Dynamic Shear Strength of Riveted Structural Connections

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ABSTRACT

Riveted lap-spliced specimens were tested to observe how the fasteners' shear strengths were affected by joint configuration, number of shear planes, and loading type. A 200,000-lbf-capacity dynamic loader was used to fail the specimens under a monotonic dynamic or monotonic quasi-static load. The test data were normalized by the number of shear planes loaded in each test and estimated ultimate tensile strength of the driven rivet. A statistical analysis (ANOVA and t-test) was conducted on data sets from the 86 tests to determine the significant factors affecting the fastener shear strength. Conclusions from the analyses indicated that the loading type has the most significant effect on shear capacity, resulting in a dynamic increase factor of 1.72 relative to the rivet's quasi-static shear capacity. Shear type did have an effect on riveted specimens performance. Joint configuration only affected the response of riveted specimens under dynamic loadings.

KEYWORDS: rivet, shear strength, dynamic loading, quasi-static loading, dynamic increase factor.

INTRODUCTION

Many national landmark bridges are relatively old, opened in early to mid-1900s. These bridges were designed and constructed using older standards and fasteners, such as hot-driven rivets.

Over the past century, rivets were tested to determine their shear only, tension only, and combined tension and shear capacities for both static and cyclic loadings. However, one scenario has yet to be tested on either bolts or rivets: a short-duration, monotonic dynamic load that causes a shear/bearing failure in the fasteners in 1 to 6 milliseconds (msec).

Civil engineers are very aware of the threat of monotonic dynamic impacts critically damaging or destroying important structural components. This is why it is important that the dynamic shear strength rivets be researched.

Few tests were conducted on the performance of riveted connections in the first years after the creation of the Research Council on Riveted and Bolted Structural Joints (RCRBSJ). Other tests were conducted in the 1930s, such as Wilson and Oliver's "Tension Tests of Rivets" (Wilson and Oliver, 1930).

The research performed in the mid-1900s tested specimens in combined tension and shear and noted the effects of initial tension in the rivet due to cooling. From that research, a ratio of ultimate shear strength of the driven rivet to ultimate tensile strength of the undriven rivet was determined to be 0.75 (Higgins and Munse, 1952; Munse and Cox, 1956; Kulak et al., 1987). It is important to note that the tensile strength was based on the undriven rivet's ultimate tensile strength. This strength is much easier to determine than the driven-rivet ultimate tensile strength. For reference, the ultimate tensile strength of the driven rivet is approximately 20% greater than the undriven strength when machine driving is used (Kulak et al., 1987; Schenker et al., 1954). Therefore, if the ratio of shear strength to tensile strength was based on the driven rivet's ultimate tensile strength, the value would be approximately 0.625. Further testing also determined that a riveted joint in double shear would perform the same as one in single shear (Jones, 1956).

OBJECTIVES

The purpose of the research presented in this article was to develop an experimental plan that examined the behavior of rivets that are subjected to both quasi-static and dynamic shear loads.

This research has the following three primary objectives:

1. Determine the dynamic and quasi-static shear strength of standard strength hot-driven rivets.
2. Compare dynamic shear strength to quasi-static shear strength for rivets in order to determine an applicable dynamic increase factor for each.
3. Determine if dynamic shear strength of the rivets is affected by joint patterns and/or number of shear

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planes, and verify that the quasi-static shear strength is not affected by joint patterns and number of shear planes as shown in previous research.

Research conducted by the Research Council on Structural Connections and others was reviewed and analyzed to determine the most appropriate type of specimens and variables to be tested. It was determined to fabricate specimens that incorporate axial bars and fasteners, as shown in Figure 1. These specimens were designed so that failure would occur in the fastener.

The loading of the specimens was performed by using a rapid-loading testing apparatus housed at the U.S. Army Corps of Engineers–Engineer Research and Development Center (USACE-ERDC) in Vicksburg, Mississippi. The 200-kip dynamic loader is capable of applying multiple loading rates to the specimen, with an approximate loading rate ranging from 10 to 100,000 lbf/msec. The loader was operated at the maximum loading rate possible and slowest loading rate possible for the dynamic loading type and quasi-static loading type tests, respectively. Failure of the fasteners occurred in approximately 1 to 6 msec for the dynamic loading type and in approximately 500 to 4,000 msec for the quasi-static loading type. The quasi-static loading rate is approximately 10 to 15 times faster than typical ASTM static loading/cross-head speeds. The actual loading rate for each specimen type was dependent on the fastener type.

The results of these tests were normalized to the number of fasteners and shear planes in the specimen and the average measured ultimate tensile strength of the respective fastener type. A statistical analysis was conducted on these results to determine the effects of the chosen variable on the specimen response.

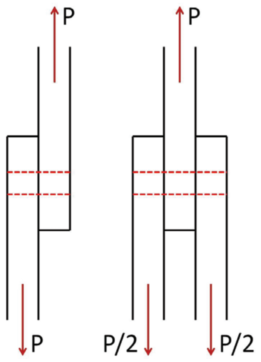

Fig. 1. Free-body diagram example of single shear (left) and double shear (right).

TEST DESIGN

Test Specimens

A test specimen for this research was defined as the combination of plates and rivet(s) to create a structural joint. Each specimen consisted of either two ½-in. plates or two ½-in. plates and one 1-in. plate, for single- and double-shear tests, respectively. The plate material complied with ASTM A36 standard specifications for carbon structural steel. The specimen plates were designed such that the only possible failure in the overall test specimen would occur from failure of the rivet in shear. A plate design was developed using connection design specifications from AISC (2011) and Kulak et al. (1987) using the "worst-case-scenario" design strengths of the test specimen components—that is, highest specified fastener strength and cross-sectional area, largest number of fasteners, double shear of the fastener, and lowest specified plate strength. Figure 2 shows the typical plate designs for the 1-in.- and ½-in.-thick specimens. The six top holes were 1¹⁄₁₆ in. in diameter, where the plates were attached to the gripping mechanism, and the bottom hole(s) was ⁹⁄₁₆ in. in diameter, where the fasteners attached the plates. All dimensions in Figure 2 were to the center of the appropriate hole.

The rivets used in the experiments were ASTM A502 (2003), "Standard Specifications for Rivets, Steel, Structural," grade 1, standard-strength rivets. Each rivet had a nominal diameter of ½ in., which is smaller than typical rivets in structural applications. The ½-in. size was chosen to replicate a component of a previous test that used ½-in. nominal fasteners. Note that previous research by Munse and Cox (1956) showed that a rivet's ultimate strength varied significantly depending on the diameter, but no conclusive trend was found.

Joint Configurations

This research tested five unique joint configurations. These configurations were selected to model typical joint patterns found in bridge and other structural connections and to keep the specimen response within the load capacity of the rapid loading machine. Figure 3 shows the selected joint configurations.

The first configuration was a single fastener in the center of the plate specimen. This configuration was selected as the control for the test series. It allowed for the determination of the capacity of a single fastener in both single and double shear. That capacity was then compared with other configurations to determine effects of multiple fasteners at a joint.

The second and third configurations utilized different two-fastener configurations. Configuration 2 has two fasteners in a horizontal line. Configuration 3 has two fasteners in a vertical line. The test results from configurations 2 and 3 would help to determine if a joint, under a monotonic impact/dynamic load, showed the same results.

The fourth and fifth configurations utilized different four-fastener configurations. Configuration 4 has four fasteners in a square pattern, and configuration 5 has four fasteners in a staggered configuration. These four-fastener configurations were chosen because they more closely mimicked the interaction between fasteners seen in actual structural joints. The staggered joint was chosen because it is the most typical joint configuration in use in the field as staggering of fasteners increases the efficiency of large joints under static loads (Munse, 1970).

All of the joint configurations were selected to have a large spectrum of tests to determine if the ultimate strength of the joint was truly additive based upon the number of failure planes in the joint. That is, if a joint has three failure planes, its ultimate strength should be three times greater than a joint with one failure plane. It is important to note the size of the components for this series of testing were much smaller than typical gusset plate connections in bridges and buildings. The smaller joint size was chosen to keep the joint's ultimate strength below the maximum capacity of the load frame.

Hot-Driven Rivets

The rivets were placed in the plate test specimens by Ballard Forge in Seattle, Washington. Ballard Forge used rivets procured from Jay-Cee Sales & Rivets Inc. in Farmington, Michigan. Rivets were heated and driven by a hydraulic riveter at a range of 1500 °F to 1950 °F. Dimensions of the rivet conformed to ANSI Standard B18.1.2. Note that the rivets placed for this research were not driven using pneumatic hammers like rivets driven in the field. The hydraulic riveter is used in most shop fabrications and considered to be superior to the field driving process.

The hot-driving process does two things to the rivet that are not considered when determining the design strength of a riveted joint: The rivet develops tension caused by the axial

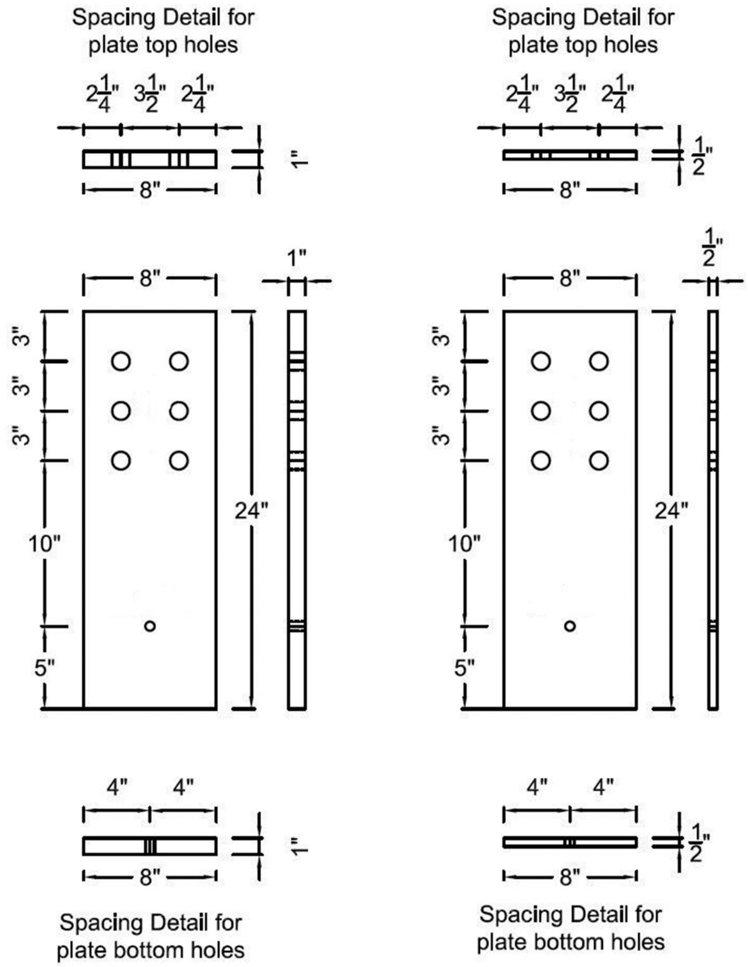

Fig. 2. Typical plate test specimens.

shrinkage of the rivet as it cools, and the rivet almost always fills the hole, as in Figure 4. Both of these effects help riveted joints to resist slip.

The nominal diameter of the rivet was 0.5 in. Post-driving, the riveted specimens that were tested had larger diameters but exhibited the characteristic of having a smaller diameter as the grip length of the rivet increased (Wilson and Oliver, 1930). The average diameter of double shear rivets was 0.545 in. for a stress area of 0.233 in.^{2} The average diameter of single shear rivets was 0.560 in. for a stress area of 0.246 in.^{2}

Samples of undriven rivets were milled and tested to ASTM E8 (2013), "Standard Test Methods for Tension Testing of Metallic Materials." The average, ultimate, undriven-rivet tensile strength was 77 ksi. An estimated value for driven-rivet strength was calculated using the hydraulic driven rivet's increase factor of 1.2 (Kulak et al., 1987; Schenker et al., 1954). Therefore, the estimated driven rivet ultimate tensile strength is 92 ksi. Size limitations of the driven rivets prevented direct measurements of the ultimate static tensile strength being taken.

Testing Machine and Instrumentation

The test specimens were failed using the 200-kip dynamic loader, shown in Figure 5. This unique loader is located at USACE-ERDC in Vicksburg, Mississippi, and has been used for many test series since the 1970s (Flathau, 1971). A uniaxial tension load was applied to the test specimen by using a compressible fluid (Xiameter/Dow Corning 100 CS silicone fluid) to apply pressure above and below a piston. The test specimen was attached to the piston and reaction structure above the piston. The bottom portion of the specimen and piston moved downward when pressure below the piston was released. The upper portion of the specimen remained stationary and resisted movement, resulting in an axial tension load applied to the specimen. Typical operating pressures of the compressible fluid for tests completed in this research ranged from 1500 to 3000 psi, depending on the number of fasteners in the specimen.

The pressure was released by a rapid-opening solenoid valve through a variable-sized orifice. The size of the orifice controlled the flow rate of the compressed fluid exiting the loader, thereby controlling the loading rate on the specimen. However, the actual load rate was dictated by the specimen's response to the load. The orifice sizes used were 4.5 in. for dynamic loading types and 1⁄16 in. for quasi-static loading types.

The typical time for the applied load to fail the test specimens was 1 to 6 msec for dynamic loading and 500 to 4000+ msec for quasi-static loading. Figures 6 and 7 show a typical load versus time curve for the dynamic and quasi-static loadings, respectively. The chosen figures were from tests with the same shear type and joint configuration but have different loading types applied.

Two load cells and two accelerometers were used to measure the forces and accelerations, respectively, during

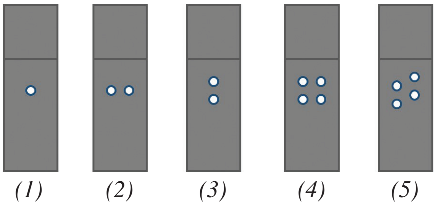

Fig. 3. Five joint configurations for testing.

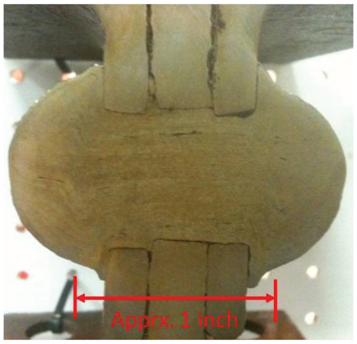

Fig. 4. Typical hot-driven, wrought iron, riveted connection cross-section.

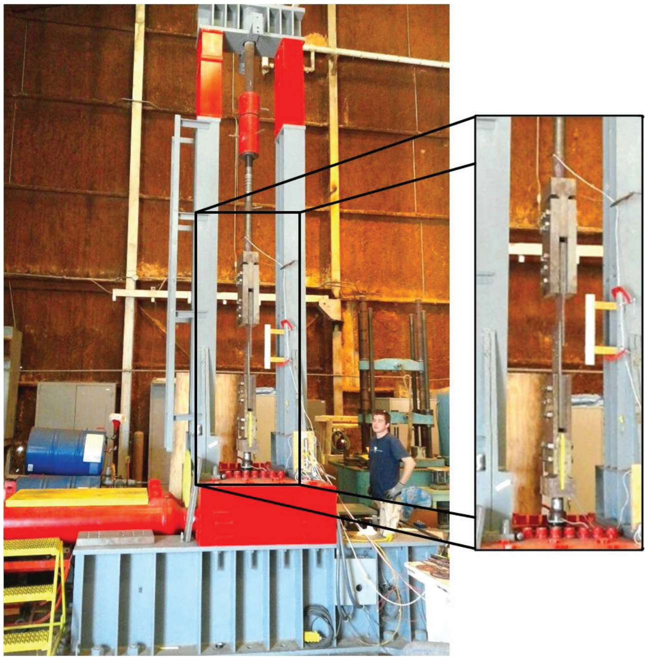

Fig. 5. 200-kip dynamic loader and test specimen.

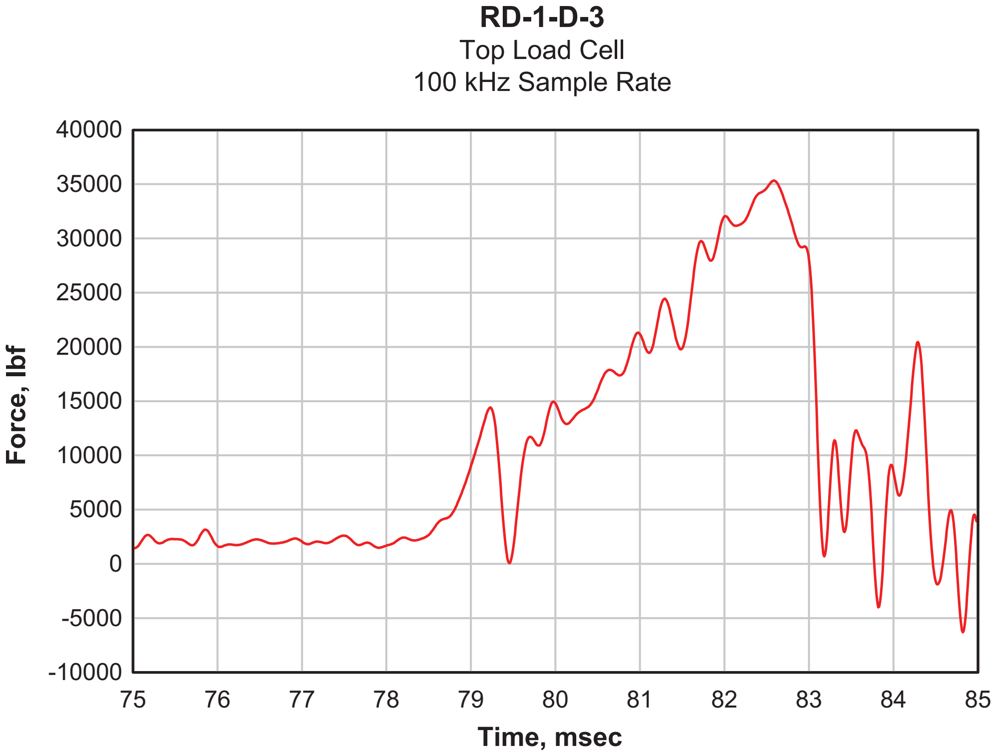

Fig. 6. Typical total load vs. time curve for dynamic loading type.

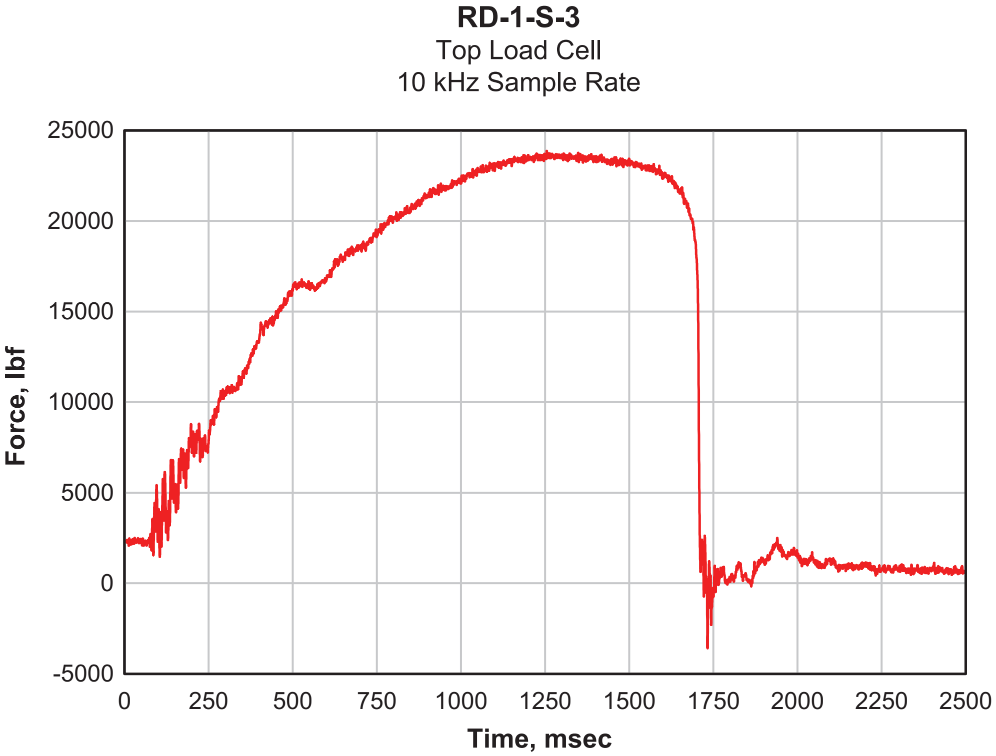

Fig. 7. Typical total load vs. time curve for quasi-static loading type.

Table 1. List of Initials Used in Test Name

Test Characteristic	Label	Description
Structural fastener type	R	Rivets
Shear type	D	Double shear
	S	Single shear
Joint configuration	1	Single fastener
	2	Two fasteners—horizontal
	3	Two fasteners—vertical
	4	Four fasteners—square
	5	Four fasteners—staggered
Loading type	D	Dynamic
	S	Quasi-static

testing. One of each was placed above and below the specimen. The two load cells were specifically designed for the 200-kip loader and were integrated into the loader structure. The load cells were comprised of a series of strain gauges arranged around a specific-diameter steel rod. The load cells were calibrated in such a way that a positive load measurement corresponded to tension, and negative load measurement corresponded to compression in the load cell.

Two Sigma 7270A 20K piezoresistive accelerometers were used initially, but they were damaged during testing of one specimen. Two PCB Electronics Model 3991A1120KG piezoresistive accelerometers were used in their place for the remainder of the tests. All four accelerometers had a peak sensitivity of 20,000 g's. The accelerometers were mounted to the specimen in a vertical orientation in order to measure the acceleration of the specimen in the direction of loading. The accelerometers were calibrated such that a positive acceleration measurement corresponded to the specimen accelerating up, and a negative acceleration measurement corresponded to the specimen accelerating down.

All the data were recorded using a Hi-Techniques Synergy P data acquisition system. The data from the instrumentation used for this test series were collected at a 100-kHz to 1000-kHz sampling rate for the dynamic loading type tests and at a 10-kHz sampling rate for the quasi-static loading type tests. Acquisition of the data was triggered remotely when the rapid-opening valve was fired.

Phantom v4.3 and v5.1 high-speed cameras were used to record footage at 8,113 frames per second (fps) for dynamic tests and 1000 fps for quasi-static tests. The resolution of the footage is limited to 256 × 256 pixels because of the frame rate needed to accurately capture footage for dynamic tests. The camera was triggered simultaneously with the data acquisition system. The high-speed camera footage was used to aid in determining the time of maximum load and failure of the specimen.

Test Labeling

The labeling system for test names in the test series was in the following order:

- Structural fastener type/shear type
- Joint configuration
- Loading type
- Test number

The list of initials used in the test name is shown in Table 1. For example, the riveted, single-shear, single-fastener, dynamic loading, test number 4 had the test name: "RS-1-D-4".

Each joint configuration was tested at least four times for each loading type and for each shear type. Some test combinations had more tests added than others due to malfunctions during testing of previous tests of that combination. A total of 86 tests were conducted on riveted lap splices.

TEST RESULTS

The table of results for each loading type is shown in Tables 2 and 3. All data values shown in the "Dynamic Load" or "Quasi-Static Load" columns of Tables 2 and 3 were values from the upper load cell (for both loading types) and accelerometer (for dynamic loading types only). Data values in the "Ratio of Ultimate Shear Stress to Ultimate Tensile Stress" column were the average ratio of shear stress to ultimate tensile stress seen by a single shear plane on the fastener (values were normalized by the number of shear planes in the test). Footnoted values in that column were excluded from analysis.

The upper load cell and accelerometer data for the dynamic tests were processed using existing processes developed in Flathau (1971) specifically for the 200-kip

Table 2. Results from Riveted, Dynamic Loading Type Specimens

Test Name	Estimated Ultimate Tensile Strength, ksi	Stress Area, in.^{2}	Dynamic Load, lbf	Shear Load of Each Rivet per Plane, lb	Shear Stress of Each Rivet per Plane, psi	Ratio of Ultimate Shear Stress to Ultimate Tensile Strength, ksi/ksi
RD-1-D-1	92	0.2333	30997	15498	66436	0.722
RD-1-D-2	92	0.2333	44711	22356	95830	1.042[1]
RD-1-D-3	92	0.2333	35320	17660	75702	0.823
RD-1-D-4	92	0.2333	33290	16645	71352	0.776
RS-1-D-1	92	0.2463	16149	16149	69224	0.713
RS-1-D-2	92	0.2463	15577	15577	66771	0.687
RS-1-D-3	92	0.2463	13717	13717	58799	0.605
RS-1-D-4	92	0.2463	16120	16120	69100	0.711
RD-2-D-1	92	0.2333	85304	21326	91417	0.994
RD-2-D-2	92	0.2333	72277	18069	77457	0.842
RD-2-D-3	92	0.2333	85538	21385	91668	0.996
RD-2-D-4	92	0.2333	55856	13964	59859	0.651
RS-2-D-1	92	0.2463	39446	19723	84546	0.870
RS-2-D-2	92	0.2463	47960	23980	102793	1.056
RS-2-D-3	92	0.2463	42505	21253	91103	0.938
RS-2-D-4	92	0.2463	79577	39789	170559	1.756
RS-2-D-5	92	0.2463	77341	38671	165767	1.707
RS-2-D-6	92	0.2463	—	—	—	—[2]
RD-3-D-1	92	0.2333	79761	19940	85476	0.929
RD-3-D-2	92	0.2333	132608	33152	142111	1.545
RD-3-D-3	92	0.2333	—	—	—	—[3]
RD-3-D-4	92	0.2333	106104	26526	113708	1.236
RS-3-D-1	92	0.2463	55509	27754	118973	1.225
RS-3-D-2	92	0.2463	60093	30047	128799	1.326
RS-3-D-3	92	0.2463	60332	30166	129311	1.331
RS-3-D-4	92	0.2463	54216	27108	116203	1.196
RD-4-D-1	92	0.2333	209128	26141	112057	1.218
RD-4-D-2	92	0.2333	157324	19665	84299	0.916
RD-4-D-3	92	0.2333	113424	14178	60776	0.661
RD-4-D-4	92	0.2333	246880	30860	132286	1.438
RD-4-D-5	92	0.2333	79875	9984	42800	0.465
RD-4-D-6	92	0.2333	—	—	—	—[4]
RS-4-D-1	92	0.2463	66323	16581	71076	0.732
RS-4-D-2	92	0.2463	54412	13603	58311	0.600
RS-4-D-3	92	0.2463	117432	29358	125847	1.296
RS-4-D-4	92	0.2463	101994	25498	109303	1.125
RS-4-D-5	92	0.2463	85437	21359	91559	0.943
RS-4-D-6	92	0.2463	79230	19808	84908	0.874
RD-5-D-1	92	0.2333	147573	18447	79074	0.860
RD-5-D-2	92	0.2333	160638	20080	86075	0.936
RD-5-D-3	92	0.2333	213216	26652	114247	1.242
RD-5-D-4	92	0.2333	167113	20889	89544	0.973
RS-5-D-1	92	0.2463	—	—	—	—[3]
RS-5-D-2	92	0.2463	66400	16600	71159	0.733
RS-5-D-3	92	0.2463	94465	23616	101234	1.042
RS-5-D-4	92	0.2463	83951	20988	89967	0.926

[1] Malfunction of top accelerometer and maximum load value is omitted from analysis.

[2] No usable data were collected.

[3] No data were recorded.

[4] Malfunction of top accelerometer and maximum load value is omitted from analysis.

Table 3. Results from Riveted, Quasi-Static Loading Type Specimens

Test Name	Estimated Ultimate Tensile Strength, ksi	Stress Area, in.^{2}	Dynamic Load, lbf	Shear Load of Each Rivet per Plane, lb	Shear Stress of Each Rivet per Plane, psi	Ratio of Ultimate Shear Stress to Ultimate Tensile Strength, ksi/ksi
RD-1-S-1	92	0.2333	23973	11987	51382	0.559
RD-1-S-2	92	0.2333	20460	10230	43852	0.477
RD-1-S-3	92	0.2333	23868	11934	51156	0.556
RD-1-S-4	92	0.2333	21347	10674	45754	0.497
RS-1-S-1	92	0.2463	16745	16745	71778	0.739
RS-1-S-2	92	0.2463	15885	15885	68094	0.701
RS-1-S-3	92	0.2463	15774	15774	67618	0.696
RS-1-S-4	92	0.2463	12597	12597	53998	0.556
RD-2-S-1	92	0.2333	45063	11266	48292	0.525
RD-2-S-2	92	0.2333	47787	11947	51212	0.557
RD-2-S-3	92	0.2333	—	—	—	—[1]
RD-2-S-4	92	0.2333	41680	10420	44667	0.486
RS-2-S-1	92	0.2463	34049	17024	72977	0.751
RS-2-S-2	92	0.2463	29164	14582	62509	0.644
RS-2-S-3	92	0.2463	31753	15876	68056	0.701
RS-2-S-4	92	0.2463	—	—	—	—[1]
RD-3-S-1	92	0.2333	42087	10522	45103	0.490
RD-3-S-2	92	0.2333	56375	14094	60415	0.657
RD-3-S-3	92	0.2333	50915	12729	54563	0.593
RD-3-S-4	92	0.2333	42020	10505	45031	0.489
RS-3-S-1	92	0.2463	33036	16518	70806	0.729
RS-3-S-2	92	0.2463	23757	11878	50918	0.524
RS-3-S-3	92	0.2463	25103	12552	53805	0.554
RS-3-S-4	92	0.2463	29604	14802	63451	0.653
RD-4-S-1	92	0.2333	85417	10677	45769	0.497
RD-4-S-2	92	0.2333	87479	10935	46874	0.509
RD-4-S-3	92	0.2333	98195	12274	52616	0.572
RD-4-S-4	92	0.2333	—	—	—	—[1]
RS-4-S-1	92	0.2463	51894	12974	55613	0.573
RS-4-S-2	92	0.2463	44832	11208	48045	0.495
RS-4-S-3	92	0.2463	51454	12864	55141	0.568
RS-4-S-4	92	0.2463	54607	13652	58520	0.602
RD-5-S-1	92	0.2333	86537	10817	46369	0.504
RD-5-S-2	92	0.2333	88741	11093	47550	0.517
RD-5-S-3	92	0.2333	96454	12057	51683	0.562
RD-5-S-4	92	0.2333	—	—	—	—[1]
RS-5-S-1	92	0.2463	—	—	—	—[1]
RS-5-S-2	92	0.2463	52404	13101	56160	0.578
RS-5-S-3	92	0.2463	45432	11358	48688	0.501
RS-5-S-4	92	0.2463	53620	13405	57463	0.592

[1] No data were recorded.

loader to determine the total load applied to the specimen during testing. Other data processing, such as filtering techniques detailed in Carleton (1970), was typical of the techniques used by USACE-ERDC. Further explanation of data-processing techniques is given in Rabalais (2015).

STATISTICAL ANALYSIS OF RIVETED SPECIMEN RESPONSE

The rivet specimen data were analyzed using two statistical testing techniques: the multifactor analysis of variance (ANOVA) and the t-test. The three factors that could affect the riveted specimen response, loading type, joint configuration, and shear type were inserted into a three-factor ANOVA on the data. Individual comparisons of means were conducted based on the results of this ANOVA using the t-test statistic assuming unequal sample variance so that the full significance of the results could be better understood. The probability threshold for statistical significance, or alpha value, of 0.05 is used for all statistical tests. All statistical calculations were completed using Microsoft Excel.

The ratio of ultimate shear stress to ultimate tensile strength, or "specimen response," value was selected as the response variable for the statistical analysis. This value provided for comparisons of the effects of the variables against one another.

The rivet specimen data for all tests were analyzed using the multifactor ANOVA. The three factors—loading type, joint configuration, and shear type—were inserted into a three-factor ANOVA on the riveted specimen data. The results of the rivet specimen data ANOVA indicated the most significant factor affecting the specimen response was loading type, as expected. Joint configuration also caused a statistically significantly different specimen response.

A t-test was completed on the riveted specimen data for the loading type because the ANOVA indicated it to be the most significant factor on specimen response. Figure 8 is the plot of the sample data. The t-test indicated that for riveted specimens, the two loading types caused statistically significant differences in the specimen response. The sample means were 0.992 [coefficient of variation (CV) of 30%] and 0.577 (CV of 14%) for dynamic and quasi-static loading types, respectively. The probability of the samples not being affected by loading type was less than 0.0001.

Note that for Figure 8 and other data plots herein, the individual dots were the measured data points, and the solid line across the entire plot indicated the mean of all the data points analyzed. The X-axis shows the specific samples within the factor that were being compared to one another. The medium-length line near the middle of the sample distribution was the sample mean. The first short line on either side of the mean line indicated the error bars of the mean; ±1.96 standard errors on each side of the sample mean is the range where any new sample mean will fall with 95% confidence. The outermost short lines from the mean line indicate 1 standard deviation from the sample mean.

Because the samples were very statistically significantly different, an increase in shear strength with respect to rivet ultimate static tensile strength could be quantified, referred to as the dynamic increase ratio. Computing the dynamic increase ratio for the rivet response was done by dividing the mean of the specimens subjected to dynamic loading type by the mean of the specimens subjected to quasi-static loading type. The order is specific because the increase ratio is made with respect to the ultimate static strength of the rivet. The mean difference between the samples equated to a dynamic increase ratio of 1.72.

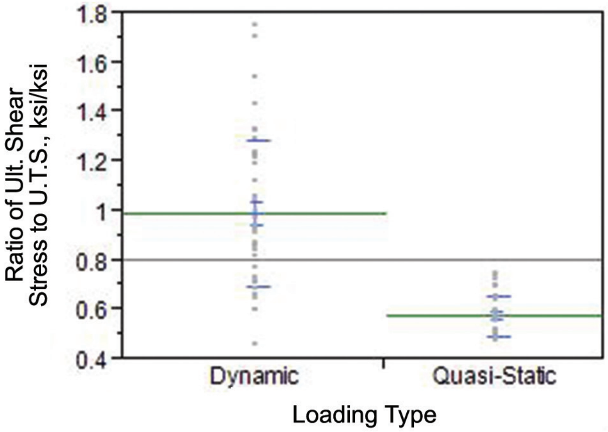

Fig. 8. Comparison by loading type for riveted specimens.

Dynamic increase ratios are not well defined for materials in shear, so it is difficult to compare the 1.72 ratio to previous research. However, results have been published for dynamic increase ratios of materials in tension. Zukas et al. (1982) show an increase in strength from approximately 60 ksi to approximately 90 ksi for SAE 1020 steel (a dynamic increase ratio of 1.5) when the tensile strain rate was increased from 0.1 s^{-1} to approximately 1000 s^{-1}. While this cannot be directly compared with the current shear tests, it does show that there is a similar increase in strength when the strain rate of a material is increased in either tension or shear.

It is important to note that the specimens' ultimate shear strength under the dynamic loading type varied more than those under quasi-static loading type. It is likely that the large variance for dynamic loading type tests is due to the much higher shear strain rates. As the load moves rapidly through the material, it will find faults in the material and will cause the material's ultimate strength to be more sensitive to local imperfections. Faults in the material vary greatly and can be attributed to several things, such as manufacturing and installation techniques. The large sample variance would significantly reduce the design shear strength used under dynamic loading conditions.

The first ANOVA also indicated the joint configuration factor caused a statistical difference for all riveted specimens and would generally be analyzed next. The next analyses performed were separate ANOVAs for riveted specimens subjected to dynamic loading type and quasi-static loading type because of the very significant difference between the loading types. This was to make sure that the statistical significance between joint configurations was not caused by the extreme difference in loading type and to clearly see if joint configuration (or shear type) had an effect on specimen response as shown in previous research.

The ANOVA results from the riveted specimens subjected to dynamic loading type indicated a statistically significant difference in the specimen response due to the joint configuration. The ANOVA results from the riveted specimens subjected to quasi-static loading type indicated a statistically significant difference in specimen response due to shear type.

The first factor analyzed using the t-test was the joint configuration for riveted specimens subjected to dynamic loading. The plot of the sample data of the riveted, dynamic-loading type specimens for each joint configuration is shown in Figure 9.

The comparisons of each configuration indicated that there were statistically significant differences in riveted specimen responses due to joint configurations. There was a significant statistical and practical difference between some configuration means. However, the variation of the data was high (numerous outliers in joint configurations 2 and 3), and the sample size was small. Therefore, it was difficult to determine the cause of the difference. More tests are needed to get a better sample distribution. Some of the difference, however, may have been due to the acceleration/inertial force data or individual sample strengths.

The next t-test was completed on the effects of shear type on the riveted specimens subjected to quasi-static loadings. Previous research had concluded that there was a difference in the response of the specimen when the grip length of compared rivets was different. The grip lengths for the rivets tested were 1 in. and 2 in. for single and double shear, respectively.

The t-test results for riveted, quasi-static specimens indicated a statistically significant difference in the specimen response due to shear type. The sample means are 0.620 (CV of 13%) and 0.532 (CV of 9%) for single and double shear, respectively. The probability that the specimen were not affected by shear type was 0.001. This was a significant difference and was practically different as well. The difference can be easily seen in the plot of the sample data shown in Figure 10. This comparison also shows that riveted

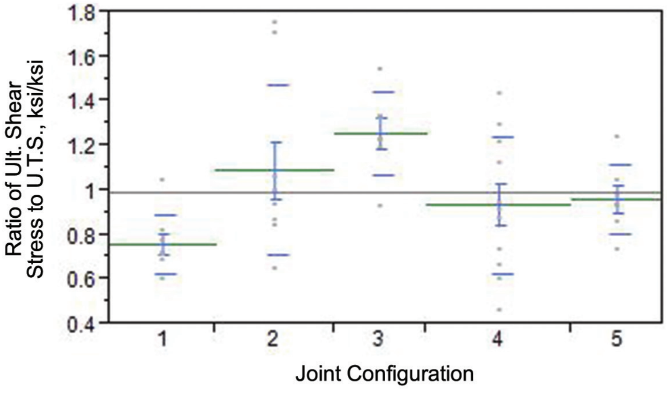

Fig. 9. Comparison by joint configuration for riveted, dynamic-loading type specimen response.

specimen response contributed significantly to the statistically significant difference due to shear type in the overall quasi-static loading–type specimens comparison.

The difference in double and single shear specimens was likely due to the longer grip length, with double shear rivets having more initial tension. Wilson and Oliver (1930) observed this effect in their testing of many rivets with multiple gauge lengths. They concluded the initial tensile stress in the rivet shank is higher in longer-grip rivets. If the double-shear rivets have a greater initial tensile stress (which is closer to the yield limit than single-shear rivets), they would not have the same amount of available strength in shear.

The riveted specimens subjected to dynamic loading type were also given a t-test comparing the response due to shear type. The results indicated no statistically significant difference, although the single-shear specimens did have a greater mean than the double-shear specimens. However, the CV of the samples was 32% and 28% for single and double shear, respectively. This large amount of variation in these samples may have masked any statistical differences in the riveted, dynamic specimen responses that were seen in the riveted, quasi-static specimens.

Design guides and other research have adjusted the measured shear strength to a factor of the undriven-rivet ultimate tensile strength. A separate analysis was completed on the normalized measured shear strength to the ultimate undriven-rivet tensile strength because testing was completed to determine the undriven-rivet ultimate tensile strength. The quasi-static specimen mean normalized to the undriven ultimate tensile strength was 0.690. The mean of single- and double-shear, quasi-static specimens was 0.741 and 0.636, respectively. This falls in line with the range of values given in Kulak et al. (1987), Wilson and Oliver (1930), and Schenker et al. (1954).

To summarize the analysis of riveted specimens, the loading type has the most significant effect on specimen response as a rivet under dynamic loading has a 72% (SD of 8.7%) increase in ultimate shear capacity when compared to a similar rivet subjected to quasi-static loading. The configuration of the joint under dynamic loading has some statistically significant effect on the specimen response. The shear type of the specimen under quasi-static loading has a statistically significant effect on the specimen response due to the grip length increasing the initial stress (decreasing available shear strength). However, the dynamic specimens show a similar result due to shear type, but there was no statistically different response, more than likely due to variation of the results.

CONCLUSIONS

The analysis of results of the tests performed in this research justified the following conclusions about the shear strength of various structural fasteners under multiple loadings, shear types, and joint configurations:

1. Loading type (dynamic or quasi-static) had the most significant effect on the shear strength of a rivet, regardless of the joint configuration or shear type. The dynamic increase factor for the quasi-static shear strength overall was 1.72.
2. Riveted specimens subjected to the quasi-static loading type were statistically significantly affected by the shear type. The riveted, double-shear specimen response was statistically significantly less than the riveted, single-shear specimen response and may be caused by an increase in initial tension (causing less available shear strength) in longer grip lengths (single-shear rivets were half the length of double-shear rivets, 1 in. to 2 in.).

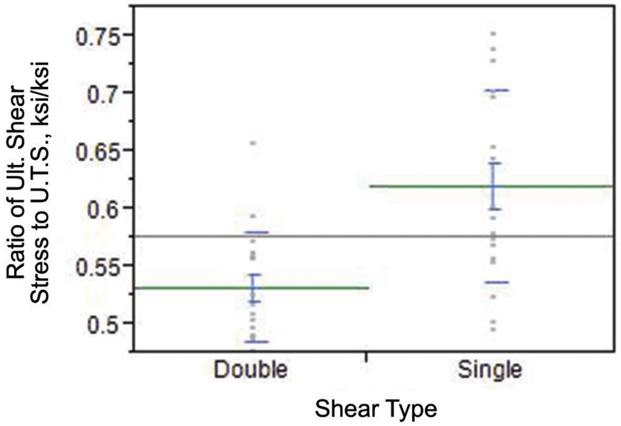

Fig. 10. Comparison by shear type of riveted, quasi-static loading-type specimen response.

3. The quasi-static shear strength of rivets, normalized to the undriven-rivet ultimate tensile strength (0.690 overall, 0.741 for single shear, 0.638 for double shear), was within the established range of values for the ratio of shear stress to tensile strength.
4. The increase factor of 1.2 for undriven-rivet ultimate tensile strength to driven-rivet ultimate tensile strength given by Kulak et al. (1987) and Schenker et al. (1954) was a good estimate for this data. The mean ratio of rivet, quasi-static specimen shear strength to the estimated ultimate driven-rivet tensile strength was 0.577, which is similar to the expected design strength for driven rivets (0.625) and von Mises failure criterion for shear strength of ductile materials (0.577).
5. The dynamic loading type induced a higher variability in the data than the quasi-static loading type (coefficient of variation of 30% and 14% for dynamic and quasi-static, respectively), possibly masking any significant differences in the data.

These conclusions are based solely on the data gathered during testing of the 86 specimens. Their individual responses may or may not be indicative of the global responses of the specimen types. The tests were completed on new steel rivets and may not be indicative of existing field rivets.

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