strength, f_u	90 ksi (621 MPa)	104 ksi (717 MPa)	100 ksi (690 MPa)	96 ksi (662 MPa)
elongation at rupture	11%[1]	19%[2]	19%[2]	23%[2]

[1] elongation calculated over 8 inches (203 mm)
[2] elongation calculated over 3 inches (76 mm)

2.3 FAILURE MODES

For consistency in reporting, four failure modes are identified and denoted A through D as shown in Table 2-2. These failure modes were only recorded in the direct tension tests (DT) and the restrained tension tests (RT). Failure A was a rupture of the reinforcing bar at a significant distance from the splice, similar to a straight bar test. Failure B was a rupture of the reinforcing bar at the wedge or the bolt. Failure C was a rupture of the reinforcing bar located just outside of splice caused by the kinking of the bar at this location. Failure D did not result in a ruptured bar but the splice slipping a distance greater than one inch (25.4 mm).

Table 2-2 Description of failure modes.

	Failure Mode A	Failure Mode B	Failure Mode C	Failure Mode D
Schematic BarSplice				
Schematic QuickWedge				
BarSplice				
QuickWedge				
Description	Rupture of the reinforcing bar at a significant distance from the splice, similar to a straight bar test.	Rupture of the reinforcing bar at the wedge or the bolt.	Rupture of the reinforcing bar located just outside of the splice caused by the kinking of the bar at this location.	Failure that did not result in a ruptured bar but the splice slipping a distance greater than one inch.

2.4 DIRECT TENSION SETUP

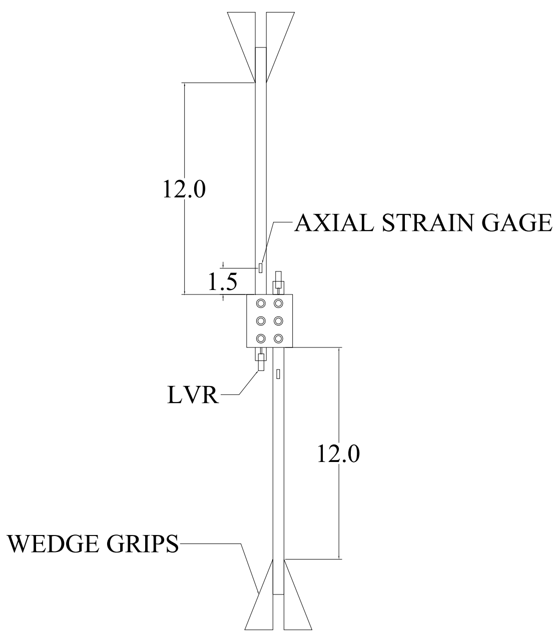
Direct tension tests (DT) were performed in a 200 kip (890 kN) capacity universal testing machine (UTM) with mechanical wedge grips appropriate for monotonic (pseudo-static) tension tests. The UTM had three different load ranges to allow for greater accuracy at lower load ranges. For each of the #4 and #5 bar tests, the 40 kip (178 kN) load range was used; for #6 bar specimens, the 200 kip (890 kN) load range was used. The specimens were loaded monotonically at a rate of approximately 200 lbs/sec (0.89 kN/sec) until rupture of the bar occurred or the recorded slip exceeded one inch (25.4 mm).

Five specimens of each splice type (BarSplice and QuickWedge) and each bar size (#4, #5 and #6) were tested. All specimens were prepared at the University of Pittsburgh's laboratory according to the manufacturers guidelines and specification as described in Section 1.4. Each specimen was approximately 30 in. (760 mm) in length, composed of two bars that were spliced in the middle. It was initially intended to keep the rotational stiffness of each specimen constant as opposed to keeping the length constant. The rotational stiffness is calculated as a function of the length and bar diameter. To maintain the same stiffness, the required length quickly became impractical for testing; therefore the specimen lengths were kept constant.

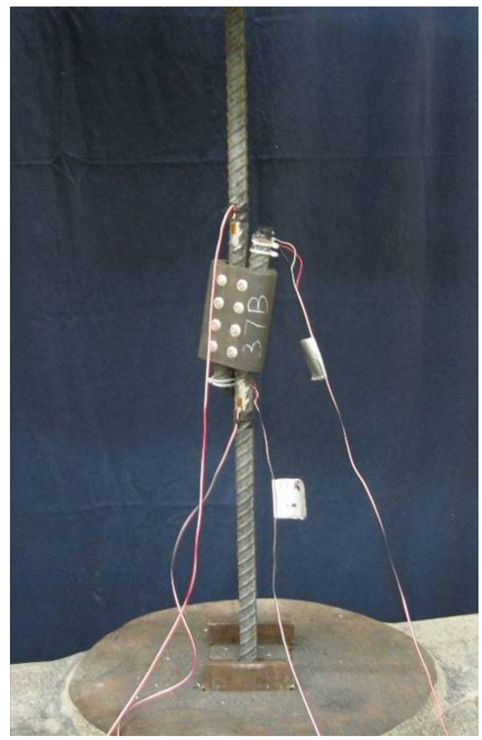
2.4.1 Instrumentation

Axial strain values in the reinforcing bars were recorded using strain gages installed approximately 1.5 in. (38 mm) from the splice on each side of the splice. Linear variable resistors (LVRs) were installed on each side of the splice to measure slip. The LVRs were installed on the unloaded projection of the spliced bar, thus the recorded displacement includes only the slip component over the spliced region not any elastic or inelastic deformation in the bar.

The applied load was obtained from a voltage output from the load cell. Load, strain and displacements were recorded continuously during each test. A figure of the test setup is shown in Figure 2-1.



(a) schematic diagram of DT set-up.



(b) photograph of DT set-up.

Figure 2-1 Direct tension test set-up.

2.5 DIRECT TENSION RESULTS AND DISCUSSION

In Figures 2-2 through 2-4, the representative stress vs. reinforcing bar strain relationships are presented. In these plots, the control (no splice) specimens are plotted to the left in blue followed by the BarSplice specimens in black and QuickWedge specimens in red. The axial strain gages are located above and below the splice. In Figures 2-4 through 2-6, both gauges are shown where the "a" gage is located above the splice and the "b" gage is below the splice. In each of the figures, the strain values are shifted 10,000 με horizontally for clarity.

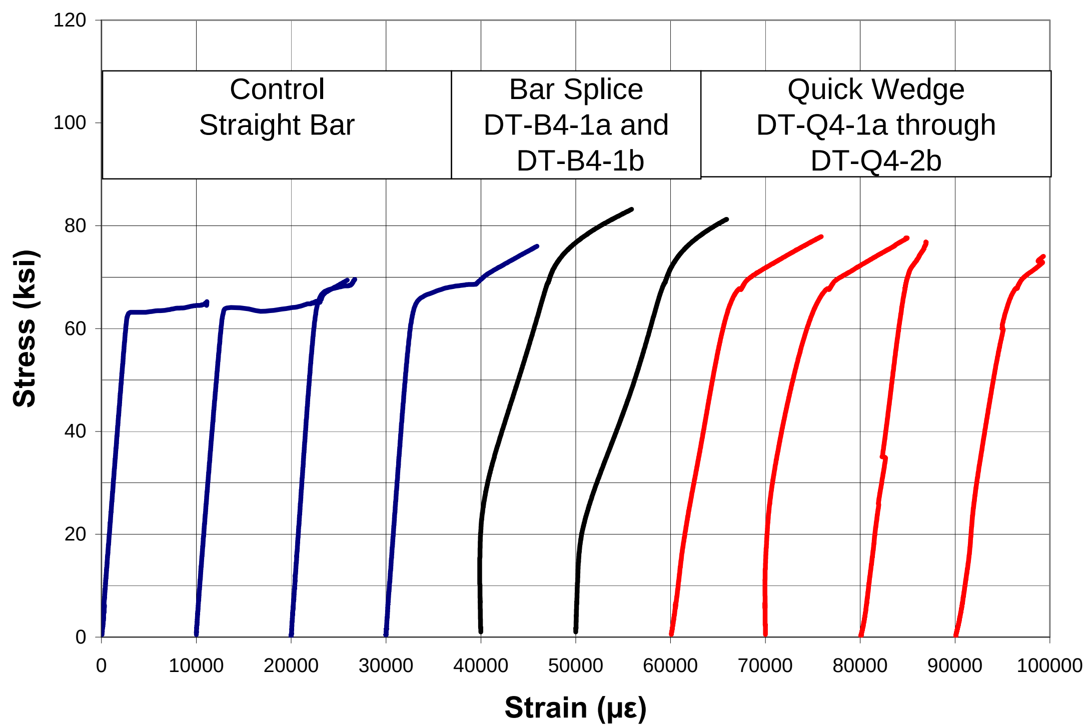


Figure 2-2 Direct tension test results: stress vs. strain #4 bar.

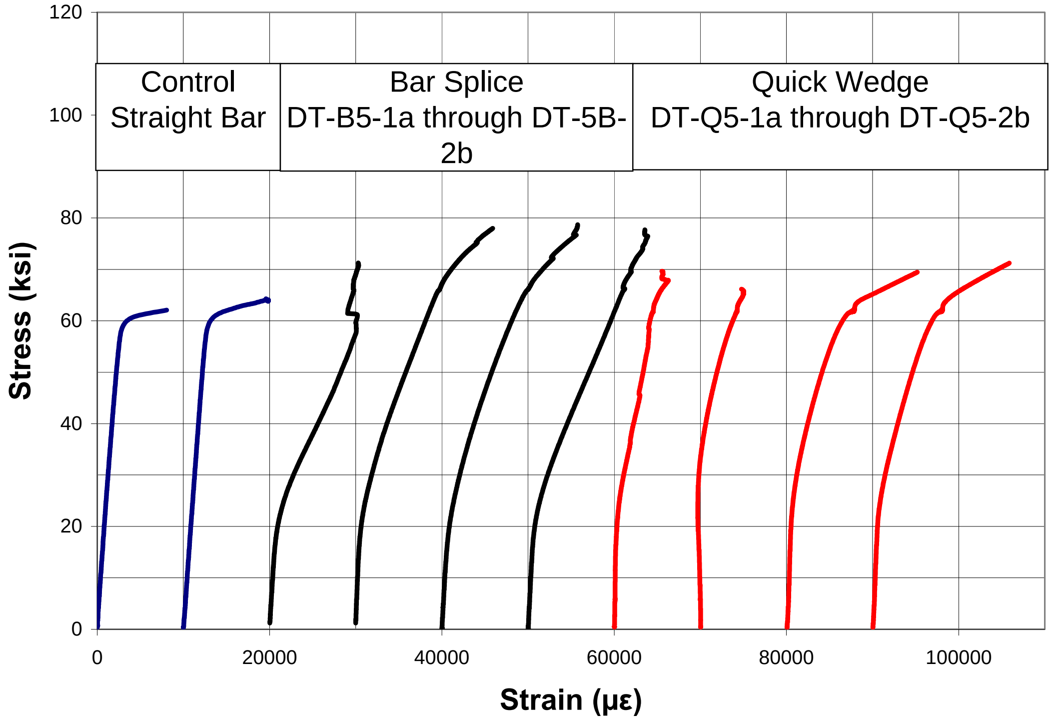


Figure 2-3 Direct tension test results: stress vs. strain #5 bar.

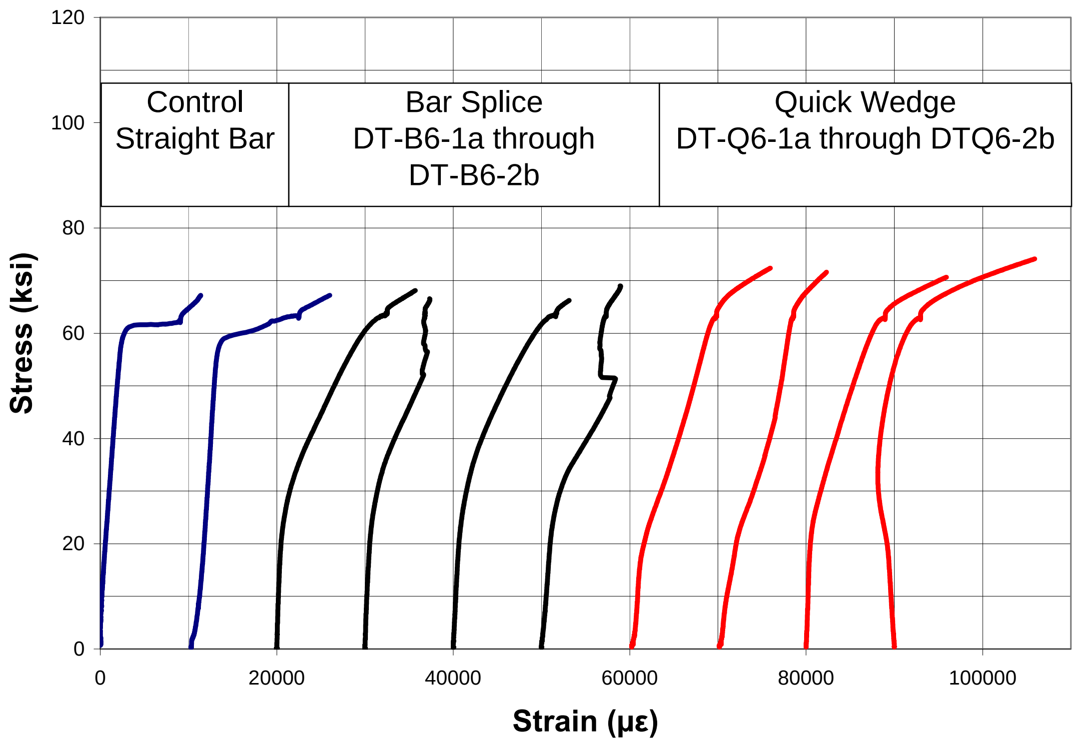


Figure 2-4 Direct tension test results: stress vs. strain #6 bar.

In Figures 2-5 through 2-7, the stress vs. slip relationship obtained from *one side of the splice* are presented. In each case, the spliced bar exhibiting the greatest slip (of the two spliced bars in each connection) is shown. In these plots the BarSplice specimens are plotted in black and QuickWedge specimens in red. For clarity, all slip data for DT tests were shifted 0.25 in. horizontally. Table 2-3 provides a summary of ultimate stress, slip at 29 ksi (200 MPa) and failure mode for each specimen.

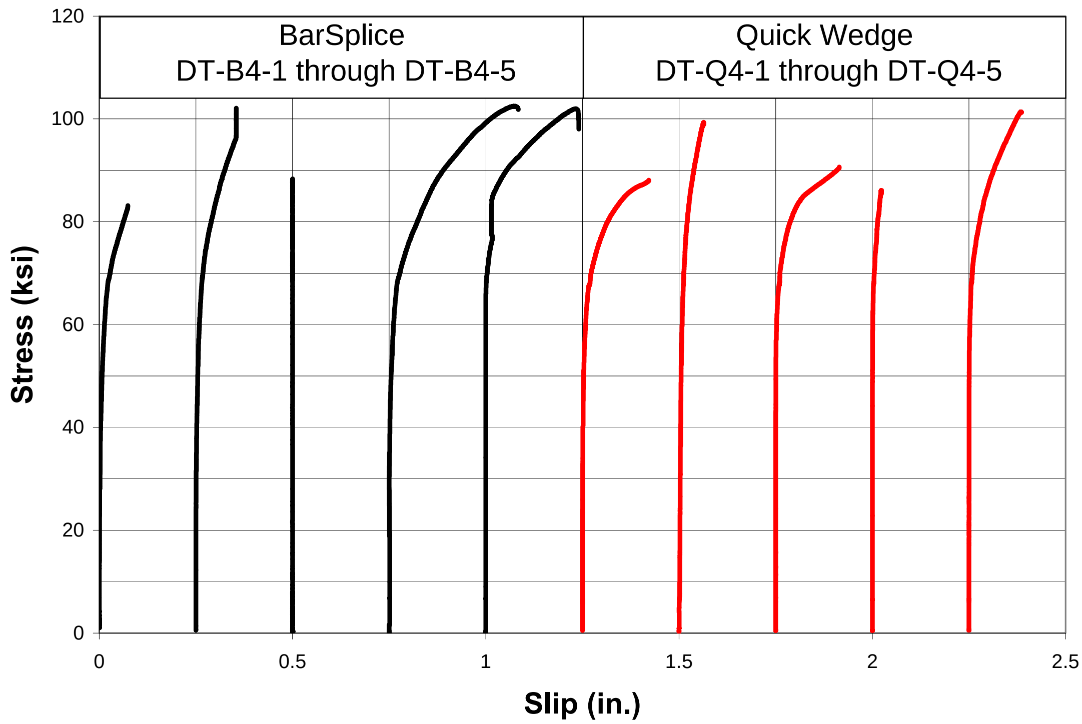


Figure 2-5 Direct tension test results: stress vs. slip #4 bar.

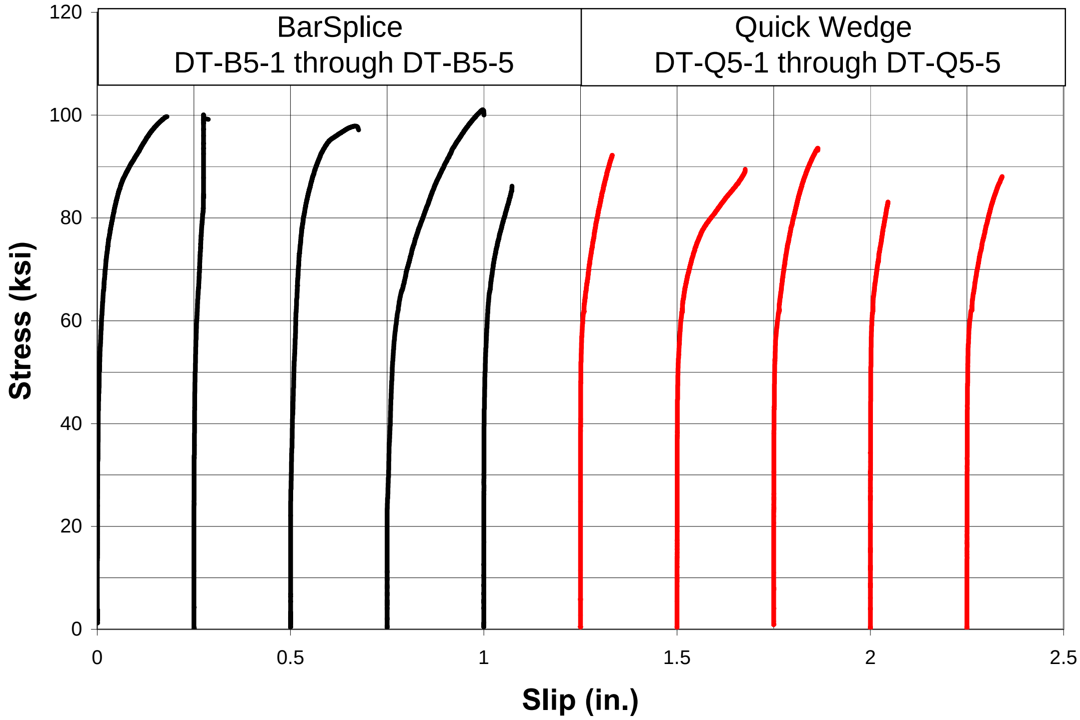


Figure 2-6 Direct tension test results: stress vs. slip #5 bar

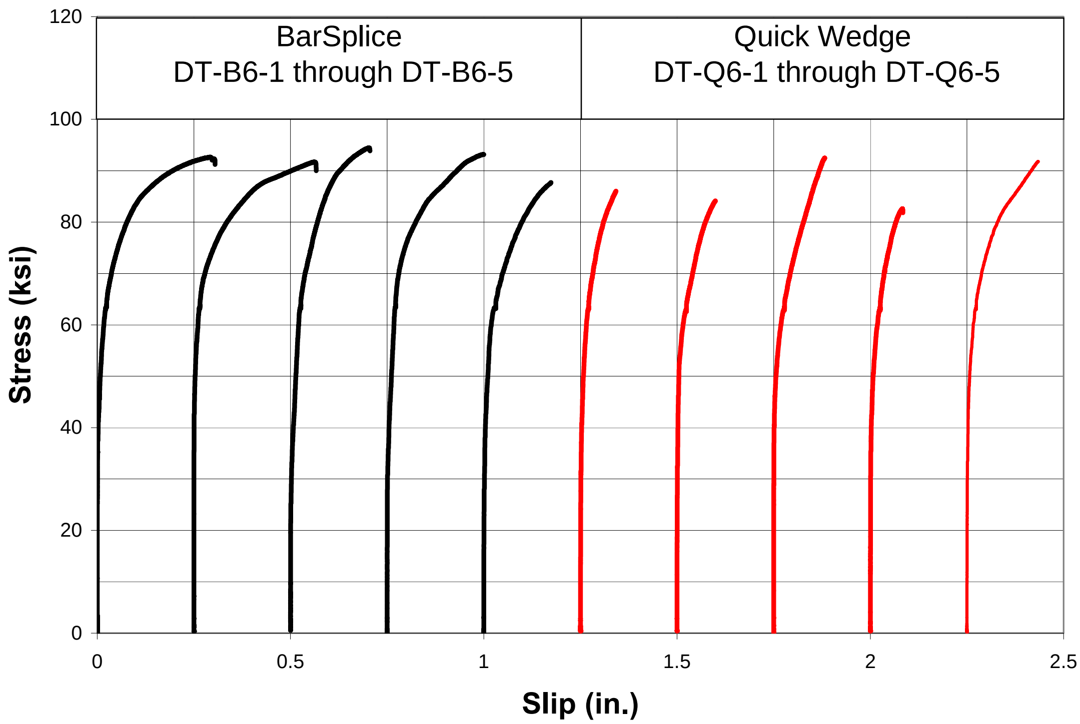


Figure 2-7 Direct tension test results: stress vs. slip #6 bar.

Figures 2-8 through 2-10 illustrate the behavior of each specimen relative to the Publication 408, Section 1002.2(c) acceptance Criteria I through III given in Table 1-1. In these figures, values are normalized to the nominal reinforcing bar strength values of f_y = 60 ksi (414 MPa) and f_u = 90 ksi (621MPa) (Table 2-1) for Criteria I and III. For Criteria II, slip measured from one side of the splice is considered; therefore the acceptance criteria is one half that given in Table 1-1. This presentation of the acceptance criteria is based on the fact that the total slip across the splice is the sum of the slip of each spliced bar. The critical case is therefore where the greatest single bar slip is doubled (i.e. assumed to occur on both sides of the splice). Therefore for Figure 2-9, the slip values have been normalized with the limiting slip of 0.01/2 = 0.005 in. (0.13 mm) (Table 1-1). A value of unity or above indicates that the test passed acceptance Criteria I and III; while unity or below indicates a passing test of Criteria II. The observed failure mode from each specimen is also noted in these figures.

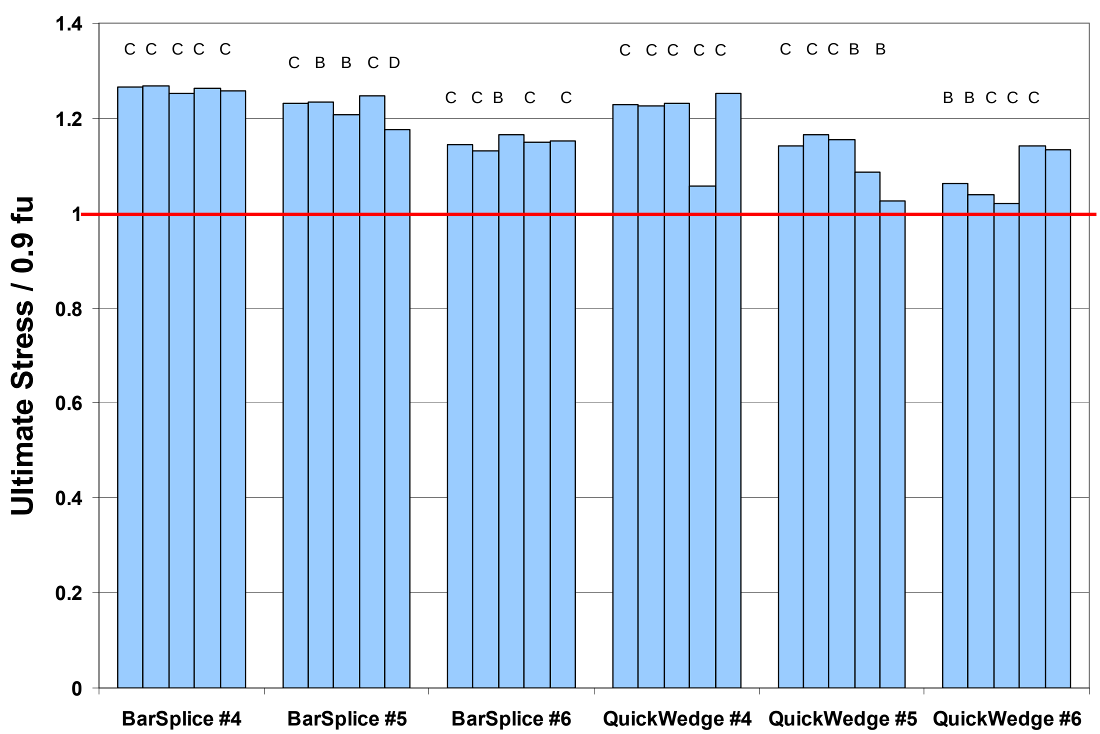


Figure 2-8 Direct tension test results assessment of Criteria I.

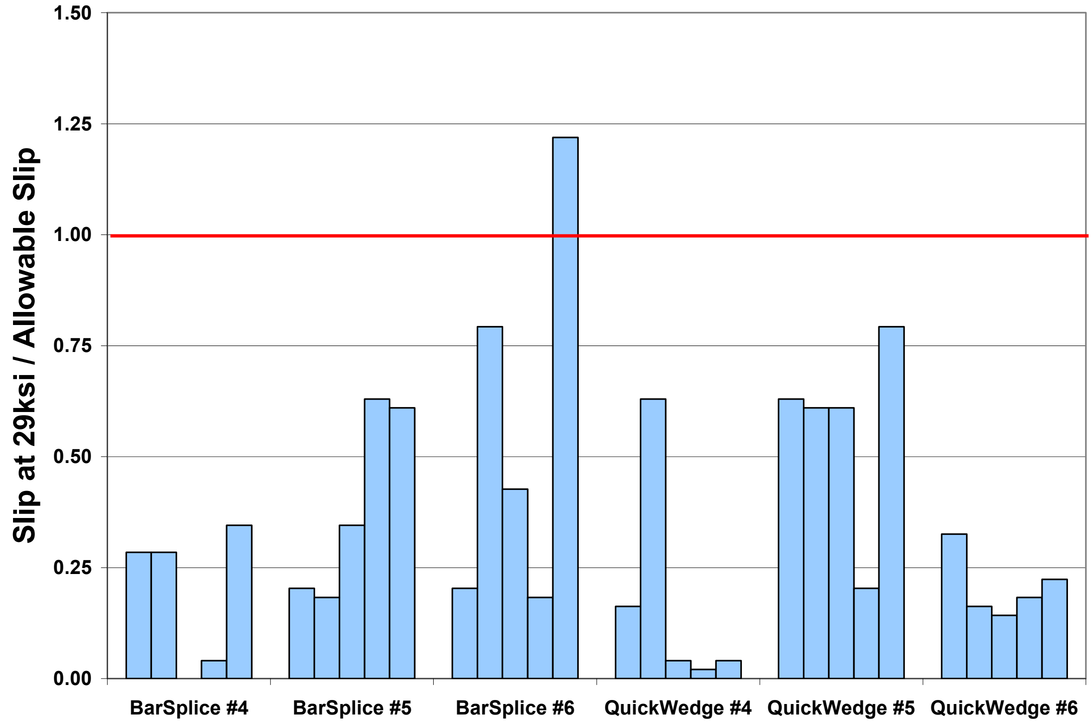


Figure 2-9 Direct tension test results assessment of Criteria II.

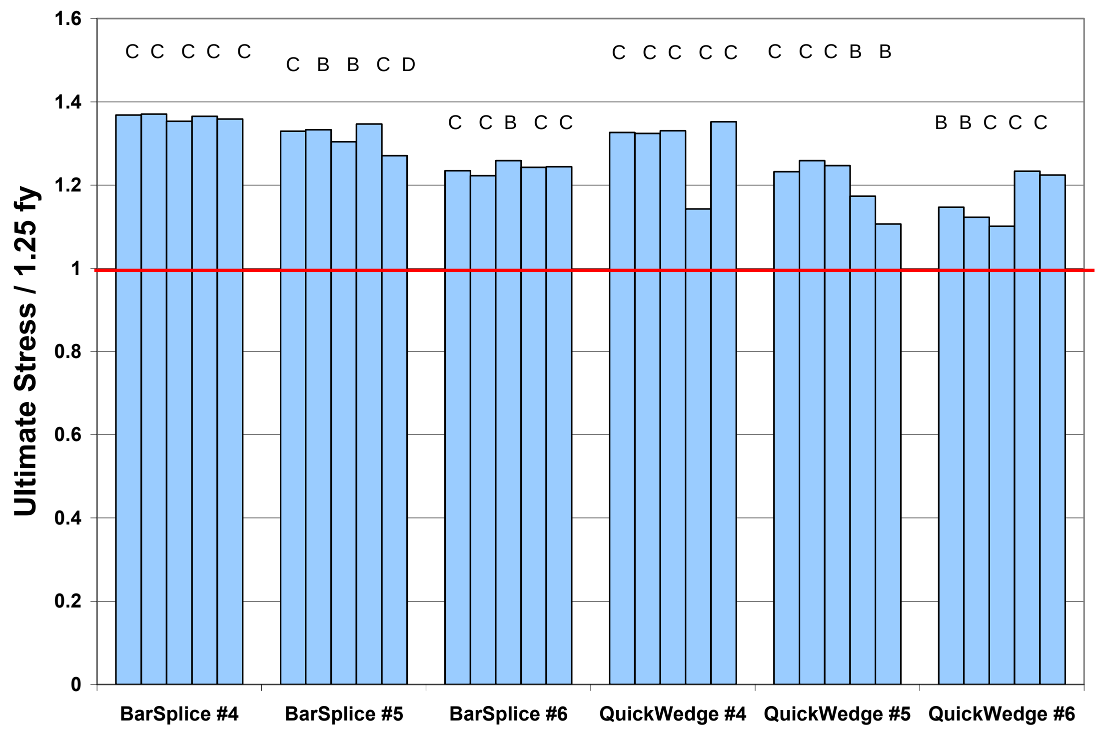


Figure 2-10 Direct tension test results assessment of Criteria III.

Only data that reflects specimen behavior is plotted, if the strain gage or LVR became disconnected or was removed during testing that data is not plotted. Therefore the peak stress may not be achieved on all graphs because the strain or displacement readings were removed.

2.5.1 Key Specimen Behavior

The stress vs. strain relationship appears to be predictable and repeatable in lower stress ranges. There is an initial linear elastic portion. At an applied stress of 20-30 ksi (138-207 MPa) for each specimen there tends to be softening of the system indicated by a decrease in the slope. This apparent change in stiffness is caused by the rotation of the splice, the system sustains increasing loads but the reinforcing bar is no longer only in axial tension. In Figure 2-4, for example, specimen DT-B6-2 captured the compression resulting from bending of the bar associated with splice rotation.

The strain vs. slip relationship is also predictable and repeatable. The stress-slip relationship is generally linear until yield of the reinforcing bar, near 60 ksi (414 MPa). Following yield, the slip begins to increase greatly, often to more than 0.25 inch (6 mm) before eventual bar rupture.

Specimen DT-B5-5 was the only DT specimen that resulted in Failure Mode D – excessive slip prior to rupture. The ultimate stress achieved was 95.3 ksi (657 MPa) which was the lowest result of the DT-B5 series; the specimen was still able to satisfy Criteria I and III. Figure 2-11 shows the damage to the ribs caused by penetration and then gouging of the anchor bolts. There was also severe damage to the ribs on the side of the splice caused by the kinking of the reinforcement bar and its being drawn across the edge of the splice unit; this is shown in Figure 2-12.

Each splice method satisfied the first and third performance criteria given in Table 1-1. BarSplice had one specimen DT-B6-5 that did not pass acceptance Criteria II. Generally performance of each splice deteriorated as bar diameter increased. The BarSplice specimens out-performed the QuickWedge in terms of Criteria I and III. There was a great deal of scatter associated with Criteria II; no splice type out-performed the other.

Figure 2-11 Specimen DT-B5-5, Failure Mode D.

Figure 2-12 Specimen DT-B5-5, smoothing of reinforcement bar deformations.

Table 2-3 Summary of DT test results.

specimen	ultimate stress, fu,exp (ksi)	Criteria III $f_{u,exp}/1.25f_y$	Criteria I $f_{u,exp}/0.9f_u$	slip @ 29ksi (in.)	Criteria II slip/0.005 in.	failure mode
DT-B4-1	102.6	1.37	1.27	0.0014	0.28	C
DT-B4-2	102.8	1.37	1.27	0.0014	0.28	C
DT-B4-3	101.5	1.35	1.25	[1]	[1]	C
DT-B4-4	102.4	1.37	1.26	0.0002	0.04	C
DT-B4-5	101.9	1.36	1.26	0.0017	0.34	C
	102.24	Average RT-B4		0.0012		
	0.53	Standard Deviation RT-B4		0.0007		
DT-B5-1	99.7	1.32	1.22	0.0010	0.20	C
DT-B5-2	100	1.32	1.22	0.0009	0.18	B
DT-B5-3	97.8	1.30	1.21	0.0017	0.34	B
DT-B5-4	101	1.35	1.25	0.0031	0.62	C
DT-B5-5	95.3	1.27	1.18	0.0030	0.60	D
	98.76	Average RT-B5		0.0019		
	2.25	Standard Deviation RT-B5		0.0011		
DT-B6-1	92.6	1.23	1.14	0.0010	0.20	C
DT-B6-2	91.7	1.22	1.13	0.0039	0.78	C
DT-B6-3	94.4	1.26	1.17	0.0021	0.42	B
DT-B6-4	93.2	1.24	1.15	0.0009	0.18	C
DT-B6-5	93.3	1.24	1.15	0.0060	1.20	C
	93.04	Average RT-B6		0.0028		
	0.99	Standard Deviation RT-B6		0.0022		
DT-Q4-1	99.5	1.33	1.23	0.0008	0.16	C
DT-Q4-2	99.3	1.32	1.23	0.0031	0.62	C
DT-Q4-3	99.8	1.33	1.23	0.0002	0.04	C
DT-Q4-4	85.7	1.14	1.06	0.0001	0.02	C
DT-Q4-5	101.4	1.35	1.25	0.0002	0.04	C
	97.14	Average RT-Q4		0.0008		
	6.45	Standard Deviation RT-Q4		0.0013		
DT-Q5-1	92.4	1.23	1.14	0.0003	0.06	C
DT-Q5-2	94.4	1.26	1.17	0.0003	0.06	C
DT-Q5-3	93.5	1.25	1.15	0.0008	0.16	C
DT-Q5-4	88	1.11	1.02	0.0005	0.10	B
DT-Q5-5	83	1.17	1.09	0.0007	0.14	B
	90.26	Average RT-Q5		0.0005		
	4.74	Standard Deviation RT-Q5		0.0002		
DT-Q6-1	86	1.15	1.06	0.0016	0.32	B
DT-Q6-2	84.2	1.12	1.04	0.0008	0.16	B
DT-Q6-3	82.6	1.10	1.02	0.0007	0.14	C
DT-Q6-4	92.5	1.10	1.02	0.0009	0.18	C
DT-Q6-5	91.8	1.24	1.15	0.0011	0.22	C
	87.42	Average RT-Q6		0.0010		
	4.49	Standard Deviation RT-Q6		0.0004		

[1] not recorded due to instrument failure

3.0 RESTRAINED TENSION TESTING

This chapter presents the restrained testing setup and discussion of results. Additionally, the evolution of the restrained test is presented.

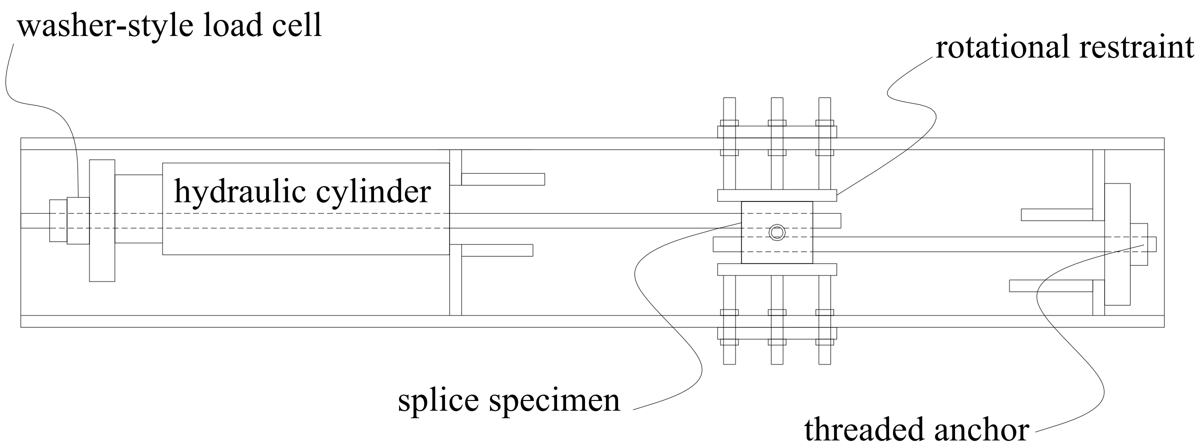
3.1 BACKGROUND

To understand the *in situ* behavior of offset mechanical splices, a method of testing to restrain the splice from rotating was attempted. Result from such restrained tests are compared with those from the direct tension test method reported in the previous chapter in order to assess the appropriateness of tension test methods in assessing mechanical splice performance and acceptance criteria. The required restrained testing method would essentially confine the splice as if it were embedded in concrete. Several designs were tested but none were able to satisfy the criteria without causing severe damage to the splice and resulting in significant friction forces, which mask the actual forces applied to the spliced bars.

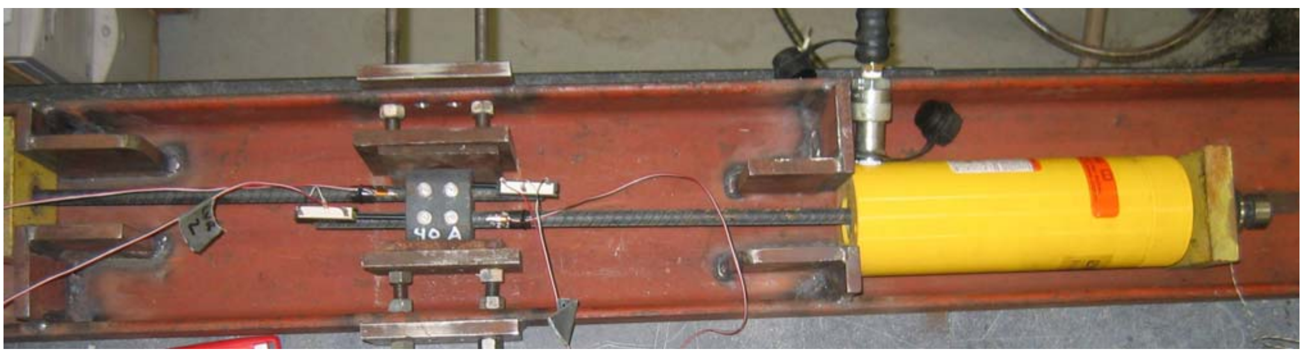
In each of the restrained test setups attempted, it was necessary to provide threads at the bar ends to allow anchorage using a threaded bar termination product. The threaded anchorage results in a reduction in bar area and will typically not permit the ultimate capacity of the bar (or splice) to be achieved prior to failure at the threaded bar termination. The alternative to threaded terminations is “potted” or grouted anchorages. These are impractical for a large series of tests, require a cure time and it is difficult to achieve uniform quality with their use.

Once the bars were provided with their threaded anchorages, they were spliced using each type of mechanical splice and were placed in the self-reacting test set-up shown in Figure 3-1a. The base of the frame was a structural channel lying on its web with its flanges upstanding. The threaded reinforcement bar was passed through the hollow hydraulic cylinder used to apply the force on one end of the bar. At the opposite end, the threaded bar termination was used to react against the welded plates.

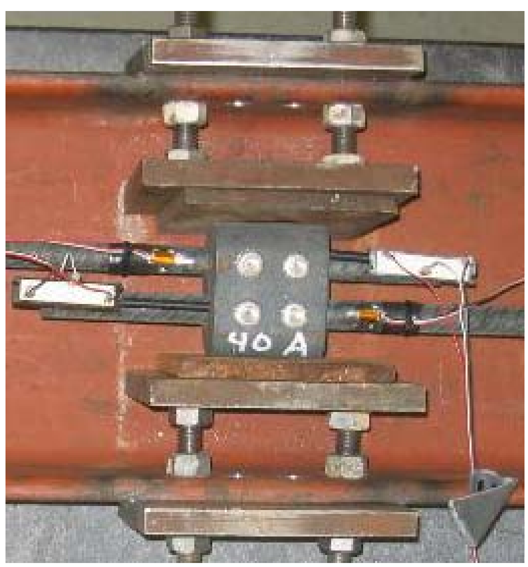
The initial setup had vertically-oriented lateral supports attached to thread rods running through the flanges of the channel allowing the supports to be adjustable to accommodate different splice sizes. The lateral supports were tightened against the specimen, using the thread rods and nuts applied to each side of the channel flange (Figure 3-1b). Due to the shape of the mechanical splices, when the axial load was applied to the bars, the splice began to roll and rotate vertically. Modifications where made in an attempt to restrain rotation in the lateral and vertical directions.



(a) Schematic of initial restrain tension tests



(b) Initial test setup



(c) Restraining method for initial test setup

Figure 3-1 Initial design for restraining rotation of the splice.

In the second test set-up shown in Figure 3-2, the adjustable thread rods were run through solid round steel rollers. The steel rounds would fit on the chamfer between the top and side of the splice effectively securing it laterally and vertically; steel shim plates were installed under the splice to ensure the splice remained securely in plane. After testing several splices in this configuration, it was determined that the clamping forces required to restrain the rotation were simply too large. The large forces are manifest as an unknown friction force which result in a) unbalanced forces in the spliced bars; and b) an additional undetermined force recorded by the load cell. The clamping force was sufficiently large to cause damage to the splices as shown in Figure 3-3.

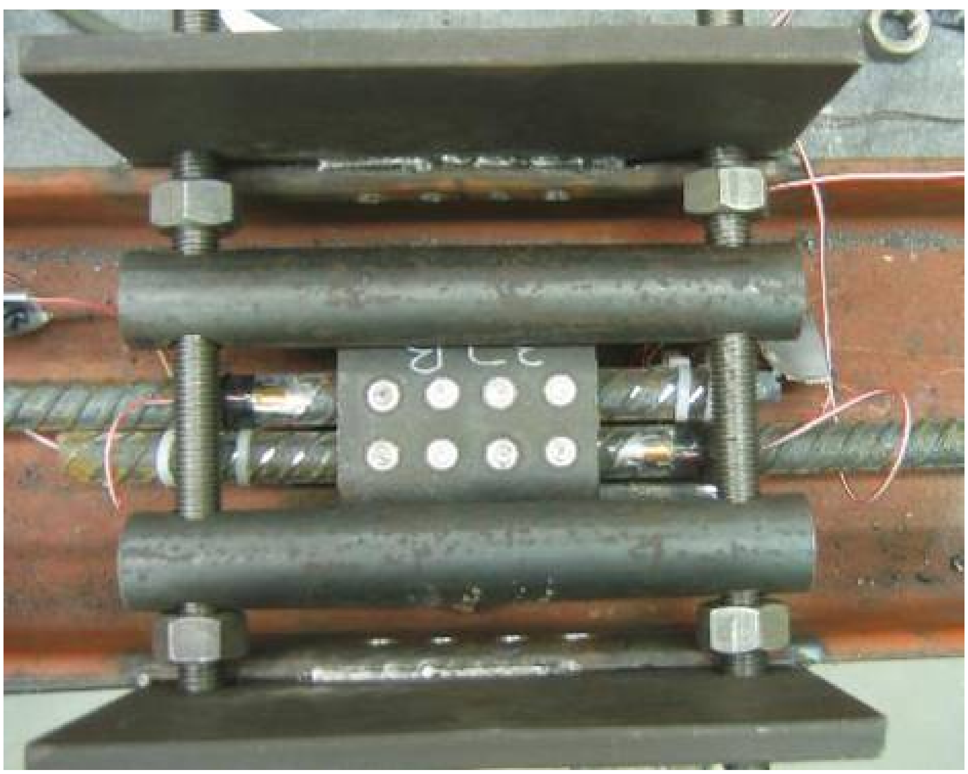


Figure 3-2 Restraining method in later tests.

Figure 3-3 Damage from restraining a QuickWedge specimen.

The results from the initial restrained tests provided little practical data about the *in situ* behavior of offset splices. Due to the large clamping forces required to restrain rotation (see Table 3-1) the stress in the bar on each side of the coupler was no longer uniform. In some cases, the large forces required deformations to the couplers, as they were not designed for this applied force. Other limiting factors to this means of testing offset splices include the ability to grip the ends of the bar. For this series of tests, the bar end termination product used required threading of the ends of the bar, which proved relatively costly[3]. More importantly, the threading process results in a large reduction in the cross sectional area of the bar. This reduction in area produces a stress raisor, and results in a premature failure of the specimen at the threaded bar end. In this

[3] Because reinforcing steel is not perfectly round, machine threading is difficult. Alternate tapered thread configurations are available although these required specialized tools (available from the terminator manufacturer) to prepare the bar end. These tools are also impractical unless very large numbers of bars are to be threaded.

series of tests, the ultimate stress observed was often below 75 ksi (517 MPa), only approximately 75% of the measured capacity of the bar (see Chapter 2).

As an indication of the restraining forces required to attain the yield strength of the reinforcing steel, the following simple calculation is made. This calculation assumes a simple linear distribution of restraining force provided along both sides of the splice as shown in Figure 3-4. A summary of restraining forces is provided in Table 3-1.

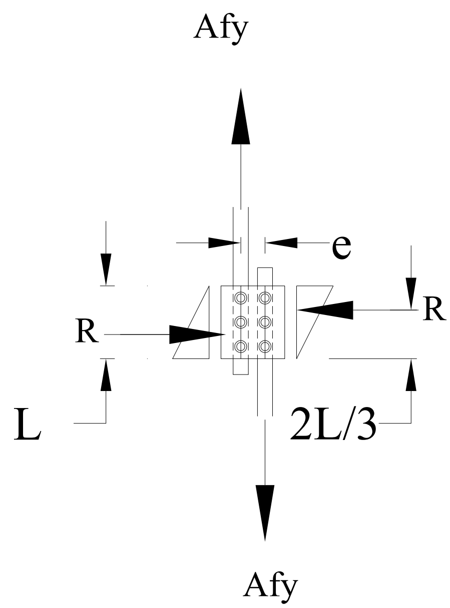


Figure 3-4 Schematic of required restraining forces.

$$\frac{3Af_y e}{L} = R \tag{3.1}$$

Where

f_y = yield strength of the reinforcing bar

A = area of reinforcing bar

e = eccentricity of the splice measured between centers of the spliced bars

L = length of the splice

R = reaction force required

Table 3-1 Required reaction forces (at yield) to restrain rotation.

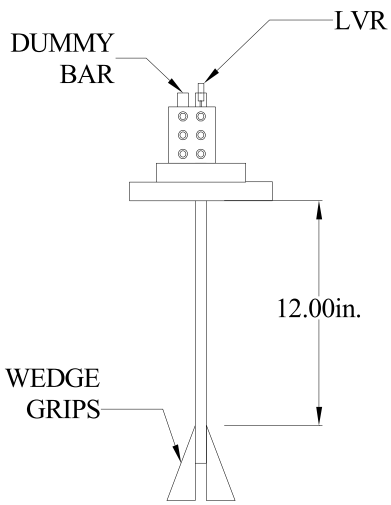
	Reaction Force Required, kips (kN)		
bar size	**#4**	**#5**	**#6**
BarSplice	16.3 (72.5)	18.0 (79.8)	19.5 (86.7)
QuickWedge	13.1 (58.3)	20.0 (89.0)	27.5 (122.2)

It was determined that in order to more accurately test the capacity of the mechanical coupler when restrained, a simple one-sided pullout test would be more appropriate. This is described in the following section.

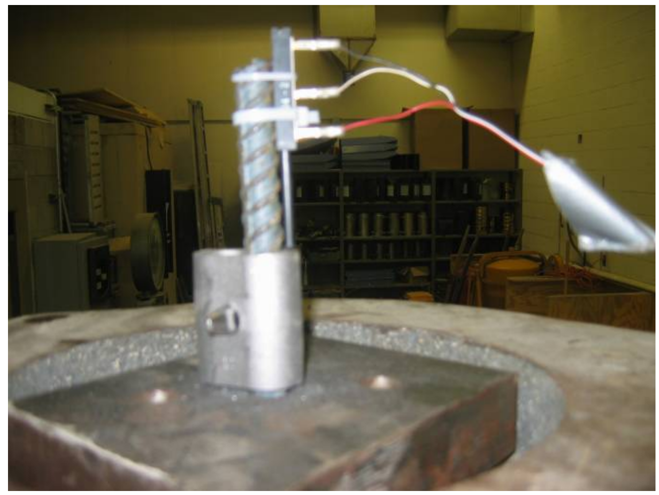
3.2 RESTRAINED TEST (RT) SETUP

The restrained tests (RT) were designed to assess the strength of the mechanical coupler in the case where rotation of the coupler is inhibited. For these tests, only one straight bar was subject to tension with the reaction being provided by the coupler itself. A short dummy bar was installed in the other side of the splice to ensure correct functioning of the splice. The tension bar was passed through a reaction plate having a hole approximately 0.125 in. (3.2 mm) larger than the bar diameter. The tension force was then applied to bar using a 200 kip (890 kN) capacity universal testing machine with wedge grips used to grip the loaded end of the bar. The specimens were loaded monotonically at a rate of approximately 200 lbs/sec (0.89 kN/sec) until rupture of the bar occurred or the recorded slip exceeded one inch (25.4 mm). The uniform reaction between the coupler and loading plate effectively restrains the tendency of the coupler to rotate. Five specimens of each splice type (BarSplice and QuickWedge) and each bar size (#4, #5 and

#6) were tested in this manner. In this series of tests, similar to those of the DT tests, LVRs were used to measure slip through the splice. A picture of the setup is shown in Figure 3-5.



(a) schematic diagram of RT set-up.



(b) photograph of RT set-up.

Figure 3-5 Restrained tension test set-up.

3.3 RT TEST RESULTS

In Figures 3-6 through 3-8, the stress vs. slip results obtained from *one side of the splice* are presented. In each case, the single bar exhibiting the greatest slip is shown. In each of these plots, the BarSplice results are plotted to the left in black and the QuickWedge results are plotted to the right in red. In Figures 3-6 through 3-8, all plots are offset 2 inches to the right for clarity. Table 3-2 provides a summary of ultimate stress, slip at 29 ksi (200 MPa) and failure mode for each specimen.

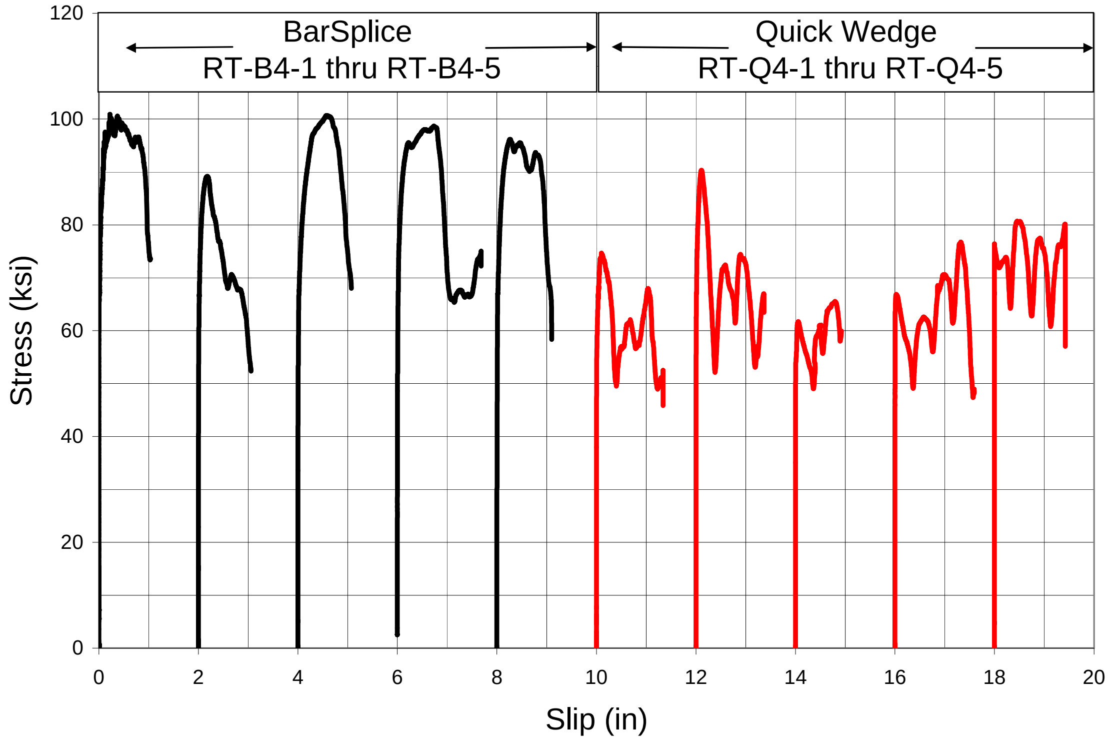


Figure 3-6 Restrained tension test results: stress vs. slip #4 bar.

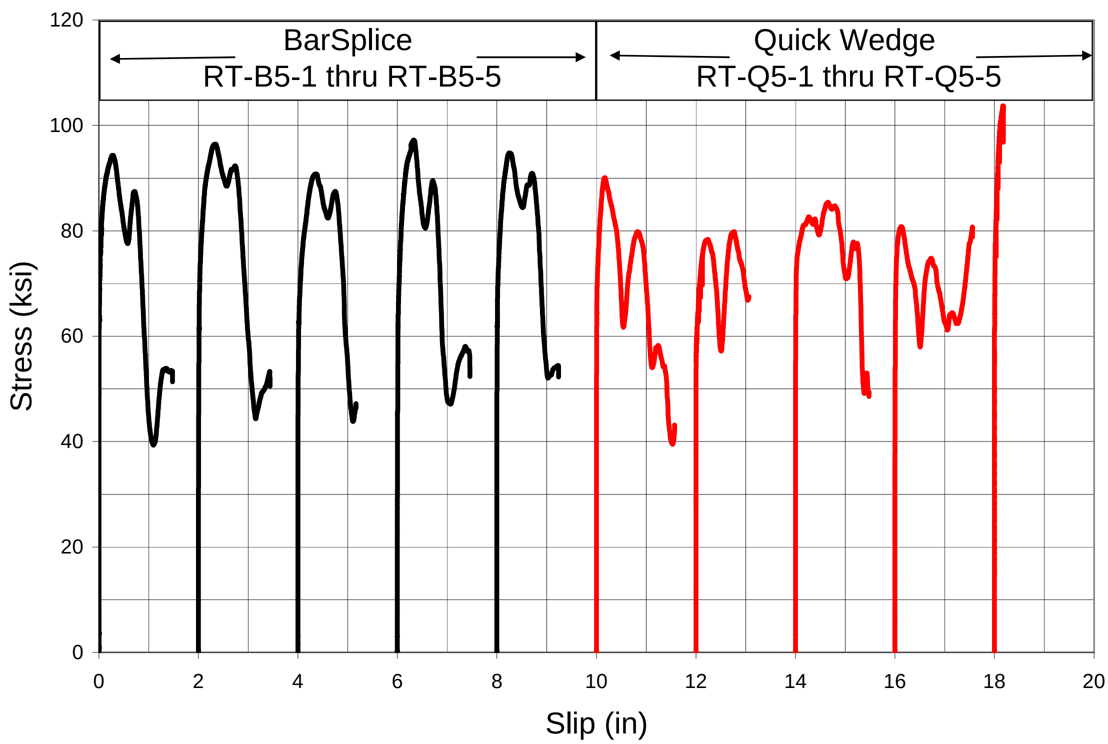


Figure 3-7 Restrained tension test results: stress vs. slip #5 bar.

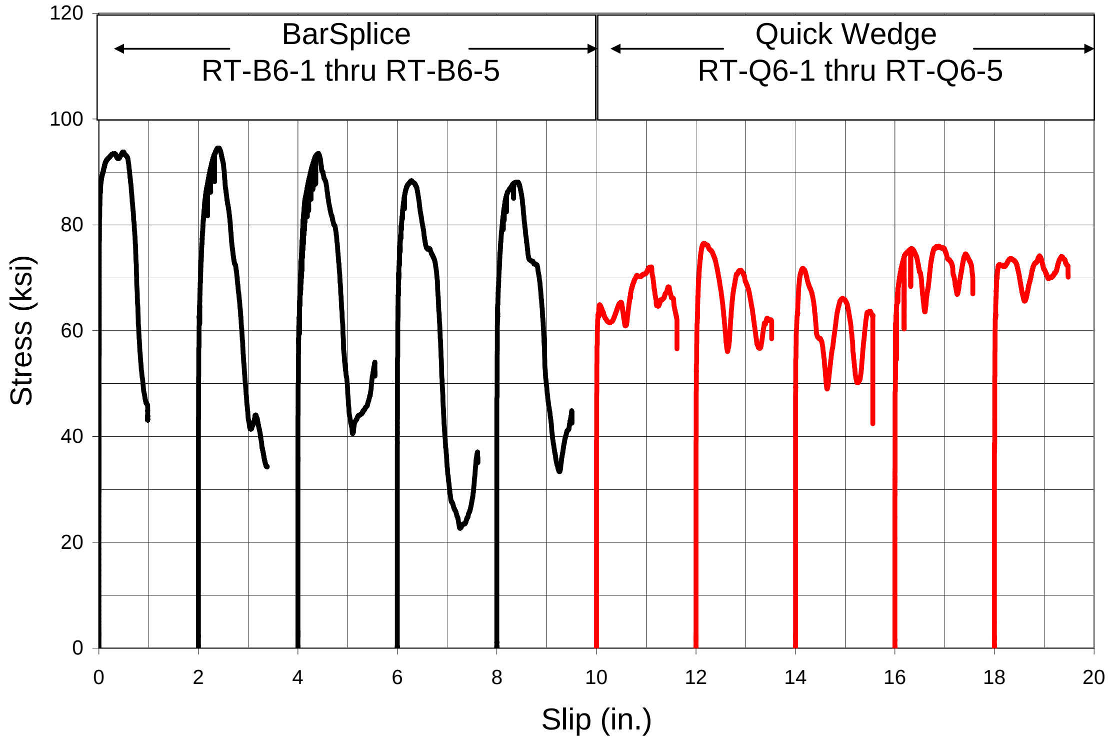


Figure 3-8 Restrained tension test results: stress vs. slip #6 bar.

Figures 3-9 through 3-11 illustrate the behavior of each specimen relative to the Publication 408, Section 1002.2(c) acceptance Criteria I through III given in Table 1-1. In these figures, values are normalized to the nominal reinforcing bar strength values of f_y = 60 ksi (414 MPa) and f_u = 90 ksi (621MPa) (Table 2-1) for Criteria I and III. For Criteria II, slip measured from one side of the splice is considered; therefore the acceptance criteria is one half that given in Table 1-1. This presentation of the acceptance criteria is based on the fact that the total slip across the splice is the sum of the slips of each bar. The critical case is therefore where the greatest single bar slip is doubled (i.e. assumed to occur on both sides of the splice). Therefore for Figure 3-11, the slip values have been normalized with the limiting slip of 0.005 in. (0.13 mm) (Table 1-1). A value of unity or above indicates that the test passed acceptance Criteria I and III; while unity or below indicates a passing test of Criteria II. The observed failure mode from each specimen is also noted in these figures.

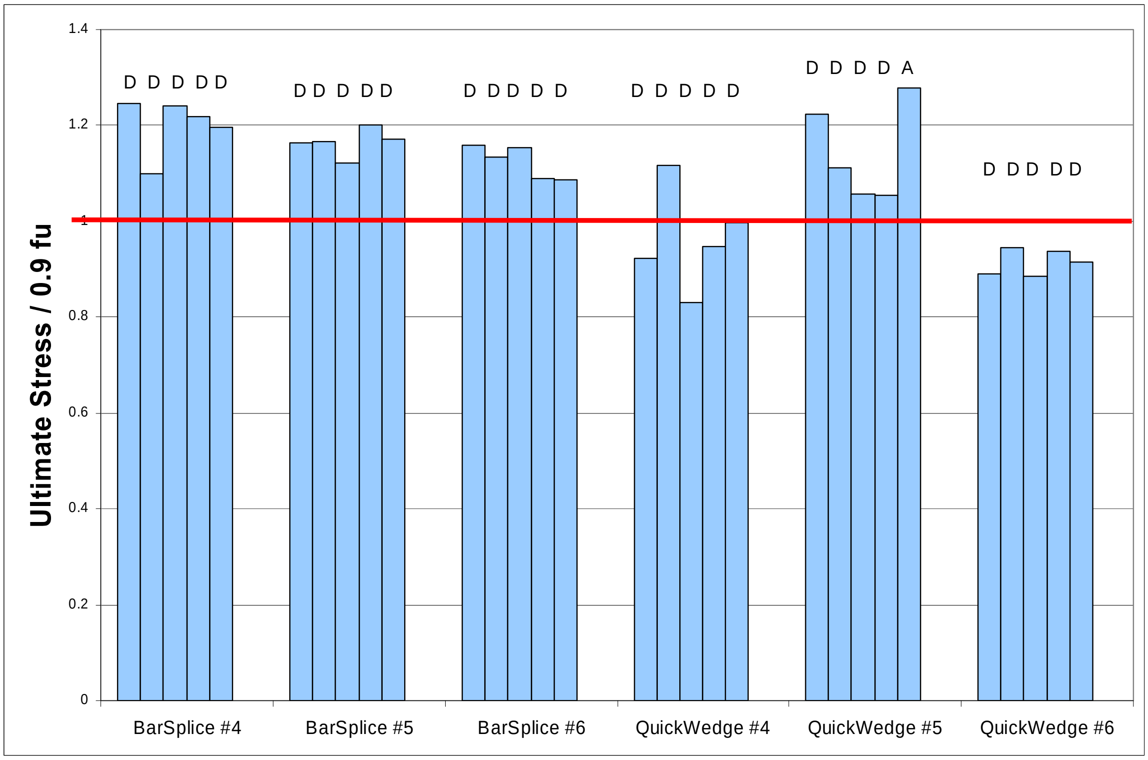


Figure 3-9 Restrained tension test results assessment of Criteria I.

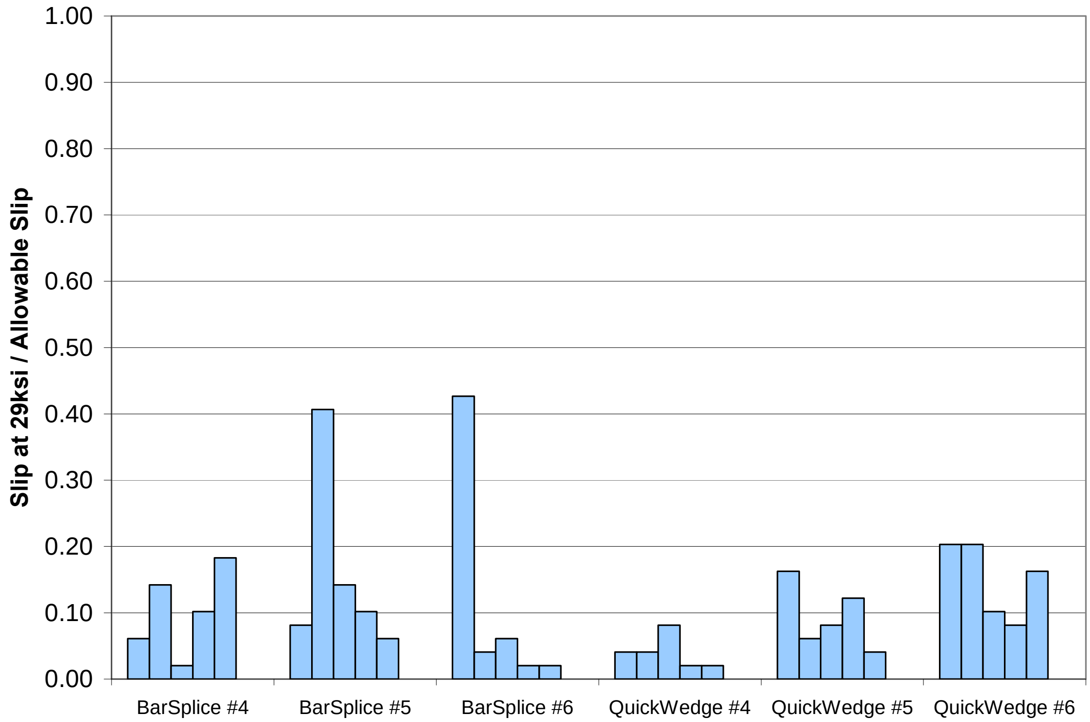


Figure 3-10 Restrained tension test results assessment of Criteria II.

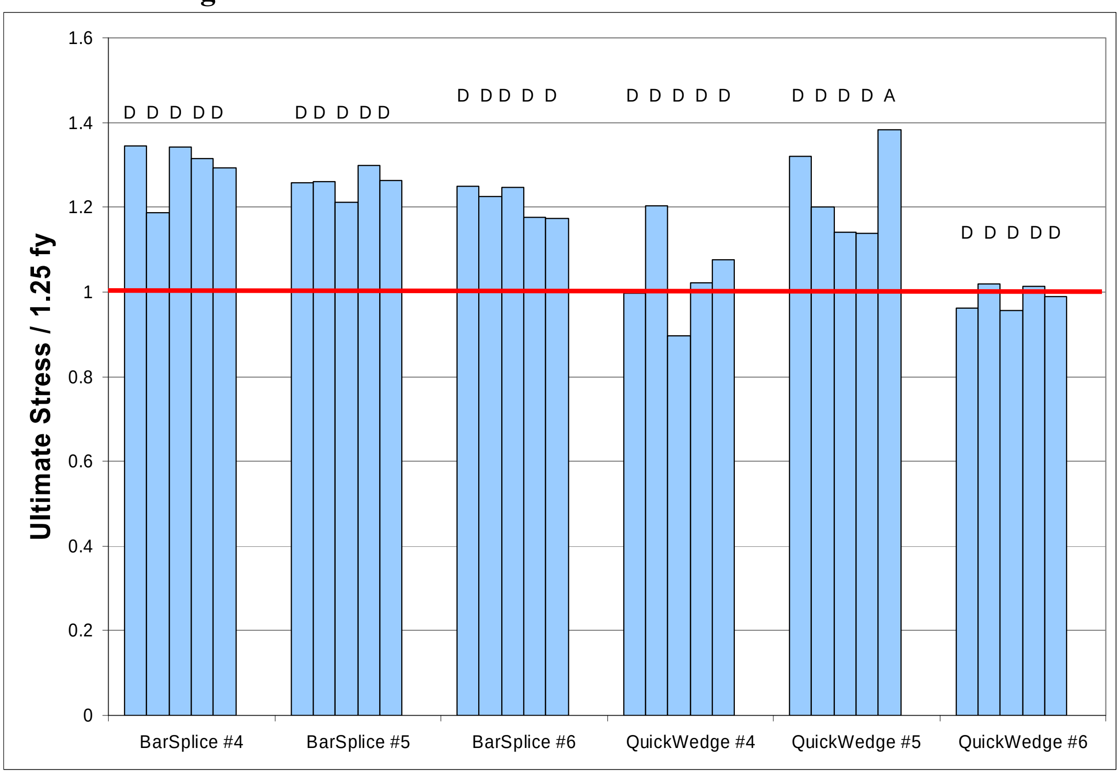


Figure 3-11 Restrained tension test results assessment of Criteria III.

3.4 RT SPECIMEN BEHAVIOR AND DISCUSSION

The strain vs. slip relationship is predictable and repeatable. The stress-slip relationship is generally linear until yield of the reinforcing bar, near 60 ksi (414 MPa). Following yield, the slip begins to increase greatly, often to more than 1.5 in. (38 mm). In each of the tests, the specimen reaches an ultimate stress and the load begins to decrease as the reinforcement bar begins to be pulled through the splice, indicating a Failure Mode D. After a given displacement, the load tends to increase and then decrease again. This effect was more pronounced for the QuickWedge specimens but was evident in nearly all RT tests. It was determined the reinforcing bar ribs contributed to this apparent increase in load carrying capacity: As the bar slipped, the bolt or wedge engaged subsequent reinforcing bar ribs. The pullout force was increased as the rib passed over the bolt or wedge. This conclusion is confirmed in the QuickWedge results where the "spacing", in terms of slip measurements, of the load increases correspond to the bar rib spacing. Such behavior is less evident in the BarSplice product as the bolt gouges into the bar as the bar slips in this case (see Figure 2-13).

Specimen RT-Q5-5 resulted in a failure that was not expected. The specimen was tested with a reaction plate that had a diameter greater than 0.125 in. (3.2 mm) larger than the bar diameter. In this case, the larger opening allowed the splice to rotate and resulted in a failure similar to the failure mode C, but caused severe damage to the splice as shown in Figure 3-12. Since this was not how the test was intended to function, this result was not used and a replacement test was performed. Nonetheless, this result illustrates the importance of customizing the reaction plate for each bar size tested.

Figure 3-12 Specimen RT-Q5-5 failure mode C tested with improper reaction plate. Damage to splice from pulling through the reaction plate is clearly evident.

Specimen RT-Q5-6 was the only specimen in all tension tests that resulted in Failure Mode A. This specimen also had the highest ultimate stress of all tension tests. The failure occurred in the middle of the specimen away from the splice and the wedge grips. The specimens had very small slip through failure as shown in Figure 3-8.

Similarly to the DT tests, the increase in bar size resulted in a decrease in performance in the performance Criteria I and III (Table 1-1) for the BarSplice specimens as shown in Figures 3-10 and 3-12. The QuickWedge specimens did not follow this trend and performed marginally overall with respect to Criteria I and III. For the #4 QuickWedge specimens, only two specimens passed the first performance criteria, and one specimen of this bar size had an ultimate stress just 67.3 ksi (464.0 MPa), the lowest of all tension tests. The QuickWedge specimens with the #5 bar size performed better with all specimens passing Criteria I and III. The #6 QuickWedge specimens performed poorly, uniformly failing Criteria I. In contrast, the BarSplice specimens performed as expected in this series of tests, there was much less scatter in results from the BarSplice specimens. All tests results exceeded Criteria I and III.

In Criteria II (Figure 3-11), all specimens satisfied the criteria with most exhibiting a slip below 45% of that allowable at an applied load of 29 ksi (200 MPa). In general, the BarSplice specimens had more scatter in this result but still performed well. For the QuickWedge specimens, the slip increased with bar size but still remained very small: under 20% of that allowed for the largest bar size.

It is important to note that the measured slip in this one-sided test is only one half that expected across the entire splice. In this case it is assumed that both bars slip an equivalent amount. There is no reason that this is the case, thus, when considering one-sided slip measurements, it is best to consider the greatest slip observed as representing one half of the total slip expected. Nonetheless, considering this all specimens passed Criteria II.

3.5 APPROPRIATENESS OF RT TEST SET-UP

The final RT test set-up used considers only pullout from one side of the splice. While not reflecting *in situ* conditions, this set up overcomes the need for large restraining forces and results in accurate pullout capacities not affected by the kinking of the bar or the binding of the bar along the edge of the splice thought to affect the DT tests (Section 2.5). Thus, for the purposes of product evaluation, it is felt that this simple test is appropriate.

Table 3-2 Results from RT tests

specimen	ultimate stress, $f_{u,exp}$	Criteria III $f_{u,exp}/1.25f_y$	Criteria I $f_{u,exp}/0.9f_u$	slip @ 29ksi	Criteria II slip/0.005	failure mode
RT-B4-1	100.9	1.35	1.25	0.0003	0.06	D
RT-B4-2	89.1	1.19	1.10	0.0007	0.14	D
RT-B4-3	100.6	1.34	1.24	0.0001	0.02	D
RT-B4-4	98.7	1.32	1.22	0.0005	0.10	D
RT-B4-5	96.9	1.29	1.20	0.0009	0.18	D
	97.24	Average RT-B4		0.0005		
	4.83	Standard Deviation RT-B4		0.0003		
RT-B5-1	94.3	1.26	1.16	0.0004	0.08	D
RT-B5-2	94.5	1.26	1.17	0.0020	0.40	D
RT-B5-3	90.8	1.21	1.12	0.0007	0.14	D
RT-B5-4	97.3	1.3	1.2	0.0005	0.10	D
RT-B5-5	94.8	1.26	1.17	0.0003	0.06	D
	94.34	Average RT-B5		0.0008		
	2.32	Standard Deviation RT-B5		0.0007		
RT-B6-1	93.8	1.25	1.16	0.0021	0.42	D
RT-B6-2	91.8	1.22	1.13	0.0002	0.04	D
RT-B6-3	93.5	1.25	1.15	0.0003	0.06	D
RT-B6-4	88.3	1.18	1.09	0.0001	0.02	D
RT-B6-5	88.1	1.17	1.09	0.0001	0.02	D
	91.10	Average RT-B6		0.0006		
	2.76	Standard Deviation RT-B6		0.0009		
RT-Q4-1	74.7	1.00	0.92	0.0002	0.04	D
RT-Q4-2	90.3	1.20	1.12	0.0002	0.04	D
RT-Q4-3	67.3	0.90	0.83	0.0004	0.08	D
RT-Q4-4	76.7	1.02	0.95	0.0001	0.02	D
RT-Q4-5	80.7	1.08	1.00	0.0001	0.02	D
	77.94	Average RT-Q4		0.0002		
	8.45	Standard Deviation RT-Q4		0.0001		
RT-Q5-1	99.0	1.32	1.22	0.0008	0.16	D
RT-Q5-2	90.0	1.20	1.11	0.0003	0.06	D
RT-Q5-3	85.6	1.14	1.06	0.0004	0.08	D
RT-Q5-4	85.4	1.14	1.05	0.0006	0.12	D
RT-Q5-5	80.8	1.08	1.00	0.0003	0.06	--
RT-Q5-6	103.6	1.38	1.28	0.0002	0.02	A
	92.72	Average RT-Q5		0.0005		
	8.21	Standard Deviation RT-Q5		0.0003		
RT-Q6-1	72.1	0.96	0.89	0.0010	0.20	D
RT-Q6-2	76.5	1.02	0.94	0.0010	0.20	D
RT-Q6-3	71.7	0.96	0.89	0.0005	0.10	D
RT-Q6-4	75.9	1.01	0.94	0.0004	0.08	D
RT-Q6-5	74.1	0.98	0.91	0.0008	0.16	D
	74.06	Average RT-Q6		0.0007		
	2.17	Standard Deviation RT-Q6		0.0003		

4.0 FATIGUE TENSION TESTING

This chapter presents the fatigue testing setup and discussion of the results. Additionally, the evolution of a revised fatigue test is presented.

4.1 BACKGROUND

PennDOT Publication 408, Section 1002.2(c) Criteria IV (Table 1-1) requires cycling through a stress ranging from 25 ksi (172 MPa) compression to 25 ksi (172 MPa) in tension, a 50 ksi (345 MPa) stress range for 10,000 cycles. Due to the stress raisers induced by the couplers - bolts, wedges, and the bar kinking at the coupler face - this stress range was unachievable if 10,000 cycles of loading were required. Initial tests conducted at this stress range resulted in fatigue-induced reinforcing bar rupture (FIRR) occurring at less than 400 cycles as summarized in Table 4-1.

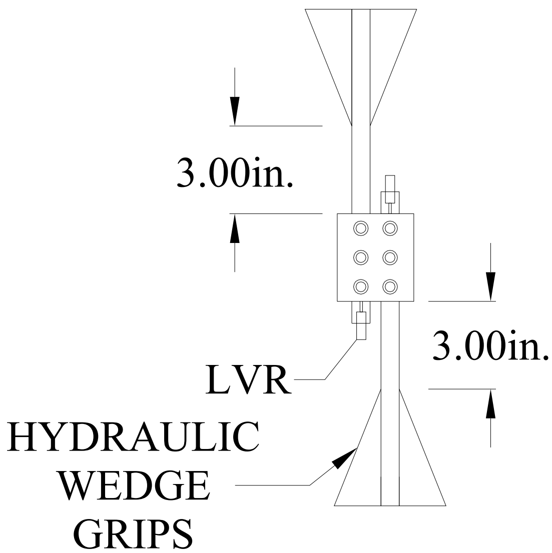
Table 4-1 Summary of preliminary fatigue testing at a stress range of 50 ksi (345 MPa).

specimen	cycles to FIRR
#4 BarSplice	296
#5 BarSplice	218
#5 BarSplice	320
#4 QuickWedge	203
#4 QuickWedge	153
#5 QuickWedge	82
#5 QuickWedge	70

Typically accepted S-N relationships for straight, unspliced reinforcing steel (such as those shown in Figure 1-3) predict a fatigue life of only around 100,000 cycles corresponding to a stress range of 50 ksi. It should be expected that mechanically spliced bars having inherent stress raisers should have significantly reduced fatigue lives. It is evident from Table 4-1 that offset couplers have a much shorter fatigue life than unspliced bars especially at higher stress ranges. A number of variations in the set-up were attempted including varying bar lengths and stress ranges. Ultimately the bar lengths had to be much shorter than the previous testing series to avoid buckling failures and the additional stresses induced by buckling. Additionally, stress ranges had to be reduced. The stress range selected for fatigue testing was 20 ksi (172 MPa), ranging from 10 ksi (86 MPa) in compression to 10 ksi (86 MPa) in tension. This stress range a) permitted 10,000 cycles to be achieved; and b) results in a similar stress range as that considered for the flexural beam tests reported in Chapter 5.

4.2 FATIGUE TEST SETUP

Fatigue testing (F) was carried out in a 20 kip (89kN) capacity universal test machine equipped with hydraulic wedge grips. With the exception of the stress range used, this testing was done in accordance to the CT-670 testing protocol. The test specimens were shorter than the DT and RT specimens to ensure that the spliced bar assembly would not buckle as it was cycled through tension and compression loading. Each specimen had a length of approximately 12 in. (305 mm) but was adjusted for each splice such that the bar length between the end of the splice and the grip was held constant at 3 in. (76 mm) as shown in Figure 4-1. Punch marks were placed on the protruding bars approximately 0.5 in. (13 mm) on each side of the splice. The exact dimension was measured before and after testing and used to calculate the slip. These values were verified using LVRs on several test specimens.



(a) schematic diagram of F set-up.

(b) photograph of F set-up.

Figure 4-1 Fatigue test set-up.

4.3 FATIGUE TEST RESULTS

In Figure 4-2, the normalized slip data is presented. The slip value reported is the maximum slip measured on one side of the splice normalized by *one half* allowable slip given in Table 1-1. This presentation of acceptance criteria is based on the fact that the total slip across the splice is the sum of the slips of each bar. The critical case is therefore where the greatest single bar slip is doubled (i.e. assumed to occur on both sides of the splice). The data from this series of tests and the performance relative to Criteria IV is presented in Table 4-2. In Table 4-2, a positive slip value is a result of the bar being pulled (tension) through the splice and negative values are the result of the bar being pushed (compression) through the splice. When the data from this test is plotted in Figure 4-2, only the magnitude of the slip value is shown.

4.4 FATIGUE SPECIMEN BEHAVIOR

Similar to the DT and RT tests, an increase in bar size resulted in a decrease in performance. The BarSplice specimens performed generally well with two specimens (F-B6-1 & F-B5-5) exhibiting a larger-than-allowable slip. The QuickWedge specimens performed well but exhibited great variability in the results. Six QuickWedge specimens experienced slip values that were greater than allowable. For the #4 and #5 bar size specimens, the QuickWedge specimens exhibited both the lowest and the highest slip values recorded for that bar size. The #6 QuickWedge specimens performed fair with all specimens having a relatively larger slip and four of the five specimens exceeding the limiting slip. The #6 BarSplice specimens performed well with 4 specimens have a slip below 80% of the allowable and one specimen had a recorded slip value of three times allowable.

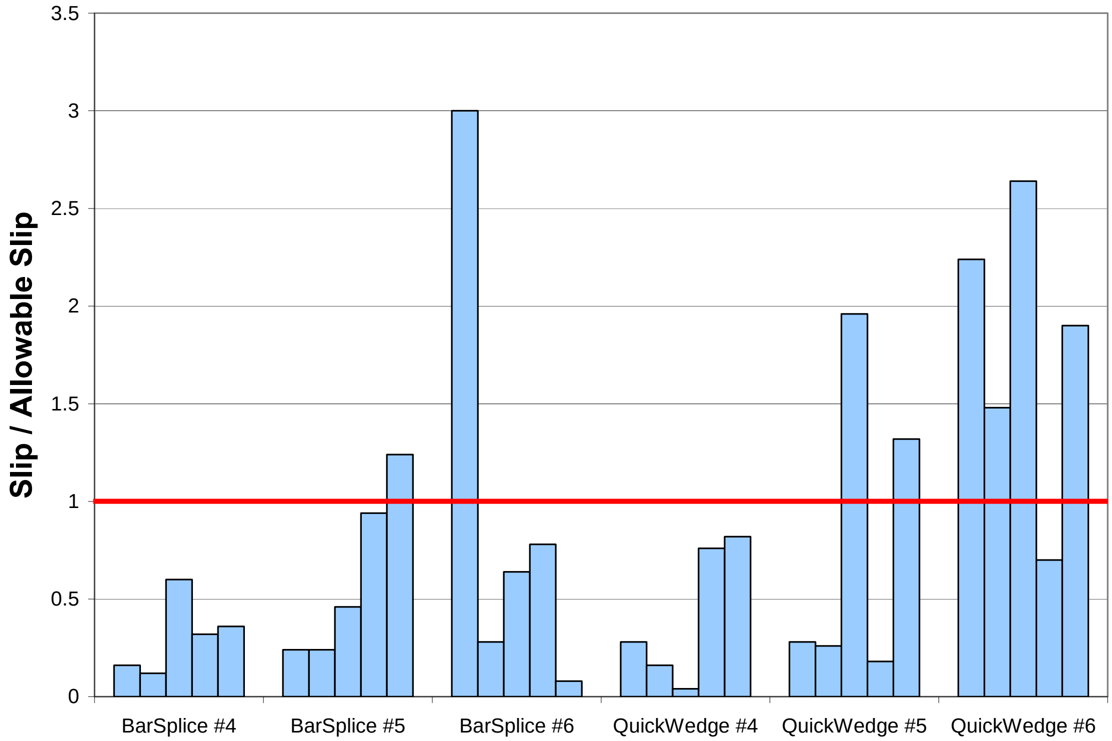


Figure 4-2 Fatigue test results assessment of Criteria IV.

Table 4-2 Summary of results for fatigue testing.

					Allowable slip	0.05 in.
					Allowable slip from one side of splice	0.025 in.
	stress range (ksi)	N (cycles)	slip (in.)		greatest slip (in.)	slip / allowable slip
			top	bottom		
FB4-1	20	10000	-0.002	-0.004	0.004	0.16
FB4-2	20	10000	0.002	0.003	0.003	0.12
FB4-3	20	10000	-0.011	0.015	0.015	0.60
FB4-4	20	10000	0.008	0.008	0.008	0.32
FB4-5	20	10000	-0.005	-0.009	0.009	0.36
			Average FB4		0.008	
			Standard Deviation FB4		0.005	
FB5-1	20	10000	0.001	-0.006	0.006	0.24
FB5-2	20	10000	-0.006	0.006	0.006	0.24
FB5-3	20	10000	0.012	0.002	0.012	0.48
FB5-4	20	10000	-0.011	-0.024	0.024	0.96
FB5-5	20	10000	0.024	-0.031	0.031	1.24
			Average FB5		0.016	
			Standard Deviation FB5		0.011	
FB6-1	20	10000	0.067	-0.075	0.075	3.00
FB6-2	20	10000	-0.007	0.001	0.007	0.28
FB6-3	20	10000	-0.007	0.016	0.016	0.64
FB6-4	20	10000	0.020	0.006	0.020	0.80
FB6-5	20	10000	-0.002	[1]	0.002	0.08
			Average FB6		0.024	
			Standard Deviation FB6		0.029	
FQ4-1	20	10000	-0.002	-0.007	0.007	0.28
FQ4-2	20	10000	0.004	0.003	0.004	0.16
FQ4-3	20	10000	-0.001	0	0.001	0.04
FQ4-4	20	10000	0.019	0.018	0.019	0.76
FQ4-5	20	10000	-0.021	-0.011	0.021	0.84
			Average FQ4		0.010	
			Standard Deviation FQ4		0.009	
FQ5-1	20	10000	0.007	-0.001	0.007	0.28
FQ5-2	20	10000	-0.006	-0.004	0.006	0.24
FQ5-3	20	10000	-0.049	-0.009	0.049	1.96
FQ5-4	20	10000	-0.005	-0.004	0.005	0.20
FQ5-5	20	10000	-0.033	0.024	0.033	1.32
			Average FQ5		0.020	
			Standard Deviation FQ5		0.020	
FQ6-1	20	10000	-0.056	-0.026	0.056	2.24
FQ6-2	20	10000	-0.011	-0.037	0.037	1.48
FQ6-3	20	10000	-0.052	0.066	0.066	2.64
FQ6-4	20	10000	0.007	0.018	0.018	0.72
FQ6-5	20	10000	0.048	0.013	0.048	1.92
			Average FQ6		0.045	
			Standard Deviation FQ6		0.019	

[1] not recorded due to instrument malfunction

5.0 FLEXURAL BEAM TESTING

This chapter presents the flexural beam testing setup and summary of the test results.

5.1 BACKGROUND

To asses the performance of offset mechanical splices, the splices were embedded in concrete beams and tested in two ways: 1) under monotonically increasing load to failure; and 2) the beams were subject to fatigue-conditioning followed by a monotonically increasing load to failure. Thus, the behavior of the splice *in situ* may be assessed and compared to the behavior of a straight unspliced bar. Additionally, the effect of fatigue loads on the splice may be assessed. Finally, the results presented demonstrate the ability for concrete to confine this type of splice.

5.2 FLEXURAL BEAM TEST PROGRAM

Eight reinforced concrete beams were cast for this testing phase. Each specimen was 10 in. (254 mm) deep, 12 in. (305 mm) wide and 187 in. (4743 mm) long. Each beam had a single #4 reinforcement bar as the primary flexural reinforcement and two #3 bars in the compression zone to ensure the beams would not be damaged during handling. The beam sections are shown in Figure 5-1a. The beams were cast in pairs, two specimens each having:

a) straight, un-spliced, bar (designated: C)

b) standard 12 inch long lap splices (AASHTO LRFD 2004) (L);

c) BarSplice couplers (B); and

d) QuickWedge couplers (Q).

One beam of each pair was tested monotonically to failure (designated as indicated above: C, L, B and Q). The second beam of each pair was subject to 10,000 cycles of repeated loading intended to result in an applied stress range in the #4 bar of 20 ksi (138 MPa) (as measured in the first cycle of load, N = 1). The latter specimens are referred to as "fatigue conditioned" and are designated with a trailing "F" (i.e: CF, LF, BF and QF). Following fatigue conditioning, the specimens were loaded monotonically to failure. The material properties for each beam are presented in Table 5-1.

Table 5-1 Experimentally determined concrete and reinforcing steel properties.

Specimen	28 Day Compressive Concrete Strength	Age at Time of Beam Test (days)	#4 Reinforcing Steel
C	f'_c = 6,030 psi (41.6 MPa)	86	f_y = 65 ksi (448 MPa) f_u = 104 ksi (717 MPa)
L		99	
B		92	
Q		89	
CF		113	
LF		119	
BF		120	
QF		121	

5.2.1 Lap Splice Length Determination

The required lap splice length for Specimens L and LF was calculated using AASHTO LRFD (2004), ACI-318-05 (2005), and AASHTO ASD (1996) provisions. The calculations are presented in Table 5-2. The governing lap splice length used in testing was the minimum length, 12 in. (305 mm), determined according to each provision.

Table 5-2 Determination of Lap Splice Length, L_d.

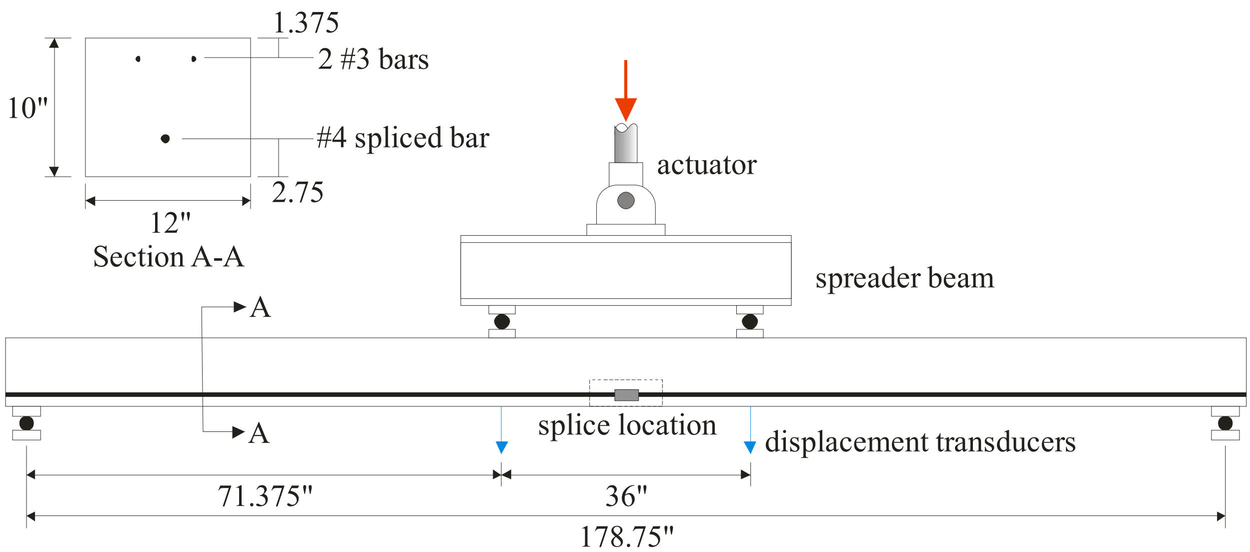
	ACI-318-05 (2005)	AASHTO LRFD (2004)	AASHTO ASD (1996)
governing lap splice length equations	$\left[\frac{3}{40}\frac{f_y}{\sqrt{f'_c}}\frac{\Psi_t\Psi_e\Psi_s\lambda}{\frac{c+K_{tr}}{d_b}}\right]d_b = L_d$ where, f_y = yield strength of bar, psi f'_c = 28 day compressive concrete strength, psi Ψ_t = reinforcement location factor, taken as 1.0 Ψ_e = coating factor, taken as 1.0 Ψ_s = reinforcement size factor, taken as 0.8 λ = lightweight aggregate factor, taken as 1.0 $\frac{c+K_{tr}}{d_b}$ = transverse reinforcing index, taken as 2.5 d_d = spliced bar diameter, in. L_d = 9.3 in. (236 mm)	$\frac{1.25A_b f_y}{\sqrt{f'_c}} = L_d$ where, A_b = area of spliced reinforcement bar, in^2 f_y = yield strength of bar, ksi f'_c = 28 day compressive concrete strength, ksi L_d = 6.1 in (155 mm)	$\frac{0.04A_b f_y}{\sqrt{f'_c}} = L_d$ where, A_b = area of reinforcement bar, in^2 f_y = yield strength of bar, psi f'_c = 28 day compressive concrete strength, psi L_d = 6.2 in (158 mm)
minimum lap splice length	$L_d \geq$ **12 in. (305 mm)**	$L_d \geq 0.4 d_b f_y$ where, d_b = reinforcement bar diameter, in. or $L_d \geq$ **12 in. (305 mm)**	$L_d \geq 0.0004 d_b f_y$ where, d_b = reinforcement bar diameter, in. or $L_d \geq$ **12 in. (305 mm)**

5.3 FLEXURAL BEAM TEST SETUP

All beams (monotonic and fatigue) were loaded in four point flexure with a 36 in. (910 mm) constant moment region located in the center of a 178.75 in. (4540 mm) simple beam span. The reinforcing bar splice was located in the center of the constant moment region. The beams were supported on 3 in. x 12 in. x 0.5 in. (76.2 mm x 305 mm x 12.7 mm) neoprene pads placed on 1 in. (25 mm) thick steel plates subsequently placed on steel rollers. The load was applied using a MTS actuator acting through a W8x31 spreader beam, the spreader beam rested on 1.5 in.(38 mm) diameter steel rollers welded to 3 in. x 12 in. x 1 in. (76.2 mm x 305 mm x 25.4 mm) steel plates placed on 0.5 in. (13 mm) thick neoprene pads. The set up is shown in Figure 5-1.

Fatigue-conditioning was applied to the "F" beams in load control with the total applied load (actuator load) ranging from 0.8 kip (3.55 kN) to 2.2 kips (9.8 kN) in a sinusoidal waveform having a frequency 1.0 Hz. The load range was selected based on the measured reinforcing bar strains from the monotonic test series. The 0.8 kip (3.55 kN) lower limit was selected to represent an applied dead load; the 2.2 kip (9.8 kN) upper limit was selected to develop the desired strain and therefore stress levels in the #4 reinforcing bar and across the splice. The target stress level was 20 ksi (138 MPa), corresponding to the Fatigue testing series described in Chapter 4.

All data in this chapter is reported in terms of total actuator applied load, P. Thus the resulting moment in the constant moment region is 35.7P (kip-in) or 0.91P (kN-m). Similarly the maximum shear in the beam is 0.5P.



(a) Schematic diagram of flexural beam test set-up.

(b) Photograph of flexural beam test set-up.
Figure 5-1 Flexural beam test set-up.

The monotonic tests and final cycle to failure, N = 10,001, for the fatigue tests were conducted in displacement control at a rate of 0.288 in/min (7.315 mm/min). Due to the stroke limitations of the MTS actuator, and the ductility of the under-reinforced beams, additional spacers where required to test the beam specimens to failure. In each monotonic test, the beams were loaded to a deflection of 3 in. (76.2 mm). The specimens were then unloaded and the resulting permanent deflection was made up with spacer plates between the actuator and spreader beam. The test was then continued to a deflection of approximately 5 in. (127 mm) where the beam came into contact with the test frame. Although not tested to their ultimate failure, the final deflections where all on the order of L/32 and thus may be reasonably assumed to have exceeded their ultimate conditions. This load history described results in the loop at a displacement of 3 in. evident in the load-deflection plots presented in this chapter.

During monotonic testing, the displacements were held constant at specified load intervals to document cracking and investigate the specimens' behavior. The tests were paused less than ten minutes in each case and the entire testing time (to failure) was kept under two hours. It was determined that these pauses did not affect the behavior of the specimen.

5.3.1 Instrumentation

Each beam was instrumented with electrical resistance strain gages on the #4 flexural reinforcement. Gages were located 12 in. (305mm) on each side of midspan and thus fell in the constant moment region. Vertical displacements were recorded using draw wire transducers (DWT) located under each load point (Figure 5-1a). The MTS hydraulic actuator was equipped with an internal linear variable displacement transducer (LVDT) and an inline 50 kip (222 kN) load cell. Strain gages, load cell, DWT, and LVDT were connected into the data acquisition system and recorded continuously during monotonic testing.

5.4 BEAM TEST RESULTS

The load vs. displacement results of each beam are shown in subsequent sections. The behavior of the load vs. deflection plots show the ductility of each under-reinforced beam and indicate evidence of slip in the splicing methods or rotation of the splice within the concrete as described further below. The "jagged" behavior of these plots reflect the relaxation that occurred when the loads were held in order to assess cracking behavior. The displacement limitations of the testing frame prevented testing of the specimens to their ultimate load carrying capacity; therefore ultimate load can not be a basis of comparison between the different specimens. Therefore, applied load resulting in a specified deflection is used as a means of comparison. To compare the stiffness for each specimen, the load and strain were recorded at specified displacements and presented in Table 5-3.

Table 5-3 Test results at given displacements.

	1	**2**	**3**
Specimen	**load at 2 in. (50.8 mm) displacement, kips (kN)**	**strain at 2 in. (50.8 mm) displacement, με**	**load at 5 in. (127 mm) displacement, kips (kN)**
C	3.40 (15.1)	2217	4.28 (19.0)
CF	3.41 (15.2)	2262	4.07 (18.1)
L	2.88 (12.8)	2094	3.67 (16.3)
LF	2.98 (13.3)	9133	3.72 (16.5)
B	3.38 (15.0)	1282	2.54 (11.3)
BF	3.12 (13.9)	9015	3.93 (17.5)
Q	3.10 (13.8)	1349	3.20 (14.2)
QF	3.21 (14.3)	2149	3.90 (17.3)

In column 1 of Table 5-3, it is evident there was little degradation of load-carrying behavior caused by the fatigue conditioning of each specimen type. Additionally, the control series (C and CF) exhibited the stiffest behavior while the and the lap splice (L and LF) was the least stiff of all specimens. There was little difference in stiffness between the BarSplice (B and BF) and QuickWedge (Q and QF) specimens although both were marginally less stiff than the control beams having a continuous reinforcing bar. The behavior described indicates a marginal reduction in capacity associated with each splice, which may be attributed to nominal slip or relative movement of the splice.

Column 2 presents the strain values at a displacement of 2 in (50.8 mm). From these values, it is evident there was some accumulated damage due to fatigue conditioning in all cases since the monotonic strain is less than the fatigue strain. The very large strains for the LF and BF specimens are likely caused by the presence of a flexural crack very near the gage location.

Column 3 is the applied load at a displacement of 5 inches (127 mm) (near the peak deflection for all specimens). The fatigue conditioned control (CF) and the lap splice specimens (L and LF) performed in a similar manner as the monotonic control Specimen C. For the BarSplice specimens, the fatigue conditioned specimen (BF) had a higher load than the monotonic loaded specimen (B). This is explained by the fact that the BarSplice monotonic specimen (B) clearly exhibited slip of the splice and began to shed load as a result (described in detail below). The QuickWedge specimens (Q and QF) performed similar to the BarSplice series with the fatigue conditioned specimen achieving higher loads than the monotonic specimen. Again, marginal slip of the splice during the monotonic tests is believed to account for this as discussed below.

5.5 BEAM SPECIMEN BEHAVIOR AND DISCUSSION

This section discusses the behavior of each test specimen.

5.5.1 Specimens C and CF

Specimen C (Figure 5-2) had the highest recorded applied load of the beam tests, which was a result of the beam having a higher post-yield stiffness than the other beam specimens. The peak load was near 4.5 kips (20 kN) although this specimen was loaded to a deflection closer to 6 inches (152 mm). During testing of the other specimens the tests were stopped at a deflection of approximately 5.5 in. (140mm); the load at this deflection value was 4.3 kips (19 kN). Specimen CF showed little degradation from the fatigue conditioning, performing similar to specimen C through most of the test history as shown in Table 5-2 and Figure 5-2. Some degradation in the behavior of Specimen CF is evident at the end of the test at displacements exceeding 5 in. (127 mm), although this behavior cannot necessarily be attributed to the effects of fatigue conditioning.

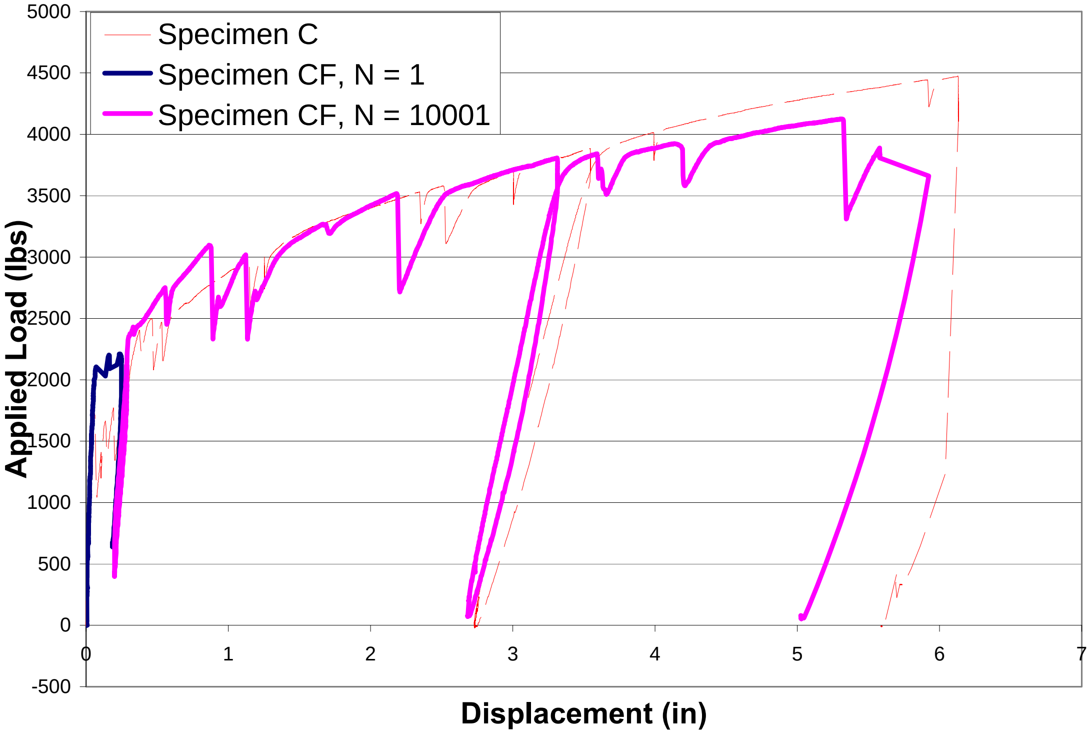


Figure 5-2 Applied load vs. displacement for unspliced control specimens.

5.5.2 Specimens L and LF

Specimen L and LF performed similarly with little difference in stiffness due to the fatigue conditioning. This series had a lower stiffness than the other specimens and a peak load of only 3.75 kips (16.7 kN).as shown in Figure 5-3.

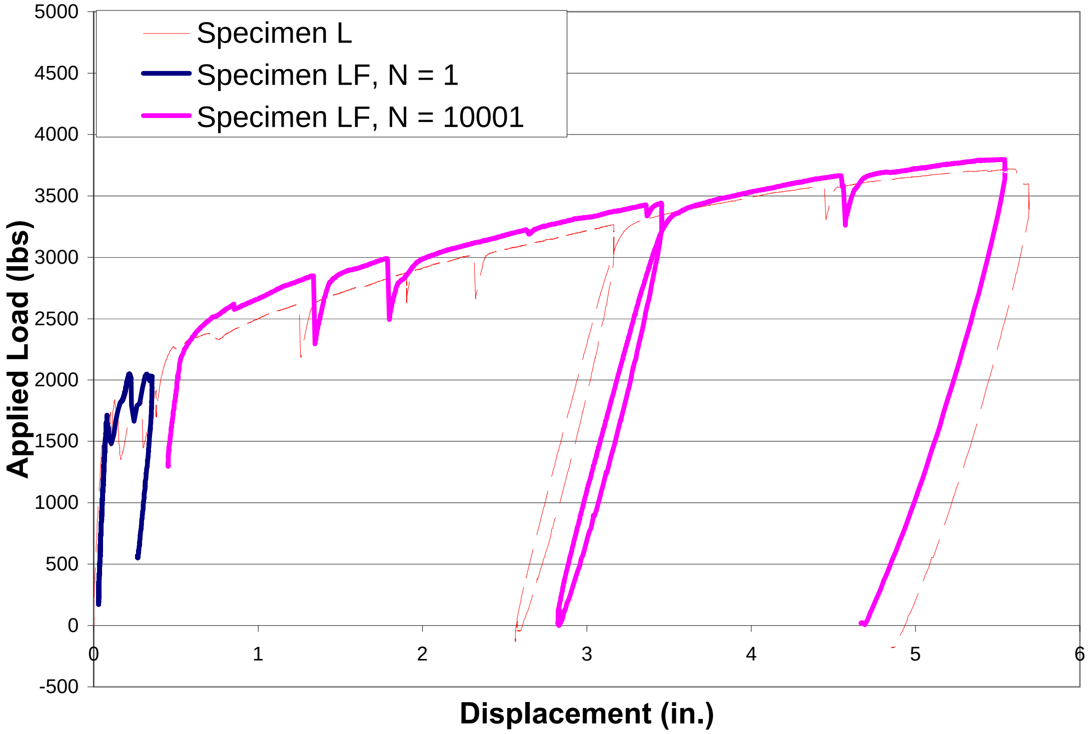


Figure 5-3 Applied load vs. displacement for Lap Splice specimens.

5.5.2.1 Lap Splice Behavior

The apparent degradation of behavior of the L specimens as compared to the C specimens may be attributed to the "softer" expected response of the lap splice as compared to the continuous bar. In a conventional lap splice, relative slip of the bars, in addition to steel strain, contribute to the measured elongation across the splice. The slip initiates immediately and increases until the bond stress is exhausted at which point the lap splice can carry no additional load and eventually fails, shedding its load carrying capacity. This behavior is shown schematically in Figure 5-4 as the bond stress-slip relationship prescribed by the Comité European du Béton (CEB 1990).

The cyclic loading response of lap-splices is observed to be significantly inferior to the monotonic loading response. The bond stresses developed in lap-splices subject to cyclic loading histories are observed to deteriorate more rapidly than bond stresses under monotonic loading

(Viwathanatepa et al. 1979). Additionally, there is a general consensus (Viwathanatepa et al. 1979; Lukose et al. 1982; MacKay et al. 1998 and others) that for cyclic loading conditions, the effects of confinement reinforcement are insignificant. For the tests conducted in this study, no transverse confinement was provided and thus the deterioration due to cycling (or rather the beneficial effects of confinement under monotonic conditions) was not evident.

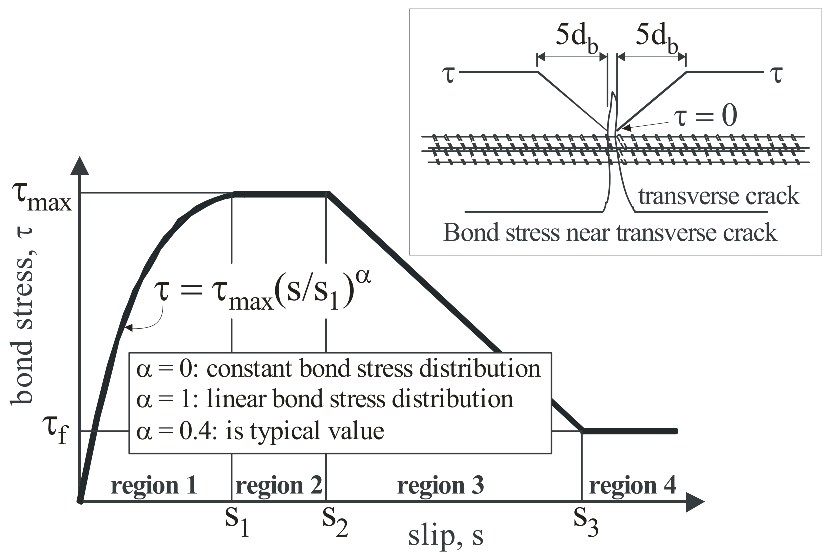


Figure 5-4 Lap-splice bond stress-slip relationship prescribed by CEB 1990 (figure from Harries et al. 2006).

5.5.3 Specimens B and BF

Specimen B (Figure 5-5) performed well initially reaching a peak load of 3.5 kips (15.6 kN). However, upon reloading following holding at this peak (to record cracking) the specimen never regained its previous capacity, achieving a capacity of only 3.2 kips (14.2 kN) before the load began to decrease as the deflection continued to increase indicating a failure of the specimen. The test was halted at a deflection of 5 in. (127 mm). Following testing, the splice was recovered and inspected. The splice exhibited clear signs of slip: one bar slipped approximately 0.5 inches (12.7 mm) through the splice. The splice is shown in Figure 5-6; the slip is not clearly visible in the figure, but from the lack of consolidation on one side of the splice it is apparent that there was noticeable slip through the splice.

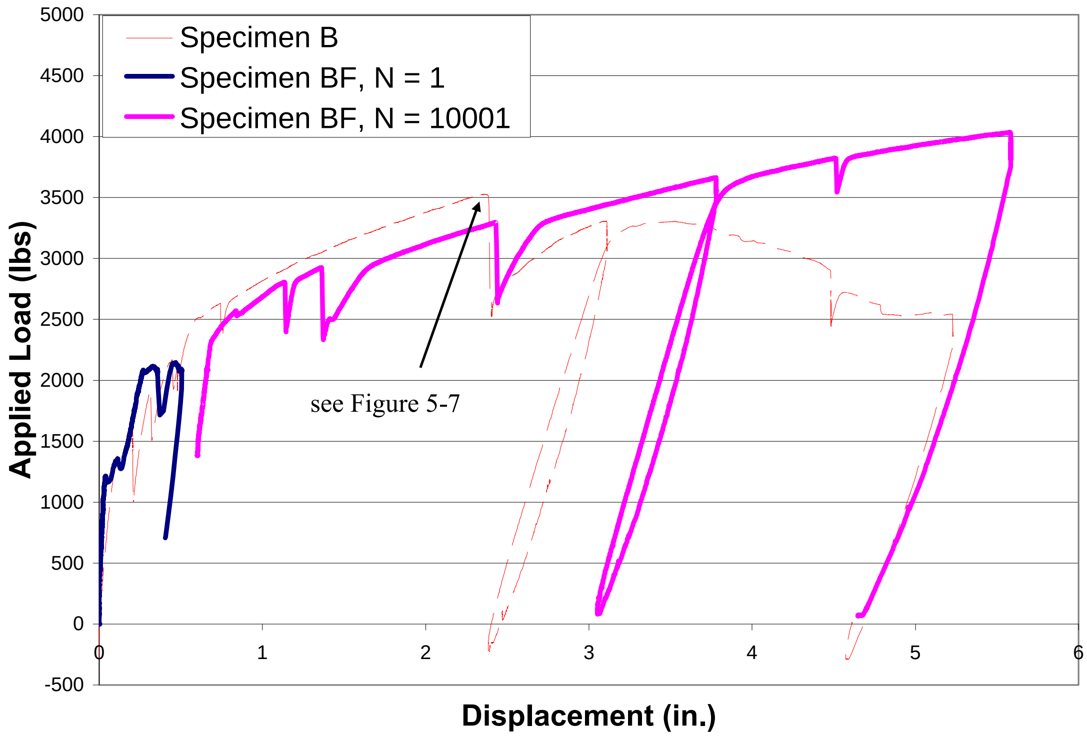


Figure 5-5 Applied load plotted vs. displacement for BarSplice specimens.

Figure 5-6 BarSplice Specimen B slip from monotonic testing.

Specimen BF showed little signs of degradation resulting from fatigue conditioning, and achieved a higher load than the monotonic test, reaching an ultimate load of 4.0 kips (17.8 kN) at a deflection of 5.25 inches (133.4 mm).

In each of the BarSplice beams, the concrete was unable to properly confine the splice and there was cracking evident on the soffit of the specimen caused by the rotation of the splice or slip of the bars through the splice. This cracking demonstrates a particular problem with offset splices: the cracking of the cover concrete would cause particular problems in structural elements exposed to the environmental and especially deicing salts. This cracking is shown on Specimen B in Figure 5-4 at a load of 3.5 kips (15.6 kN).

Figure 5-7 Soffit longitudinal cracking caused by rotation of the BarSplice coupler shown on Specimen B (figure shown looking along beam's length.)

5.5.4 Specimens Q and QF

Specimen Q (Figure 5-8) performed in a similar manner as specimen B; during the initial loading the specimen had a reasonable stiffness. At the peak load of the initial loading step, the splice began to rotate and the concrete cover began to spall. Figure 5-9 shows the effect of the splice rotation on the concrete cover. The cracking was first documented at 3.1 kips (13.8 kN) and the cracking in Figure 5-5 is shown at a load of 3.4 kips (15.1 kN) at the peak of the initial loading cycle.

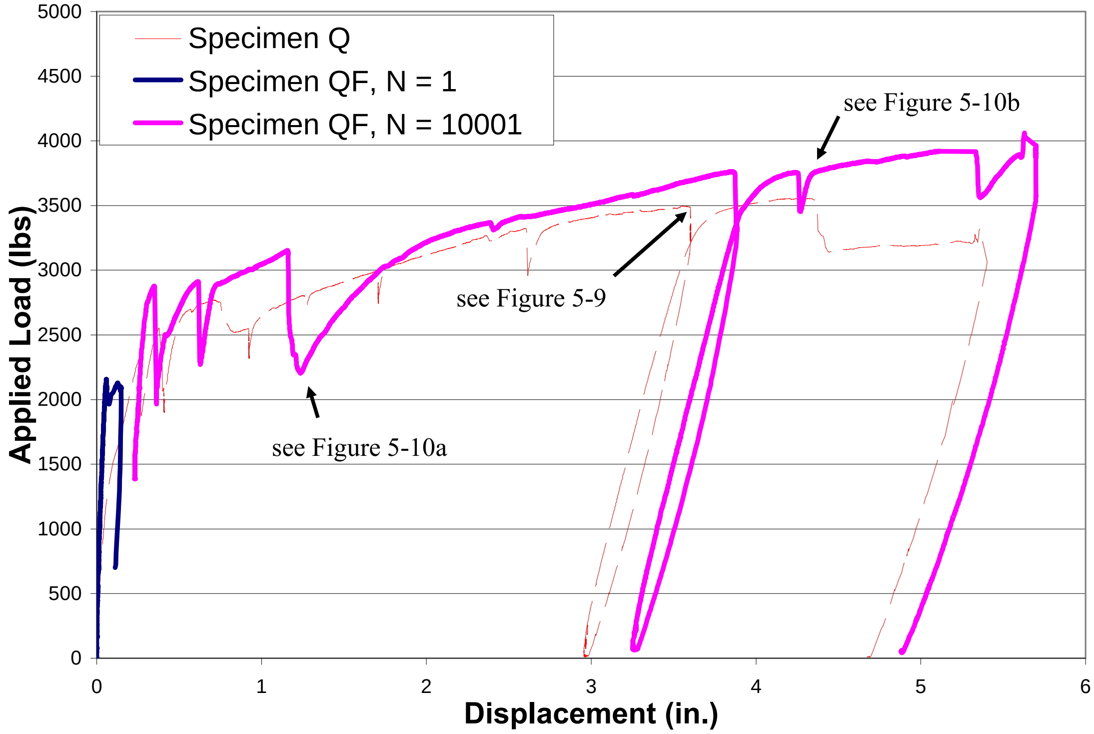


Figure 5-8 Applied load plotted vs. displacement for QuickWedge specimens

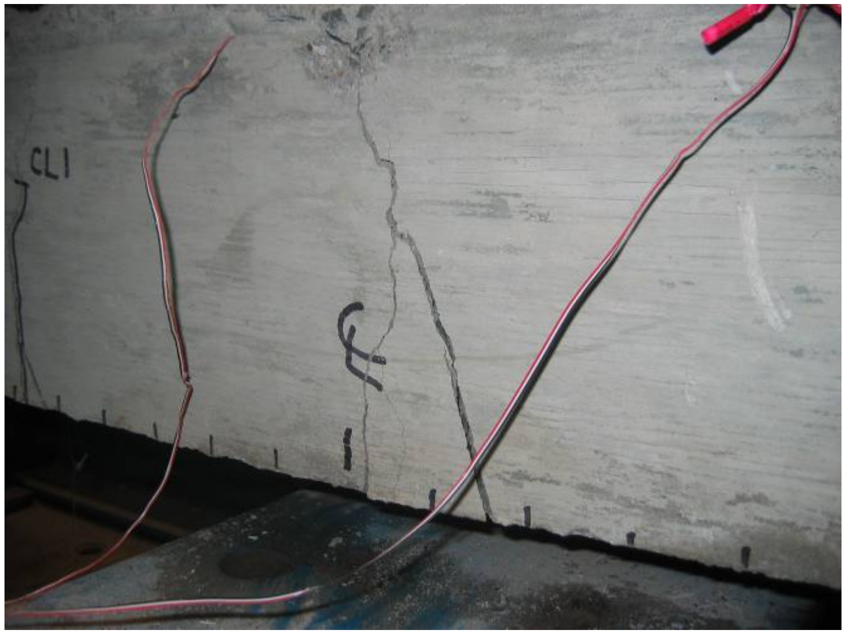
Figure 5-9 Soffit longitudinal cracking caused by rotation of the QuickWedge coupler shown on Specimen Q (figure shown looking along beam's length.)

During reloading, the specimen's performance deteriorated and was unable to achieve higher loads as the deflections continue to increase. A slipping failure similar to that observed in Specimen B was suspected. Upon post-test inspection, however, there was no noticeable slip although a great deal of rotation occurred, which would also result in an increase in deflection without an increase in load. Similar to the BarSplice specimens, the concrete cover was unable to restrain the splice from rotating. The damage caused by the rotation is shown in Figure 5-10. In Figure 5-10a, the rotation induces cracking near the spliced region on the side of the beam. In Figure 5-10b, the rotation caused the cover concrete to spall completely off.

5.5.5 Splice-induced Damage to Concrete

Figure 5-11 shows images of the beam soffits following testing. Figures 5-11a and b show the expected flexure-induced transverse cracking evident for Specimens C and L. No other damage is apparent including longitudinal cracking in Specimen L, which may indicate lap splice slip.

The rotation of the each offset splice is clearly shown in Figures 5-11c though f. The offset splices rotated in each case resulting in significant loss of cover.



(a) cracking caused by splice rotation

(b) spall caused by splice rotation

Figure 5-10 Damage to concrete cover caused by splice rotation in specimen QF.

(a) representative unspliced control specimen

(b) representative lap splice specimen

(c) specimen B

(d) specimen B-F

(e) specimen Q

(f) specimen QF

Figure 5-11 Soffit of each specimen after testing.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter reports and discusses conclusions of the experimental program. A summary of the testing procedure is presented and recommendations for future research needs.

6.1 SUMMARY OF TEST PROGRAM

Two commercially available offset mechanical splice systems, the BarSplice Double Barrel Zap Screwlok© and the Lenton QuickWedge©, were evaluated in four series of tests. The performance of each specimen was evaluated in accordance with Publication 408, Section 1002.2(c) as shown in Table 1-1. The tests conducted on each splice systems were:

- Direct Tension (DT) tested the reinforcement bar splice in open-air direct tension and allowed the splice to freely rotate. Each specimen was instrumented to record only the slip component over the spliced region not any elastic or inelastic deformation in the bar. The specimens were loaded monotonically until rupture of the bar occurred or the recorded slip exceeded one inch (25.4 mm).
- Restrained Tension (RT) tested the reinforcement bar splice in a manner that inhibited the splice from rotation. The test setup resulted in the splices being tested in a manner similar to a "pullout" method. In these tests only one straight bar was subject to tension with the

reaction being provided by the coupler itself. The uniform reaction between the coupler and loading plate effectively restrains the tendency of the coupler to rotate. In this series of tests slip through the splice was measured similar to the DT tests. Each of the specimens were loaded monotonically to failure similar to the DT tests.

- Fatigue Tension (FT) was modeled after the CT670 testing method which required cycling the specimen through a 50 ksi (345 MPa) stress range, this range was unattainable for offset splices if 10,000 cycles were required. The stress range was reduced to 20 ksi (138 MPa) and the load was cycled from 10 ksi (69 MPa) compression to 10 ksi (69 MPa) tension for 10,000 cycles. For each test the slip through the splice was recorded after cycling.
- Flexural Beam tests were conducted with the reinforcement bar splice embedded in concrete. Eight reinforced concrete beams were cast for this testing phase. Each specimen was 10 in. (254 mm) deep, 12 in. (305 mm) wide and 187 in. (4743 mm) long. Each beam had a single #4 reinforcement bar as the primary flexural reinforcement. All beams (monotonic and fatigue) were loaded in four point flexure over a 178.75 in. (4540 mm) simple beam span. The reinforcing bar splice was located in the center of the constant moment region. One beam of each pair was tested monotonically to failure. The second beam of each pair was subject to 10,000 cycles of repeated loading intended to result in an applied stress range in the #4 flexural reinforcement bar of 20 ksi (138 MPa), similar to the FT tests.

6.2 CONCLUSIONS

The performance of each specimen was evaluated in accordance with Publication 408, Section 1002.2(c) as shown in Table 1-1. From the performance in these criteria the following conclusions can be drawn from this work:

1. Table 6-1 presents the number of specimens passing the four acceptance criteria listed in Table 1-1.

Table 6-1 Number of passing specimens for each criteria.

Criteria	I	II	III	IV
Test	Ultimate tensile strength of mechanical coupler greater than 0.90 f_u	Allowable slip (resulting from applied stress of 29 ksi (200 MPa)) less than 0.01 in. (0.25mm)	Yield strength of mechanical coupler greater than 1.25 f_y	Fatigue resistance allowable slip (10 to -10 ksi (69 to -69 MPa) for 10000 cycles) less than 0.05 in. (1.25 mm) [1]
DT-B4	5/5	5/5	5/5	-
DT-Q4	5/5	5/5	5/5	-
DT-B5	5/5	5/5	5/5	-
DT-Q5	5/5	5/5	5/5	-
DT-B6	5/5	5/5	5/5	-
DT-Q6	5/5	4/5	5/5	-
RT-B4	5/5	5/5	5/5	-
RT-Q4	1/5	5/5	3/5	-
RT-B5	5/5	5/5	5/5	-
RT-Q5	5/5	5/5	5/5	-
RT-B6	5/5	5/5	5/5	-
RT-Q6	0/5	5/5	2/5	-
FT-B4	-	-	-	5/5
FT-Q4	-	-	-	5/5
FT-B5	-	-	-	4/5
FT-Q5	-	-	-	3/5
FT-B6	-	-	-	4/5
FT-Q6	-	-	-	1/5

[1]Note: Criteria 4 changed from the Publication 408 requirements as discussed in Chapter 4.

2. An increase in reinforcement bar diameter from #4 to #6 resulted in a decrease in performance for each of the criteria considered although most specimens still passed the criteria.
3. There was large variation in slip data recorded for each series of tests.

4. Contrary to manufacturers' assumptions, the DT test is not necessarily conservative; the capacity of DT tests increased in comparison to the RT tests due to friction between the kinked bar and coupler.
5. Failure mode C: rupture of the bar at the stress raisor associated with contact of the kinked bar, was the most commonly observed failure mode in DT tests.
6. Large restraining forces are required to prohibit rotation of the splice. A direct pullout test (RT type test) is proposed to mitigate this issue.
7. Failure mode D: a pullout failure, was the most common failure mode observed for the RT tests. This mode of failure results in a decrease in apparent ultimate stress for the system because of the inability to develop the full strength of the cross section.
8. A 50 ksi (345 MPa) stress range for fatigue testing (FT) results in fatigue-induced reinforcing bar rupture at a very low number of cycles. A more reasonable stress range of 20 ksi (138 MPa) is suggested for this type of splice.
9. There was no noticeable degradation of the *in situ* splice behavior following fatigue conditioning.
10. For all *in situ* testing concrete was unable to properly confine the offset splice near ultimate load levels.

6.2.1 Qualitative Conclusions

All mechanical splices were installed at the University of Pittsburgh's structural research laboratory following manufacturer's guidelines and specifications. As noted in Chapter 1 the QuickWedge product requires the use of a proprietary hydraulic wedge driver and the BarSplice product can be installed using a hand-held ratchet or torque wrench. The BarSplice product presents more options if there were clearance issues when installing, a simple ratchet could be used to install the splice. The wedge driver requires time consuming adjustments to the driver tool to splice different size bars while the BarSplice product simply adds to the number of screws that need to be tightened, the screw size remains constant.

A concern with both the BarSplice and QuickWedge are the dimensions of the product. As presented in Chapter 1 the QuickWedge specimen is much smaller and encroaches less on amount of cover present when the splice is embedded in concrete.

6.3 RECOMMENDATIONS

There is a limited body of knowledge on the testing and use offset mechanical splices. This study is the only known study that specifically addresses the use of offset mechanical splices. There needs to be further work conducted in this area before the use of these splices can be widely accepted. Some recommendations made from this study are:

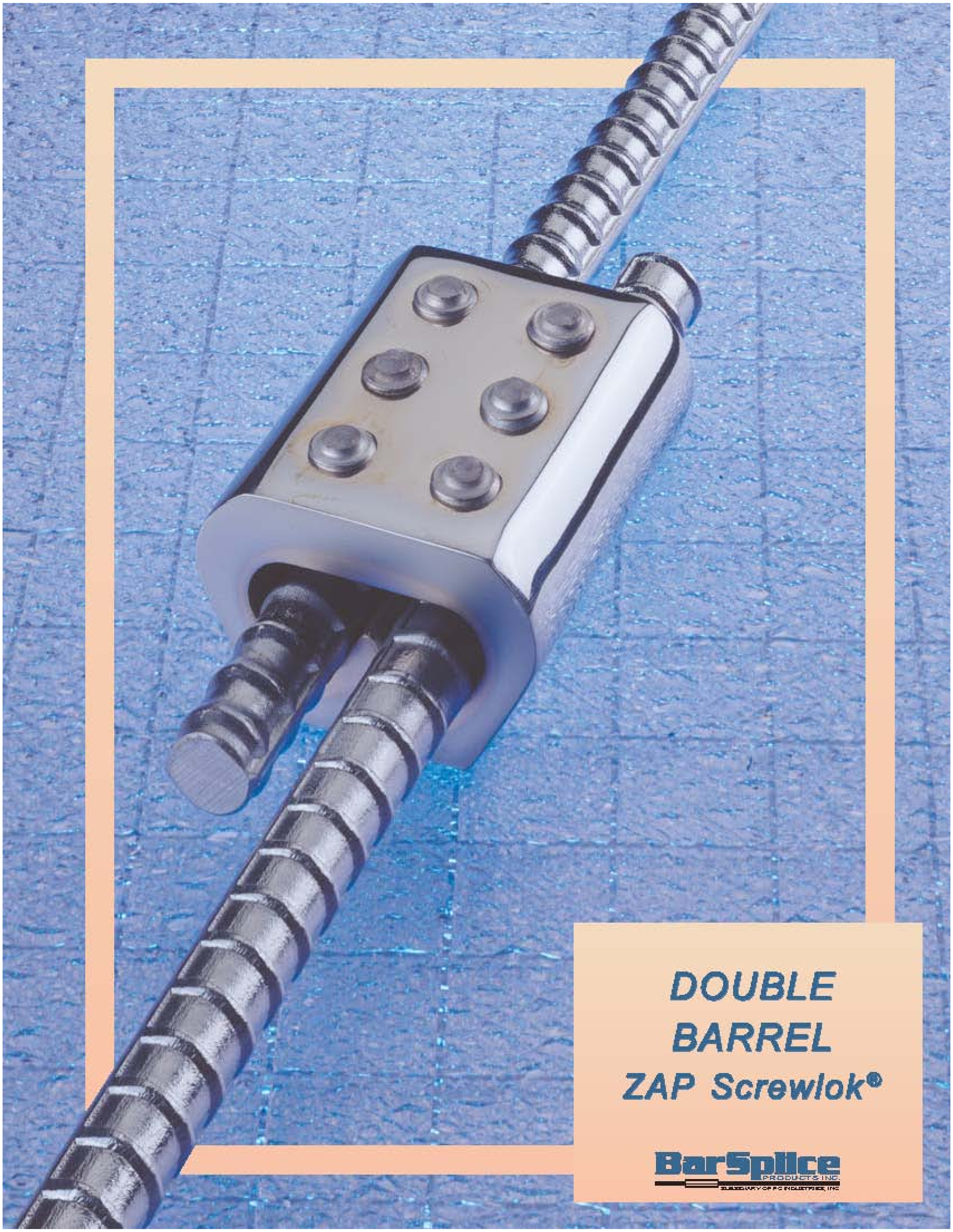
1. Modifications need to be made to testing standards and performance criteria to specifically include offset splices. Revisions were suggested to the current PennDOT acceptance criteria as a result of this work (Coogler and Harries, 2006)
2. The presence of confinement is expected to improve behavior of these types of splices; a study of this effect is required. Modifications may need to be made to current codes to address the amount of confinement required to allow the splice to properly function embedded in concrete.
3. Offset splices should be used only in non-seismic applications.

4. Offset splices are not recommended for larger bar diameters (#6 and greater) unless they can be shown to satisfy the performance criteria.
5. As with all splices, offset splices should not be located in regions of high stress or fatigue critical locations.
6. Specific applications that offset mechanical splices can be used for include providing continuity and anchorage to "hoop" or continuous spiral reinforcement used to provide confinement in columns. Other applications can include relieving congestion and reducing the reinforcement ratio in splice regions and in splicing new reinforcing steel to existing steel in patches, closure pours and structural additions.

The use of offset mechanical lap splices are a viable alternative to other types of concrete reinforcement splices, where appropriate. Further research is required to identify more specific acceptable criteria to include the use of these types of splices. With further research and design provisions, offset mechanical splices are an attractive alternative for specific uses.

APPENDIX A

BARSPLICE PRODUCT LITERATURE


DOUBLE
BARREL
ZAP Screwlok®
BarSplice

Double Barrel Zap Screwlok®

Innovative solutions for your tough splicing problems…

From the Zap Screwlok® family of mechanical splices, comes an innovative solution for your tough splicing problems...

A mechanical lap splice whose strength is independent of the concrete which surrounds it and whose performance is higher than the design strength of in-concrete wire-tie laps.

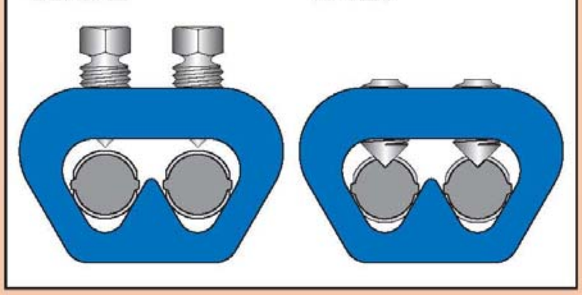
All this from a connector with a length that is a fraction of conventional lap length design!

EASY INSTALLATION…

Assemble manually with socket wrench *or* for quickest installation, use a standard air impact wrench.

*By following the instructions supplied with your order, insert the reinforcing bars through the Double Barrel Zap Screwlok® and tighten the screws until the heads twist off at a prescribed value. **It's that simple.***

The force from the screws causes the rebar deformations to interlock within the coupler wedges. At the same time, the screws embed themselves into the rebar surface. This dual mechanical action results in a full positive connection for transferring tension or compression force from bar-to-bar.



APPLICATIONS

- ✓ Retrofit, strengthen, and up-grade existing columns with supplemental confining steel.
- ✓ Create closed hoop-bars. Eliminate rebar-welds and expensive welding equipment.
- ✓ Maintain continuity in spirals from section-to-section. Positively close spiral free-ends.
- ✓ Extend deck steel to widen bridges. Use in highway patch and repair projects.
- ✓ Connect bars across closure pours.
- ✓ Use in reinforced concrete piles and columns.

BENEFITS

- Simple in nature: easy to use.
- Short connector length; short lap length.
- Positive connection; visual inspection.
- No special equipment to buy or hydraulics to maintain.
- No clearance requirements for pin guns.

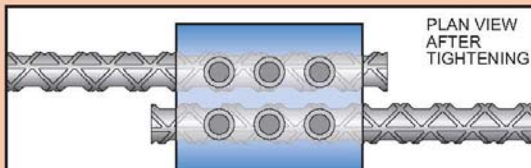
PERFORMANCE

Exceeds 125 % x specified yield strength, f_y, of the bar being connected and is capable of higher performance requirements depending upon application.

HOW TO SPECIFY

Specific: Double Barrel Zap™ by BarSplice Products, Inc. of Dayton, OH.

Generic: Mechanical lap splice with bars positively secured by means of twist-off screws in a coupling configured into a double wedge shape to develop a strength in the bar equal to 125 % x specified yield, f_y [*or state other performance requirement*].



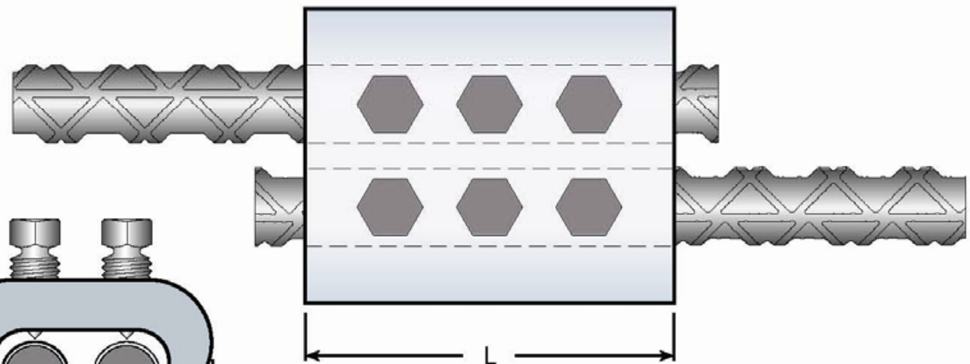
BarSplice Products, Inc., 4900 Webster Street, Dayton OH 45414, USA
●Tel: (937) 275-8700 ●Fax: (937) 275-9566 ●E-mail: bar@barsplice.com

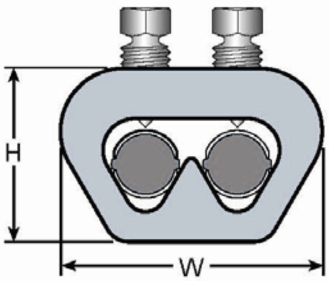
REV:B 7/10/03

Double Barrel Zap Screwlok®

Dimension Data

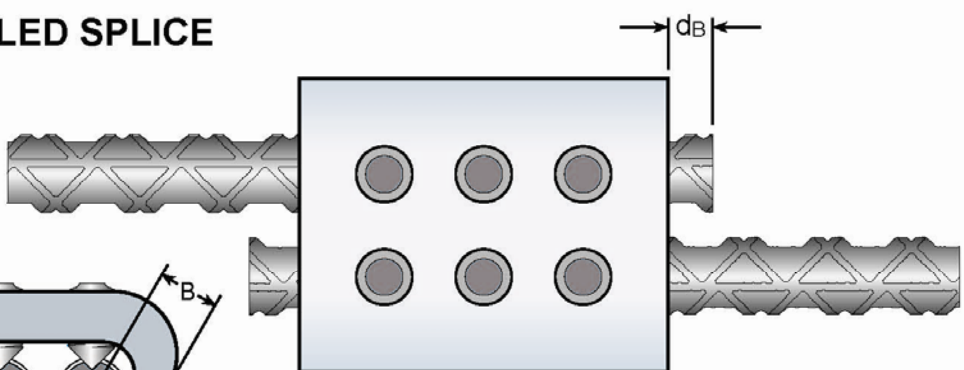
COUPLER BEFORE INSTALLATION

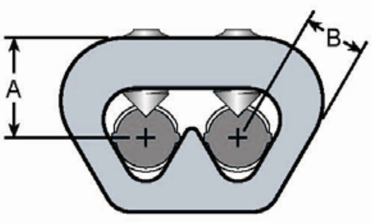




Bar Size	No. Screws per Side	Coupler Weight (lbs.)	DIMENSIONS IN INCHES (APPROX.) W	H	L	dB (min)	A	B
#4	2	1.34	2 3/8	1 5/8	2 1/8	1/2	1 1/16	1/2
#5	3	2.29	2 5/8	1 3/4	3	5/8	1 1/8	5/8
#6	4	3.24	2 3/4	1 7/8	3 7/8	3/4	1 3/16	3/4

INSTALLED SPLICE





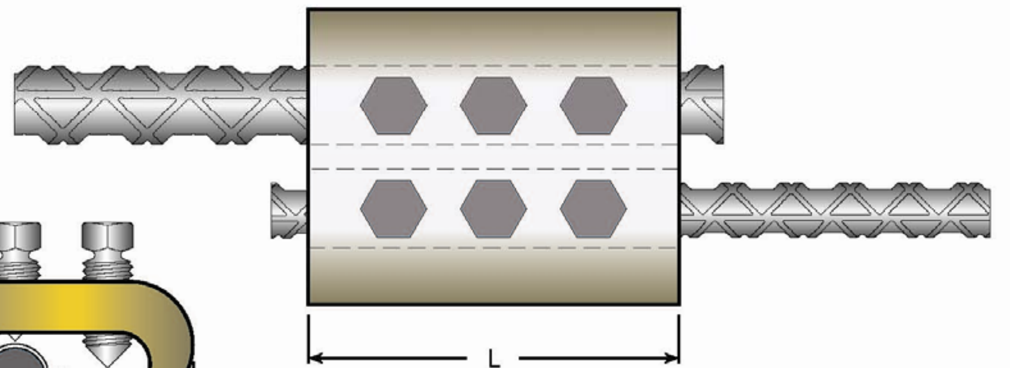
Notes: Twist-off torque value of screws is approximately 50 ft-lbs.
Follow installation sequence given in assembly instructions supplied with parts.

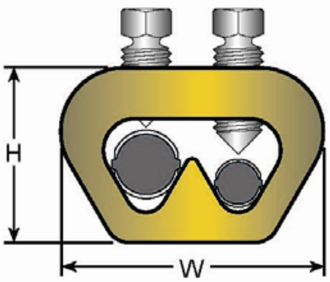
BarSplice PRODUCTS INC.
SUBSIDIARY OF FC INDUSTRIES, INC.
REV.2: 2/18/02

Transition Double Barrel Zap Screwlok®

Dimension Data

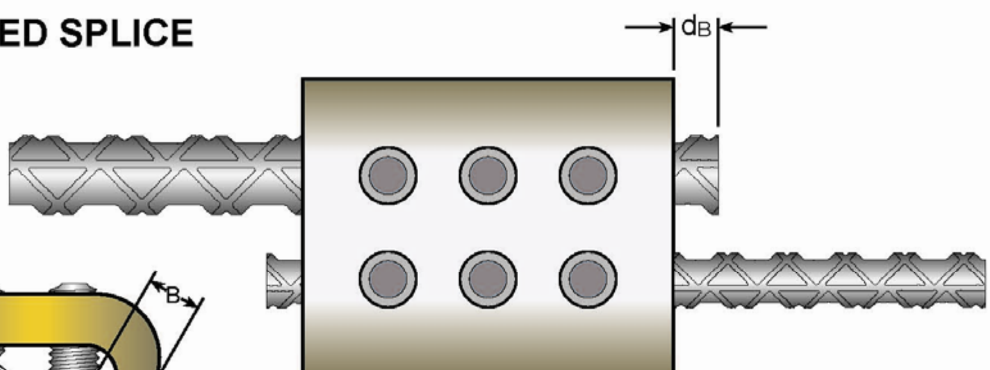
COUPLER BEFORE INSTALLATION

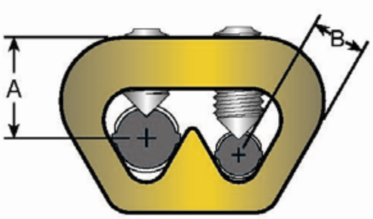




Bar Size	No. Screws per Side	Coupler Weight (lbs.)	DIMENSIONS IN INCHES (APPROX.) W	H	L	dB (min)	A	B
#4/3	2	1.34	2 3/8	1 5/8	2 1/8	3/8	1 1/16	3/8
#5/4	3	2.29	2 5/8	1 3/4	3	1/2	1 1/8	1/2
#6/5	4	3.24	2 3/4	1 7/8	3 7/8	5/8	1 3/16	5/8

INSTALLED SPLICE





Notes: Twist-off torque value of screws is approximately 50 ft-lbs. Follow installation sequence given in assembly instructions supplied with parts.

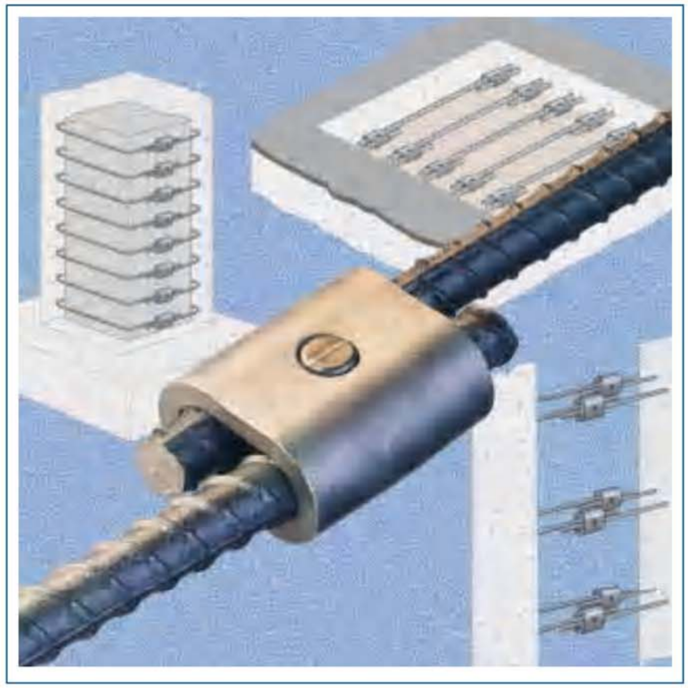
While the information contained in this document is believed to be accurate at the time of publication, BPI reserves the right to make changes, design modifications, corrections and other revisions as it sees fit, without notice. All products described herein are supplied in accordance with BPI's standard Terms and Conditions of Sale. Aspects of structural design, evaluation of product fitness for use, suitability or similar attributes are the responsibility of others.

BarSplice PRODUCTS INC.
SUBSIDIARY OF FC INDUSTRIES, INC.
REV.1: 2/18/02

APPENDIX B

QUICKWEDGE PRODUCT LITERATURE

QUICK-WEDGE



ERICO®

100 YEARS YOUNG
1903 - 2003

LENTON®

The LENTON® QUICK-WEDGE rebar splice is a mechanical lap splice designed for easy installation. It complements the extensive line of mechanical rebar splicing systems manufactured by ERICO®.

The simple and quick alternative f

The LENTON QUICK-WEDGE splice consists of an oval shaped steel sleeve and a wedge pin. The sleeve is positioned around two overlapping steel bars. The wedge pin is inserted into a handheld hydraulic pin-driver and positioned on the sleeve. The pin is then driven through the pre-drilled hole in the sleeve and between the bars to complete the connection. A pin is driven in seconds. It's that simple!

Only one pin-driver is required to install splices on bar sizes #4, #5 and #6 (12, 16 and 20 mm). Specially designed adapters are used to accommodate this range. A standard 10,000 PSI (700 Bar) hydraulic "dump pump" powers the pin-driver. The pump is available in both 110* and 220 volts.

The LENTON QUICK-WEDGE system is so simple to use that only minimal training is required. Connections can be made outdoors in virtually any weather conditions and the finished connection can be quickly inspected visually. Add to that a low cost, and you can easily see why the LENTON QUICK-WEDGE mechanical lap splice is *one of the simplest, most efficient connections available*.

*110V standard in U.S.

QUICK-WEDGE
Protruding bars from the precast wall are joined using an oval shape coupler. The bars are overlapped and assembled using a hydraulic hand tool. Cast-in-place concrete is poured after the connections are completed.

LENTON QUICK-WEDGE mechanical lap splice is one of the simplest, most efficient connections available.

The LENTON QUICK-WEDGE system is easy to use – only minimal training is required.

for joining small diameter reinforcing bars.

The LENTON QUICK-WEDGE system eliminates the need to custom cut and fit rebar to precise measurements, as in butt splicing. Instead, the bars can be cut to approximate size that will span between the rebar being joined. The final connection can be made with the bars extending beyond the coupler ends. This LENTON QUICK-WEDGE advantage will save you time in road repair and retrofit applications.

A short bar end in a minimum clearance application? No problem with LENTON QUICK-WEDGE. To achieve maximum connection strength, all you need to do is make the end of each bar flush with the ends of the splice sleeve. In fact, testing has shown LENTON QUICK-WEDGE connections with reinforcing steel according to ENV10080, BS4449 and AS3102, exceed the characteristic yield strength of the reinforcing steel. On ASTM A615 grade 60 reinforcing steel, the ACI318-02 Type 1 requirements are exceeded, with a splice strength of minimum 125% of specified yield. The system can also develop 120% of specified yield or 110% of actual yield for CSA A23.3-1994 (using G30.18-1992 grade 400 MPA reinforcing bar.)

Features and Benefits

- Quick installations result in accelerated job scheduling
- Cost effective with one-cycle tool operation
- Minimal exposed bar-ends result in reduced concrete chipping (as short as 2-9/16" (65mm)
- Only one-man "crew" needed to operate lightweight portable hydraulic pin-driver
- No special bar-end treatment gives the ability to connect virtually any bar condition
- Eliminates custom fit rebar with "lapped bar" capability
- Easy field adjustability provides greater job site versatility
- Reduces unforeseen delays because LENTON QUICK-WEDGE can be installed in any weather
- Minimal detailing eliminates incorrect interpretation and communication errors
- Visual inspection gives immediate assurance of a reliable splice

LENTON QUICK-WEDGE

Applications

Road Repair – Ideal for replacing bars removed when pavement sections require maintenance. Speed, minimum existing exposed bar requirements, reduced concrete chipping, and adjustability due to the "lapped" feature make this a natural.

Bridge Repair – Provides a fast and effective means for connecting bars required in bridge deck upgrades, especially when congestion makes the job even tougher! You realize the same advantages found in "road repair" above.

Precast – May be used to join rebar extending from concrete walls or slabs before a closure pour.

Building Extensions – Because the system can be installed on a short bar and in limited space, this is a great way to connect existing bar to new in-building expansions.

Spiral Reinforcement – Joins coils quickly and easily. Positioning and curvature of spiral is easily accommodated in the field.

Stirrups and Ties – Affords an efficient means for closing column stirrups – reducing detailing, fabrication, and congestion.

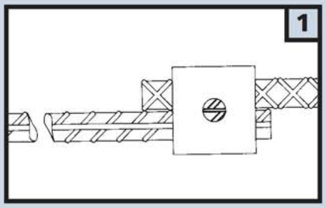
Pile Extensions – LENTON QUICK-WEDGE splices are an efficient way to extend rebar from piles that have been driven below desired elevation.

Epoxy Coated Rebar – Epoxy coated rebar can be easily joined. Contact ERICO for details.

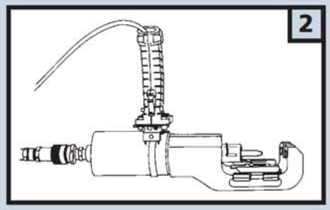
LENTON QUICK-WEDGE provides a fast, low-cost method for joining small diameter rebar. For assistance in selecting the best rebar splicing system for your application, visit us at www.erico.com.

Installation Details

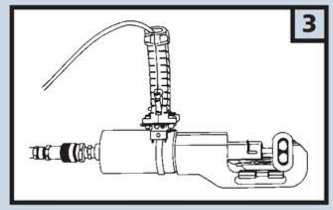
QUICK-WEDGE – as easy as...



Position the sleeve onto the rebar; bar ends must be at least flush with sleeve ends.

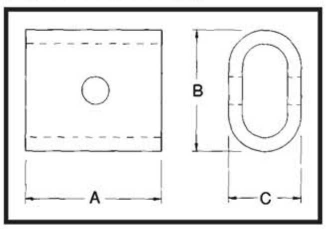


Place the pin in the driver.

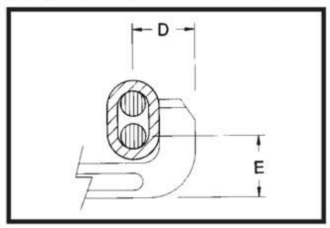


Position the pin-driver on the coupler and drive the pin.

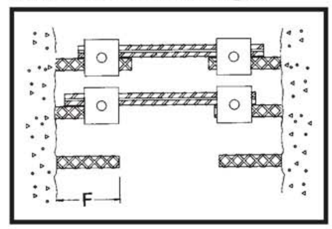
Sleeve Dimensions

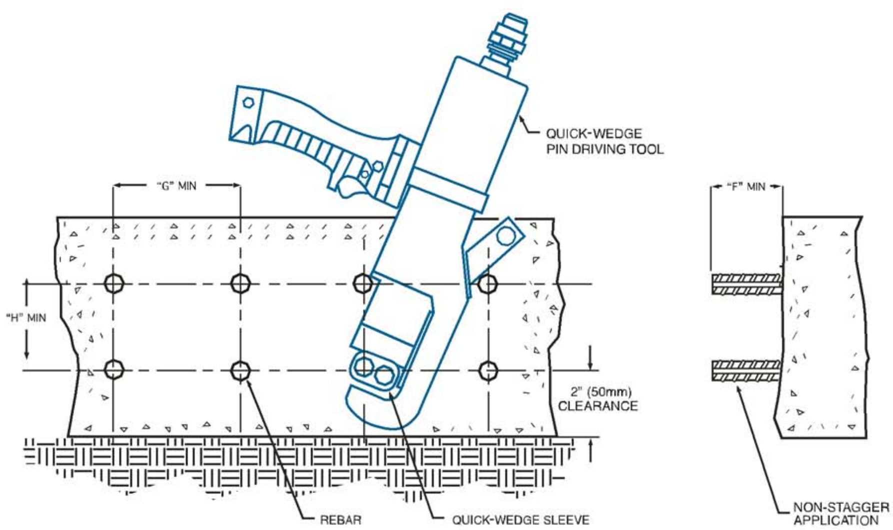


Minimum Clearance Tool End



Minimum Dowel Length





Rebar Size Designation				Part Number	Article Number	"A"		"B"		"C"		"D"		"E"		"F"		"G"		"H"		Weight	
in-lb	Metric	Canadian	Soft Metric			in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	in	mm	lb	kg
—	—	10M	—	ML12MM	—	1-7/8	48	1-5/8	41	1-1/16	27	1-5/8	41	2	51	2-9/16	65	5	127	2-1/2	64	0.42	0.19
4	12mm	—	13	ML4	145700	1-7/8	48	1-11/16	43	1-1/16	27	1-5/8	41	1-15/16	49	2-9/16	65	5	127	2-1/2	64	0.44	0.20
5	16mm	15M	16	ML5	145710	2-1/4	57	1-15/16	49	1-5/16	33	1-3/4	44	1-15/16	49	2-3/4	70	5	127	2-1/2	64	0.72	0.33
6	20mm	20M	19	ML6	145720	2-3/4	70	2-3/8	60	1-9/16	40	1-15/16	49	1-7/8	48	3	76	5	127	3	76	1.34	0.61

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