Investigation of the Dynamic Performance of Large Reinforcement Bar Mechanical Couplers

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ABSTRACT

Criteria for designing hardened, heavily-reinforced concrete structures to resist blast effects from accidental explosions are defined by Unified Facilities Criteria 3-340-02 formerly Army Technical Manual TM 5-1300 (Departments of the Army, Navy, and Air Force. 1990). Lap splicing of the required steel reinforcing bars is the current practice in the construction of these reinforced concrete structures. Lap splicing of reinforcing bars often creates congested areas within the formwork that limit working space and hinder proper placement of concrete. In 1971, a limited number of splice types were tested at the ERDC (formerly Waterways Experiment Station) to investigate their performance under dynamic load conditions (Flathau 1971). Subsequently, several types of mechanical couplers have been tested and validated for developing the strength of reinforcing steel for cyclic loading and strain rates expected during earthquakes. The ERDC recently conducted a series of high strain-rate tests on five different types of American Concrete Institute 318 type II mechanical couplers, used for splicing of flexural reinforcing steel, to obtain their measured performance when loaded at high strain-rates. This paper compares the performance of the different types of mechanical couplers to control bars tested at the same high strain rates, and evaluates their performance to meet the service requirements of UFC 3-340-02.

INTRODUCTION

Criteria for designing structures to resist the effects of accidental explosions or conventional weapons are defined by UFC 3-340-02 (Unified Facilities Criteria 2008) and UFC 3-340-01 (Unified Facilities Criteria 2002) respectively. The UFC 3-340-02 defines design methods applied to facilities used in the production, storage, and maintenance of ordnance and explosive materials. The UFC 3-340-01 defines design criteria for fixed, hardened structures.

Economic design of blast-resistant, reinforced concrete structures typically allows plastic deformations of the structural elements, which develops the ultimate strength and ductility of the steel reinforcement. Typical design details recommended in UFC 3-340-02 and UFC 3-340-01 result in congestion of steel in slabs and beams and at corners. This congestion increases construction costs and difficulty in placing concrete between steel reinforcement bars.

For accidental explosions, UFC 3-340-02 allows the use of mechanical couplers to splice flexural steel reinforcement. However, the mechanical coupler must develop the ultimate dynamic tensile strength and ductility of the steel reinforcement. High strain-rate tension tests of the splice must be conducted to validate the performance of the splice. For conventional weapons effects, UFC 3-340-01 allows the use of mechanical couplers if the dynamic response of steel reinforcement to blast loads remains elastic.

OBJECTIVE

The objective of the research reported herein was to measure the performance of mechanical couplers for splicing flexural reinforcing steel when stressed at high strain-rates. Results of the testing may validate commercially available mechanical couplers for use in structures hardened for blast effects.

APPROACH

The U.S. Army Engineer Research and Development Center conducted a series of high strain-rate tests on five types of mechanical couplers used for splicing flexural reinforcing steel (Rowell et al. 2009). Each coupler system was tested at three strain-rates. For each mechanical coupler and strain-rate combination, three specimens were tested to develop average properties defining the strength and ductility of the coupler system. A total of 45 tests were performed. This paper will focus on results of the rapid strain-rate tests only.

A 200,000-lb dynamic loader (Huff 1969) shown in Figure 1 was used to apply the required load at slow, intermediate, and rapid strain-rates. The strain-rates achieved were between 0.001 and 3.5 sec^{-1}.

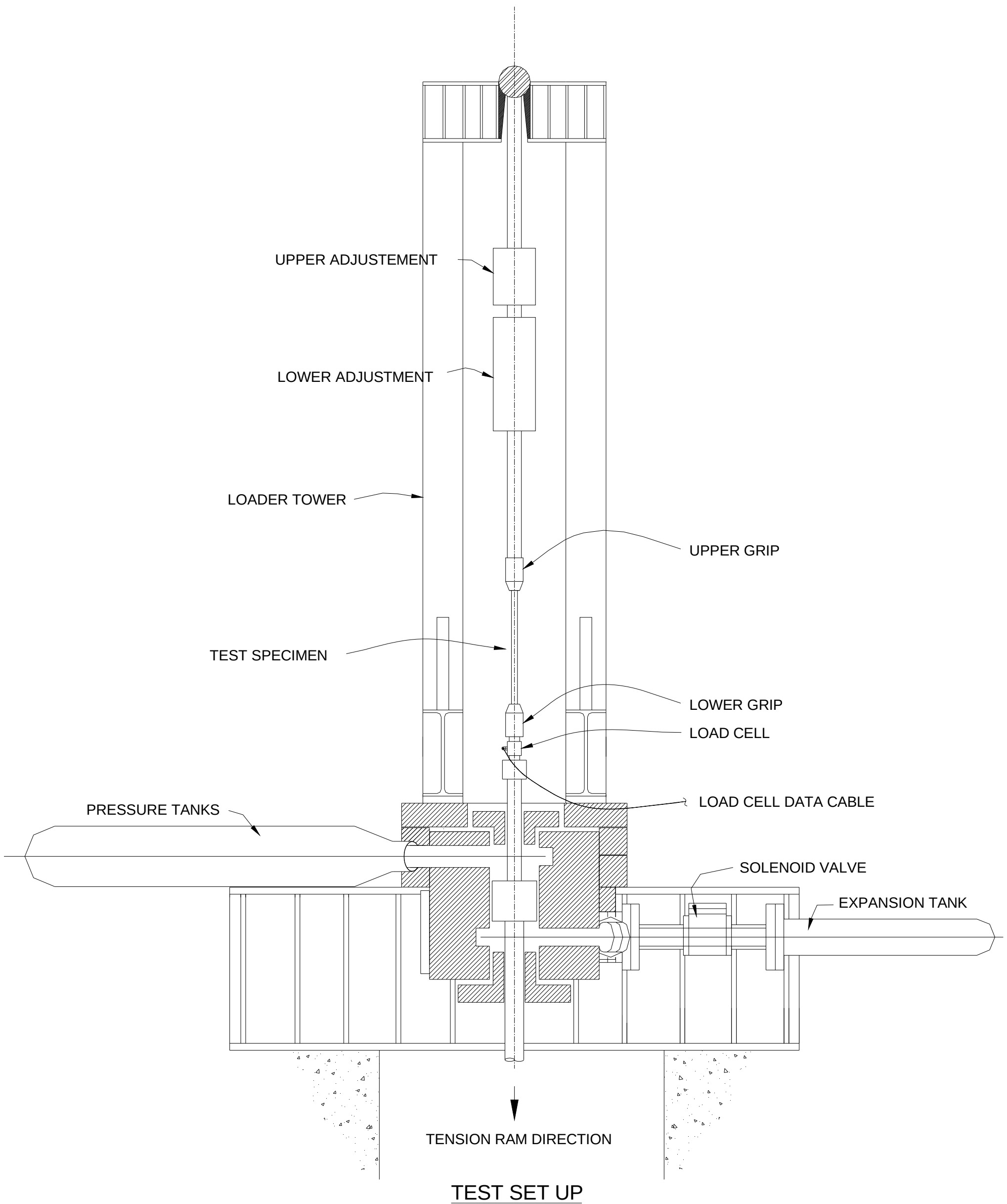

Figure 1. 200,000-lb loader with tower.

COUPLER AND CONTROL SPECIMENS

Two series of experiments conducted for this study are discussed in this paper. The first series was the control specimens that consisted of reinforcement bar tension tests in which the bars were tested in the as-rolled condition. The second series of experiments consisted of testing the mechanical couplers installed on the reinforcing bars. All test specimens were pulled in the vertical position.

The experimental parameters for the first series of experiments were the condition of the reinforcement bar (as-rolled) and the dynamic load condition (strain-rate). The experimental parameters for the second series of experiments were the type of mechanical coupler and dynamic load condition (strain-rate). These parameters are discussed in the following sections.

Coupler Selection Criteria

American Concrete Institute (ACI) standard 439.3R-07 (ACI 2007) was used as a guide for selecting five different types of mechanical couplers. Table 2.1 (ACI 2007) provides a list of the types of mechanical couplers available in the market today. The couplers chosen for the tests are suitable for tension and compression applications for both type 1 and type 2 connections using ASTM A615 Grade 60 reinforcement bar under ACI standard 318-02 (ACI 2002). ACI 439.3R-07 states that the ACI 318 type 1 connections are used in elements where there is little concern for inelastic deformations and elevated tensile stresses from seismic events. ACI 318 type 2 connections have proven, through accepted industry testing, the ability to develop the specified tensile strength of the spliced bars for resistance to elevated tensile stresses. Only ACI 318 type 2 mechanical connectors were selected for this series of tests.

Using Table 2.1 to further narrow the selection, couplers that were shown to provide versatility in the categories of application and suitability were selected. Four types of couplers were initially selected.

- Cold-swaged-steel coupling sleeve.
- Grout-filled coupling sleeve.
- Shear-screw and wedge coupling sleeve.
- Upset-bar and coupling sleeve with straight threads.

Other selection criteria were based on the ease of use and the selection of distinctly different couplers to provide a good cross section of applications and installation processes. The upset-bar type was selected over the cold-swaged type after review of its application in another government containment facility, thus warranting further investigation under this effort. The sponsor selected and added a taper-thread coupler system and a coupler system for thread-like deformed reinforcement bars to the experiment series.

The final couplers selected for this series of experiments are:

- Upset-head and coupling sleeve with straight threads.
- Grout-filled coupling sleeve.
- Shear-screw coupling sleeve.
- Taper-thread system
- Thread-like deformed reinforcement bar coupler system.

Mechanical Couplers

The criteria for selection of the couplers to be tested consisted of the coupler's prior approval for seismic use and its ease of installation. The types selected for this study are generally categorized as "upset," "grouted," "shear screw," "taper-thread," and "rebar thread." These systems provide a good representation of the types of couplers commonly available and in use today. Each system is described in the following paragraphs. Figure 2 shows the mechanical coupler systems.

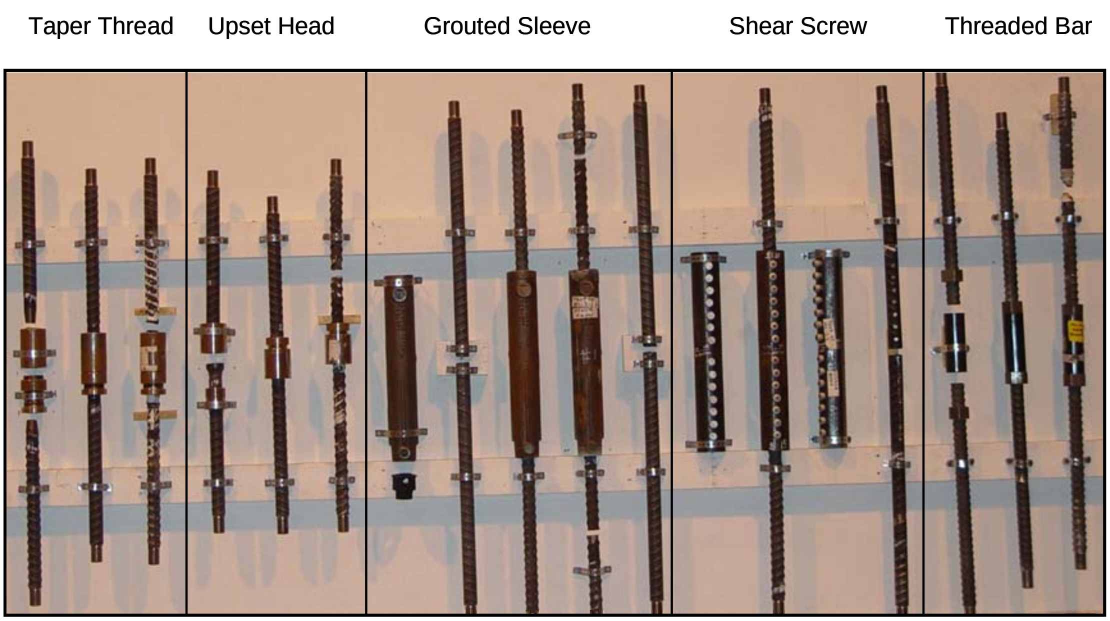

Figure 2. Mechanical coupler systems included in the test series.

From left to right in Figure 2 are:

Taper-thread system. This system consists of tapered threads on each end of the rebar along with a male/female threaded coupler to form the connection between the two ends of the rebar. This system used "MC-4" as the coupler series specimen identifier.

Upset-head system. This system is an "upset" system that uses a hot formed head on each end of the rebar along with a male/female threaded coupler. This system used "MC-1" as the coupler series specimen identifier.

Grouted-sleeve system. This system utilizes a sleeve in which the two ends of the rebar are "grouted" into the sleeve to make the connection. This system used "MC-2" as the coupler series specimen identifier.

Shear-screw system. This system consists of a wedge-shaped coupling sleeve and "shear screws" to form the connection between the two ends of the rebar. This system used "MC-3" as the coupler series specimen identifier.

Threaded-rebar system. This system consists of rebar with rolled-on deformations with a similar thread profile to that of a stub-acme thread. The coupler sleeve has matching internal threads and is locked in place with two similar threaded nuts at each end. This system used "MC-5" as the coupler series specimen identifier.

Concrete Reinforcement Bars

ASTM A615 Grade 60 and Grade 75, number 10, deformed reinforcement bars were tested at full size (as-rolled) to determine the ultimate dynamic load strength of the bar. Figure 3 shows a typical control specimen with the loader grip system. All Grade 60 reinforcement bar tested was from the same lot and manufacturer and used "RB-1" as the series specimen identifier. All Grade 75 reinforcement bar tested was from the same lot and manufacturer and used "RB-4" as the series specimen identifier.

Figure 3. As-rolled control specimen reinforcement bar.

COMPARISON OF COUPLERS AND CONTROL SPECIMEN TEST RESULTS

Comparison of the performance of the control specimen and the performance of the selected mechanical couplers must be made to determine if the criteria given in Section 4-21.8 of UFC 3-340-02 was achieved. This criteria states that devices for mechanical splices of reinforcement may be used for end anchorage and splices in reinforcement if they are capable of developing the ultimate dynamic tensile strength of the reinforcement without reducing its ductility.

To determine the adequacy of these devices, a control specimen was first tested to determine the dynamic material properties of the reinforcement material at the desired strain-rate under which the selected couplers would be subjected. The coupler systems were then tested at the same strain-rate and in the same manner in which the control specimen was tested. The data collected from the results of each of the two test series were then compared.

Several failures occurred in the rebar at the location of the strain gages. It is possible that failure occurred at this location due to a minute amount of material removed from the bar in order to provide a clean and smooth bonding surface for the strain gages. It is also possible that this affected the ultimate dynamic strengths of the specimens. However, the overall results are considered to be valid because both the control specimens and the coupler specimens were prepared for strain gages in the same location, manner, and procedure.

As-rolled Control Specimens

Two types of as-rolled (AR) reinforcement bars were tested. The first type of reinforcement bar was ASTM-615 Grade 60. This type was used in all tests except for the threaded rebar system (MC-5 and RB-4) series of tests. The second type was ASTM 615 Grade 75. Testing of the second type was required because the MC-5 coupler system required a special threaded rebar that was only available in Grade 75.

The stress and strain values at the yield point were recorded as the yield stress and yield strain respectively for all ASTM 615 Grade 60 and Grade 75 control bars tested at the rapid strain-rate. These values were compared to the stresses and strains at the yield point for all ASTM 615 grade 60 and Grade 75 coupler systems tested at the rapid strain-rate respectively.

Table 1 shows the test results from each of the as-rolled ASTM 615 Grade 60 and Grade 75 reinforcement bars pulled at the rapid strain-rates. Also shown in the table are the average values of yield stress, strain at yield, dynamic ultimate strength, maximum strain (strain at rupture), ductility ratio (strain at rupture divided by strain at yield), percent elongation, and strain-rate.

Table 1. Test results from ASTM 615 Grade 60 and Grade 75 reinforcement bar control specimens.

Specimen Name	Specimen Number	Yield Stress (psi)	Yield Strain (µin/in)	Dynamic Ultimate Strength (psi)	Maximum Strain (µin/in)	Ductility Ratio	Elongation %	Strain Rate (in/in/sec)
Grade 60								
AR4	RB-1-4	90,400	4,100	129,500	149,000	36.3	14.9	3.3
AR7	RB-1-7	89,000	5,400	130,700	144,000	26.7	14.4	3.2
AR8	RB-1-8	90,000	4,700	128,700	120,000	25.5	12.0	3.1
AR-Rapid	Average	89,800	4,700	129,600	138,000	29.5	13.8	3.2
Grade 75								
ART1	RB-4-1	100,600	4,300	123,400	125,000	29.1	12.5	3.3
ART2	RB-4-2	94,700	3,800	121,700	128,400	33.6	12.8	3.0
ART3	RB-4-3	101,600	4,000	123,300	112,000	27.8	11.2	3.4
ATR-Rapid	Average	99,000	4,000	129,600	122,000	30.2	12.2	3.2

Upset Head Coupler Specimens (UHC)

The specimens failed in three different failure modes. Specimen UHC3 (bottom right in Figure 4) failed in the rebar in the heated area. UHC5 (middle right in Figure 4) failed in the rebar outside the heated area. UHC12 (top right in figure 4) failed just under the upset head in the heated area. Specimens UHC3 and UHC12 failed to develop the dynamic ultimate tensile strength or the required ductility. Specimen UHC5 did achieve the dynamic ultimate tensile strength, came very close to developing the required maximum strain, but did not achieve the required ductility prior to failure. The left post-test photo in Figure 4 shows the failure that occurred inside the coupler just under the upset head in the heated area.

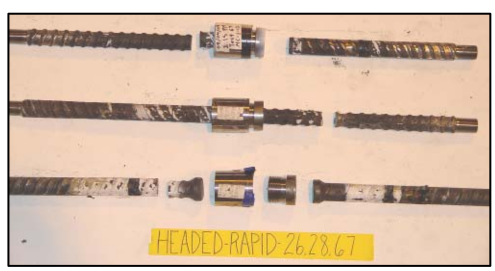

Figure 4. Post-test photos of upset head specimens tested at rapid strain-rate.

Table 2 compares the test results of each of the upset head coupler specimens to the average test results of the ASTM 615 Grade 60 control bars pulled at the rapid strain-rate. Also shown in the table are the average values for each measurement set.

Table 2. Test results of upset head coupler system at rapid strain-rates.

Specimen Name	Specimen Number	Yield Stress (psi)	Yield Strain (μin/in)	Dynamic Ultimate Strength (psi)	Maximum Strain (μin/in)	Ductility Ratio	Elongation %	Strain Rate (in/in/sec)
AR-Rapid	Average	89,800	4,700	129,600	138,000	29.5	13.8	3.2
UHC3	MC-1-3	85,300	5,900	97,500	21,300	3.6	2.1	3.2
UHC5	MC-1-5	89,500	5,200	129,900	132,600	25.5	13.3	3.1
UHC12	MC-1-12	88,300	3,800	123,100	54,448	14.3	5.4	3.2
UHCA	Average	87,700	5,000	116,800	69,464	14.5	6.9	3.2

Grouted Coupler Specimens (GSC)

The specimens failed in three different failure modes. Specimen GSC3 failed due to rebar pullout failure, specimen GSC2 failed due to sleeve failure, and specimen GSC1 failed due to rebar failure (bottom, middle, and top right, respectively, in figure 5). Specimens GSC2 and GSC3 did not achieve the dynamic ultimate tensile strength or the required ductility of the control bar prior to failure. Specimen GSC1 did achieve the dynamic ultimate tensile strength but did not achieve the required ductility prior to failure. The left photo in Figure 5 shows the very violent mid-point sleeve failure.

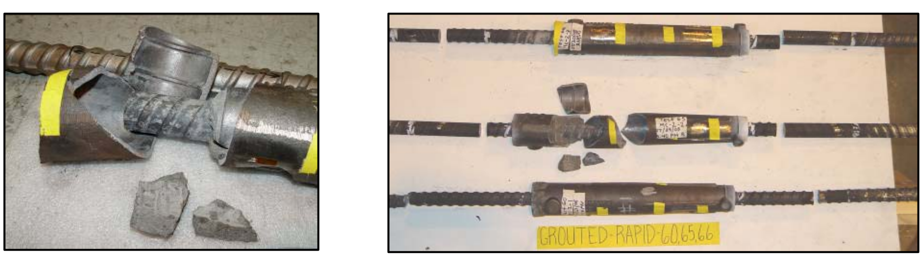

Figure 5. Post-test photos of grouted specimens tested at the rapid strain-rate.

Table 3 compares the test results of each of the grouted coupler sleeves specimens to the average results of the as-rolled ASTM-615 Grade 60 control bars tested at the rapid strain-rate. Also shown in the table are the average values for each measurement set.

Table 3. Test results of grouted coupler system at rapid strain-rates.

Specimen Name	Specimen Number	Yield Point (psi)	Yield Strain (µin/in)	Dynamic Ultimate Strength (psi)	Maximum Strain (µin/in)	Ductility Ratio	Elongation %	Strain Rate (in/in/sec)
AR-Rapid	Average	89,800	4,700	129,600	138,000	29.5	13.8	3.2
GSC1	MC-2-1	85,700	6,400	130,300	144,500	22.5	14.5	3.5
GSC2	MC-2-2	82,600	4,600	124,700	58,400	12.7	5.8	3.0
GSC3	MC-2-3	82,300	4,200	119,200	49,000	11.6	4.9	3.2
GSCA	Average	83,600	5,100	124,700	84,000	15.6	8.4	3.2

Shear Screw Coupler Specimens (SSC)

The specimens failed in two different failure modes. Specimen SSC1 (bottom right in Figure 6) failed by breaking the rebar at the first shear screw due to stress concentration at the deformation in the rebar made by the shear screw. Specimens SSC2 and SSC3 failed by complete strip-out of the rebar from the sleeve. All specimens failed prior to developing the required dynamic ultimate tensile strength and the required ductility. The left photo in Figure 6 shows the indention in the rebar left by the shear screws at strip out. The tips of the shear screw formed a trough imbedded in the rebar.

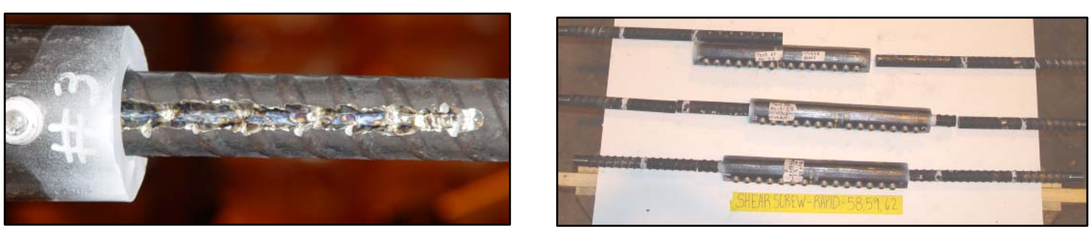

Figure 6. Post-test photos of shear screw specimens tested at the rapid strain-rate.

Table 4 compares the test results of each of the shear screw coupler sleeves to the average results of the as-rolled ASTM-615 Grade 60 control bars tested at the rapid strain-rate. Also shown in the table are the average values for each measurement set.

Table 4. Test results of shear screw coupler system at rapid strain-rates.

Specimen Name	Specimen Number	Yield Point (psi)	Yield Strain (μin/in)	Dynamic Ultimate Strength (psi)	Maximum Strain (μin/in)	Ductility Ratio	Elongation %	Strain Rate (in/in/sec)
AR-Rapid	Average	89,800	4,700	129,600	138,000	29.5	13.8	3.2
SSC1	MC-3-1	80,500	4,800	93,600	25,700	5.3	2.6	3.5
SSC2	MC-3-2	81,100	5,900	98,300	26,300	4.5	2.6	3.2
SSC3	MC-3-3	78,200	6,200	104,500	27,300	4.4	2.7	3.8
SSCA	Average	80,000	5,600	98,800	26,400	4.7	2.6	3.5

Taper Thread Coupler Specimens

All three specimens failed just outside the coupler in the last few threads in the rebar due to stress concentration at those threads (right photo in Figure 7). All failed prior to developing the dynamic ultimate tensile strength and the required ductility. The left photo in Figure 7 shows the typical mode of failure in the rebar.

Figure 7. Post-test photos of taper thread specimens tested at rapid strain-rate.

Table 5 compares the test results of the taper thread couplers to the average results of the as-rolled ASTM-615 Grade 60 control bars tested at the rapid strain-rate. Also shown in the table are the average values of each measurement set.

Table 5. Test results of taper thread coupler system at rapid strain-rates.

Specimen Name	Specimen Number	Yield Stress (psi)	Yield Strain (μin/in)	Dynamic Ultimate Strength (psi)	Maximum Strain (μin/in)	Ductility Ratio	Elongation %	Strain Rate (in/in/sec)
AR-Rapid	Average	89,800	4,700	129,600	138,000	29.5	13.8	3.2
TTC1	MC-4-1	86,400	5,900	87,800	13,300	2.3	1.3	3.0
TTC2	MC-4-2	86,900	5,700	106,000	24,300	4.3	2.4	3.0
TTC3	MC-4-3	86,300	4,400	102,400	19,700	4.5	2.0	3.7
TTCA	Average	86,500	5,300	98,800	19,100	3.7	1.9	3.2

Threaded Bar Coupler Specimens

All three specimens failed in the rebar (right photo in Figure 8). Specimen TBC1 almost achieved the dynamic ultimate tensile strength as that of the control bar but did not achieve the required ductility prior to failure. Specimen TBC2 achieved the required dynamic ultimate tensile strength of the control bar but also did not achieve the required ductility prior to failure. Specimen TBC3 achieved both the required dynamic ultimate tensile strength and the required ductility as that of the control bar prior to failure. The left photo in Figure 8 shows a typical mode of failure in the rebar.

Figure 8. Post-test photos of threaded bar specimens tested at rapid strain-rate.

Table 6 compares the test results of the threaded bar couplers to the average results of the as-rolled ASTM-615 Grade 75 control bars tested at the rapid strain-rate. Also shown in the table are the average values for each measurement set.

Table 6. Test results of threaded rebar coupler system at rapid strain-rates.

Specimen Name	Specimen Number	Yield Point (psi)	Yield Strain (µin/in)	Dynamic Ultimate Strength (psi)	Maximum Strain (µin/in)	Ductility Ratio	Elongation %	Strain Rate (in/in/sec)
ART-Rapid	Average	99,000	4,000	122,800	122,000	30.2	12.2	3.2
TBC1	MC-5-1	92,600	4,400	120,900	92,900	21.2	9.3	3.2
TBC2	MC-5-2	99,700	5,300	122,500	109,700	21.7	11.0	3.4
TBC3	MC-5-3	97,700	4,200	122,000	130,000	31.1	12.9	3.3
TBCA	Average	96,400	4,600	121,800	110,800	24.7	11.1	3.3

SUMMARY

Upset Head Coupler Specimens

Under the rapid strain-rate loading condition, the UHC system developed an average of 90% of the dynamic ultimate strength, 50% of the maximum strain, and 49% of the ductility achieved by the control bar. One specimen failed outside the heated area while the other two specimens failed in the heated area with one of the latter two specimens failing just under the upset head.

Table 7 contains individual specimen performances as well as the average UHC system performance.

No couplers were observed to fail within the coupler connection itself. Failure for this system occurred either within the rebar heated area or in the rebar just outside the heated area. Couplers subjected to the slow and intermediate strain-rates could be disassembled post-test. Couplers subjected to the high strain-rate could not be disassembled post-test, which indicated deformation of the internal threads in the male-female threaded connection.

Grouted Coupler Specimens

The GSC system, under the rapid strain-rate loading condition, developed on average 96% of the dynamic ultimate strength, 61% of the maximum strain, and 53% of the ductility achieved by the control bar (see Table 7). One specimen failed due to rebar pull out, one specimen failed in the rebar outside the grout sleeve, and one specimen failed due to a violent failure of the cast steel grout sleeve.

Shear Screw Coupler Specimens

The SSC system, under the rapid strain-rate loading condition, developed on average 76% of the dynamic ultimate strength, 19% of the maximum strain, and 16% of the ductility achieved by the control bar (see Table 7). Failure occurred in two modes. Two specimens failed by complete strip-out of the rebar from the coupler sleeve, and one specimen failed in the rebar at the first shear screw location just inside the steel sleeve.

No couplers were observed to fail in the steel sleeve itself. However, the stress concentration in the rebar caused by the tip of the shear screw embedded in the rebar caused premature failure prior to development of the required dynamic ultimate tensile strength and the required maximum strain.

Taper Thread Coupler Specimens

Under the rapid strain-rate loading, the TTC system developed on average 76% of the dynamic ultimate strength, 14% of the maximum strain, and 13% of the ductility achieved by the control bar (see Table 7). All three specimens failed in the rebar in the last threads of the taper thread due to the stress concentration caused by the taper threads in the rebar.

No couplers were observed to fail within the coupler connection itself. Failure for this system occurred either within the rebar outside the threads or in the rebar in the last of the taper threads. Couplers subjected to the all three strain-rates could be disassembled post-test, indicating no detrimental deformation of the internal threads in the male-female threaded connection.

Threaded Bar Coupler Specimens

The TBC system under the rapid strain-rate loading condition developed on average 99% of the dynamic ultimate strength, 91% of the maximum strain, and 82% of the ductility achieved by the control bar (see Table 7). All three specimens failed in the rebar outside the coupler.

No couplers were observed to fail within the coupler connection itself. Failure for this system occurred in the rebar outside of the coupler. Couplers subjected to the all three strain-rates could be disassembled post-test, indicating no detrimental deformation of the internal threads in the threaded bar connection. Minor deformation was observed post-test when the couplers were disassembled.

Table 7. Percent of response of mechanical coupler system compared to response of as-rolled control bars.

	Slow Strain-Rate			Intermediate Strain-Rate			Rapid Strain-Rate		
Specimen Name	% Dynamic Ultimate Strength	% Maximum Strain	% Ductility Ratio	% Dynamic Ultimate Strength	% Maximum Strain	% Ductility Ratio	% Dynamic Ultimate Strength	% Maximum Strain	% Ductility Ratio
UHC									
1	--	--	--	101	73	70	75	15	12
2	102	111	115	100	67	68	100	96	86
3	102	101	104	95	43	43	95	39	48
Average	102	106	110	99	61	60	90	50	49
GSC									
1	99	65	64	102	85	81	101	105	76
2	97	57	60	102	82	80	96	42	43
3	97	59	60	102	78	77	92	36	39
Average	98	61	61	102	82	79	96	61	53
SSC									
1	69	17	16	81	25	24	72	19	18
2	82	27	28	98	60	57	76	19	15
3	70	17	18	72	15	14	81	20	15
Average	73	20	21	84	33	32	76	19	16
TTC									
1	101	121	123	81	24	25	68	10	8
2	98	121	126	101	96	99	82	18	15
3	101	97	101	92	36	35	79	14	15
Average	100	113	116	91	52	53	76	14	13
TBC									
1	--	--	--	99	95	88	98	76	70
2	101	64	55	98	95	95	100	90	72
3	101	61	71	99	81	61	99	106	103
Average	101	62	63	99	90	81	99	91	82

CONCLUSIONS

The cast-steel grout sleeve was the only "sleeve" that failed. Most failures that occurred appeared to be due to the process required to prepare or make the mechanical connections. For example, the upset head failed in the heated area. The shear screw failed at the first or second shear screw embedment. The taper threaded coupler failed at the last taper threads just outside the coupler itself. The only coupler system that did not exhibit this type of failure was the threaded bar coupler.

Many of the couplers had successful or near successful individual test results. However, when combined with the rest of the results of the other couplers within the series, the average results of the series were less than the requirements.

The threaded rebar coupler performed the best compared to the other couplers at the high strain-rate. It developed 99% of the dynamic ultimate tensile strength, 91% of the maximum strain, and 81% of the ductility ration of the control bar.

RECOMMENDATIONS

The threaded bar coupler should be further investigated and additional tests conducted at all three strain-rates to provide additional test results for review.

The standard lap splice specified in the UFC 3-340-02 should be tested experimentally in the same manner and at the same strain-rates as performed on mechanical couplers in this effort, and the results compared to the performances of the control bars and the mechanical couplers documented herein.

The upset head, grout sleeve, and threaded rebar couplers should be tested in either subscale or full-scale reinforced concrete slabs at strain-rates similar to those used in this study to determine their performances when combined with concrete cover. The subscale tests could be conducted in the ERDC blast load simulator. Full-scale tests could be conducted in the field. This group of couplers should also be modeled using a finite element code so that comparisons can be made between experimental results and analytical results obtained through the high performance computational models. These models could also be used to validate and extrapolate results so that optimum designs can be evaluated without costly field experiments.

Although system failures occurred at lower capacity than the control bars, the failure occurred in the rebar and not in the coupler; therefore consideration should be given to modification of the failure and acceptance criteria.

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REFERENCES

American Concrete Institute (ACI). (2002). “Building Code Requirements for Structural Concrete,” ACI report 318-02, ACI Committee 318, American Concrete Institute, Farmington Hills, MI.

American Concrete Institute (ACI). (2007). “Types of Mechanical Splices for Reinforcing Bars,” ACI report 439.3R-07, ACI Committee 439, American Concrete Institute, Farmington Hills, MI.

Departments of the Army, Navy, and Air Force (1990). “Structures to Resist the Effects of Accidental Explosions,” Department of the Army Technical Manual TM 5-1300; Department of the Navy Publication NAVFAC P-397; Department of the Air Force Manual AFR 88-22, Washington DC.

Flathau, W.J. (1971). “Dynamic Tests of Large Reinforcing Bar Splices,” Technical Report N-71-2, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huff, W.L. (1969). “Test Devices Blast Load Generator Facility,” Miscellaneous Paper N-69-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Rowell, S.P, Grey, C.E., Woodson, S.C., and Hager, K.P. (2009). “High Strain-Rate Testing of Mechanical Couplers,” Technical Report TR-09-8, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Unified Facilities Criteria. (2002). UFC 3-340-01 “Design and Analysis of Hardened Structures to Conventional Weapons Effects,” Department of Defense, Washington DC.

Unified Facilities Criteria. (2008). UFC 3-340-02 “Structures to Resist the Effects of Accidental Explosions,” Department of Defense, Washington DC.