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BEHAVIOR OF WELDED BOLT SHEAR CONNECTORS SUBJECTED TO REVERSED CYCLIC LOADING

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Abstract

Conventional bolts fillet-welded to steel and embedded in concrete have been a common method of force transfer between steel and concrete materials in composite construction in some Latin American countries. Welded bolt shear connectors have been used in both low-rise and mid-rise constructions replacing headed steel stud shear connectors. Whereas the installation of headed studs requires the use of a special high voltage equipment, welded bolts can be welded with fillet welds using shielded metal arc welding process more economically.

Welded bolt shear connectors are also used in lateral load resisting composite systems. Natural cyclic loads from earthquakes cause connectors to be subjected to alternating shear forces. For this reason, the cyclic behavior of shear connectors is particularly important in these systems.

In this study, a series of experimental tests on composite push-out specimens with welded bolt shear connectors were performed to investigate the behavior of shear connectors subjected to fully reversed cyclic loading. Of specific interest was the behavior under low-cycle fatigue. Results show up to 57 % reduction in connector shear capacity under reversed cyclic loading compared to static capacity.

Keywords: shear connectors, welded bolts, low-cycle fatigue, composite structures, push-out tests.

1. Introduction

Composite steel-concrete structural systems are commonly used worldwide to resist both gravity loads and seismic forces due to the high strength and stiffness these systems provide. In both cases, it is essential that shear connectors can transfer the shear forces between the steel and concrete. In composite beams, for example, shear connectors must transfer the longitudinal shear forces between the steel beam and the concrete slab to provide higher strength and stiffness, thus reducing the mid-span deflection with a higher span-to-depth ratio compared to the bare steel or the concrete counterparts [1]. In collector elements of a seismic resistance system, the shear connectors must transmit diaphragm shear forces, even when the overall structure is designed without composite action [2]. In seismic resistance systems, such as in the system called steel frame with reinforced concrete infill wall and semirigid joints (SRCW), with headed studs as shear connectors in all around the infill wall perimeter, the composite interactions are achieved by the headed studs that transfer the shear forces between the steel frames and infill walls. According to [3], the headed studs are responsible for transferring most of lateral load (80-100 %), while the steel frames transfer around 10-20%, and the diagonal struts transfer around 10-15%.

The inertial forces induced in buildings during seismic events are cyclical with similar magnitudes in both directions. This is a significant difference from the cyclic loading expected on highway bridges where, even when loading is reverse, one direction loading is dominant. Furthermore, the number of cycles in a seismic event is much lower than those examined in fatigue studies. Low-cycle fatigue generally refers to loads that approach or exceed the yield capacity of a section, with failure occurring prior to 1000 load cycles [2]. In this research, the behavior of low-cycle fatigue of headed studs was studied from modified push-out tests and its results showed that there is a significant reduction in shear stud capacity when subjected to reverse cyclic loading. This reduction in capacity is due to a combination of strength degradation in the stud combined with concrete crushing, which causes the stress distribution to migrate up the shank of the stud. This increased bending stresses in the stud causing earlier failures. Strength degradation occurred at less than 5 mm, so the authors recommended applying a reduction factor of 0.6 or less to the ultimate strength of the corresponding static push-out tests.

In [1], the cyclic behavior of bolted shear connectors in steel-concrete composite beams was experimentally studied from push-out tests. One conclusion of this research was that the load capacity of the bolted shear connectors in the monotonic specimens are much higher than that in the cyclic specimens at the same level of slip.

This paper focusses on the low-cycle fatigue behavior of welded bolts from push-out tests since, in some low-rise and mid-rise constructions in some Latin American countries (e.g., Colombia and Mexico), standard steel headed stud anchors are replaced by conventional steel bolts that are manually welded (SMAW) to the steel beam with fillet weld around the shank. Steel headed studs are replaced due to logistical issues in the installation process, particularly for the need of special high voltage equipment, and consequently, construction costs with welded bolts are expected to be less than with steel headed studs.

2. Materials and methods

Push-out tests with welded bolt shear connectors was performed at the Structures Laboratory of the Department of Civil Engineering at the National University of Colombia, campus Manizales. Bolts were fillet welded to the beam flange using shielded metal arc welding with E7018 electrode. The variables considered were diameter of bolt and the type of load (i.e., static, and cyclic). Three bolt diameters were considered: 12.7 mm (1/2 in), 15.9 mm (5/8 in) and 19.1 mm (3/4 in). Each specimen was tested with monotonic static loading and with reverse cyclic loading. A total of 18 specimens were tested.

2.1. Specimens

The specimens in this research are fabricated and tested in accordance with the modified tests of Annex B of Eurocode 4 [4]. They consist of two reinforced concrete slabs and an IPE200 steel beam with SAE grade 2 headed hexagonal bolts (F_u = 510 MPa = 74 ksi) welded by manual procedure (SMAW) according to the AWS D1.1. [5]. All concrete slabs have a strength of 27.6 MPa (4000 psi), reinforced by two electro-welded mesh with 6 mm bars spaced 150 mm apart, and dimensions of 120×500×600 mm. Figure 1 and Table 1 shows details of the specimens. The effective height-to-diameter ratio (h_{ef}/d) of the bolt was at least 4.0 (where h_{ef} is measured to the bottom of the bolt head), so failure is expected to occur in the bolt connector.

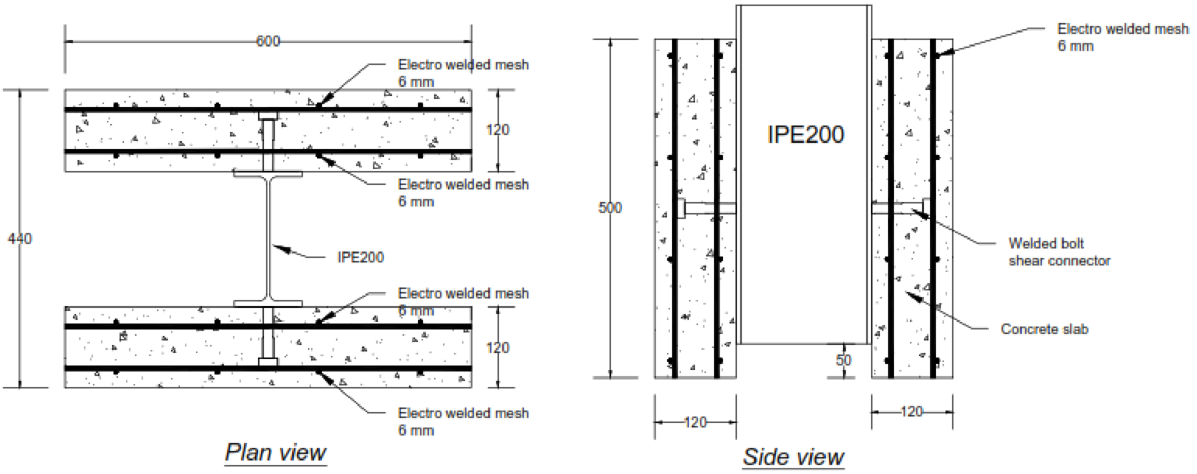

Figure 1. Specimen details (units: mm)

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Table 1 – Tested specimens

Specimen	**No of connectors per slab**	**Diameter (mm – in)**	**Effective height (h_{ef}) (mm – in)**	**h_{ef} / d**	**Dimensions of concrete slabs (mm)**
PT1	1	12.7 – 1/2	72.6 – 3.0	6.0	120×500×600
PT2	1	15.9 – 5/8	72.6 – 3.0	4.8	120×500×600
PT3	1	19.1 – 3/4	72.6 – 3.0	4.0	120×500×600
PT1-RC	1	12.7 – 1/2	72.6 – 3.0	6.0	120×500×600
PT2-RC	1	15.9 – 5/8	72.6 – 3.0	4.8	120×500×600
PT3-RC	1	19.1 – 3/4	72.6 – 3.0	4.0	120×500×600

2.2. Experimental setup

The vertical force was applied in displacement control by the hydraulic jack having the capacity of 500 kN. In the first series of tests, the load was applied continually until failure. In the seconds series of tests, the specimens were loaded with cyclic loading according to the test method B of ASTM E2126 standard [6]. Displacement controlled loading procedure involves displacement cycles grouped in phases at incrementally increasing displacement levels. Loading schedule consists of two displacement patterns. The first displacement pattern consists of five single fully reversed cycles at displacements of 1.25%, 2.5%, 5%, 7.5%, and 10% of the ultimate displacement Δ_m. The second displacement pattern consists of phases, each containing three fully reversed cycles of equal amplitude, at displacements of 20%, 40%, 60%, 80%, 100%, and 120% of the ultimate displacement Δ_m. The sequence of amplitudes is a function of the mean value of the ultimate displacement (Δ_m) obtained from specimens in the monotonic tests.

In monotonic tests, compressive load was applied through contact between plate of loading and the beam of the specimen as shown in Figure 2a. In reversal cyclic tests, with the aim to avoid any vertical displacement of the concrete slabs when tension load is applied, two steel beams were placed on the top of the concrete slabs and eight steel rods were used to connect these steel beams to the base steel beam as shown in Figure 2b.

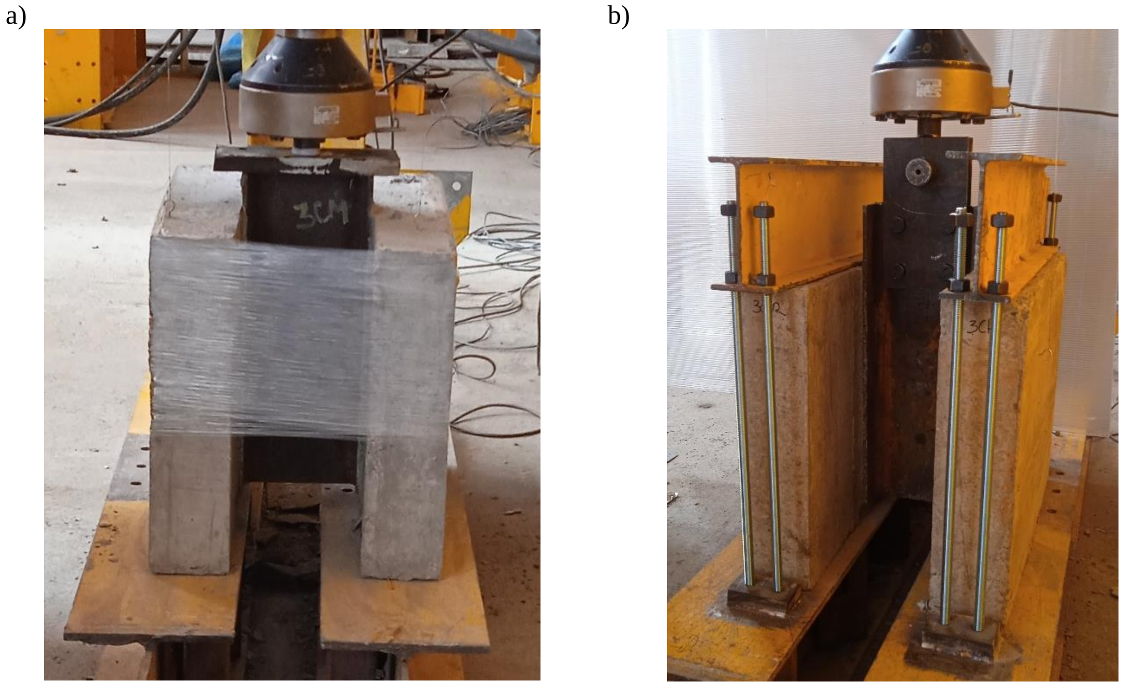

Figure 2. Experimental setup: a) monotonic test b) cyclic test

3. Results and discussion

The results were analyzed just in terms of load because the slip at the interface of both materials couldn't be measure. The displacement measured was the displacement of all system. Table 2 shows the maximum load results of the experimental monotonic tests. Figure 3 presents the load-displacement curves from monotonic push-out tests. We can see increases in capacity with the increase in diameter.

Table 2 – Load results of experimental monotonic tests

Specimen	Maximum load (kN)	Maximum load per connector (kN)	Failure mode
PT1-1	101.2	50.6	Shank failure
PT1-2	116.8	58.4	Shank failure
PT1-3	112.5	56.3	Shank failure
Mean	**110.2**	**55.1**	
PT2-1	153.2	76.6	Shank failure
PT2-2	151.0	75.5	Shank failure
PT2-3	164.7	82.4	Shank failure
Mean	**156.3**	**78.2**	
PT3-1	213.4	106.7	Shank failure
PT3-2	223.3	111.7	Shank failure
PT3-3	214.2	107.1	Shank failure
Mean	**217.0**	**108.5**	

Table 3 – Main results of experimental cyclic tests

Specimen	Maximum compression load (+) (kN)	Maximum tension load (–) (kN)	Failure load (kN)	Failure cycle	Δ_m (mm)	Failure mode
PT1-RC-1	75.8	-72.8	-48.4	Phase 80% Δ_m 2nd cycle tension		Shank failure
PT1-RC-2	78.1	-81.6	-81.6	Phase 80% Δ_m 1st cycle tension		Shank failure
PT1-RC-3	72.3	-71.1	-54.5	Phase 80% Δ_m 1st cycle tension		Shank failure
Mean	**75.4**	**-75.2**			**11.0**	
PT2-RC-1	157.8	-134.5	-109.8	Phase 100% Δ_m 2nd cycle tension		Shank failure
PT2-RC-2	124.3	-109.3	-105.4	Phase 100% Δ_m 1st cycle tension		Welding failure
PT2-RC-3	120.6	-101.1	-67.3	Phase 100% Δ_m 1st cycle tension		Welding failure
Mean	**134.2**	**-115.0**			**12.8**	
PT3-RC-1	203.8	-128.6	173	Phase 100% Δ_m 1st cycle compression		Shank failure
PT3-RC-2	178.9	-128.2	-96.5	Phase 100% Δ_m 1st cycle tension		Shank failure
PT3-RC-3	152.7	-160.7	152.7	Phase 100% Δ_m 1st cycle compression		Shank failure
Mean	**178.5**	**-139.2**			**16.0**	

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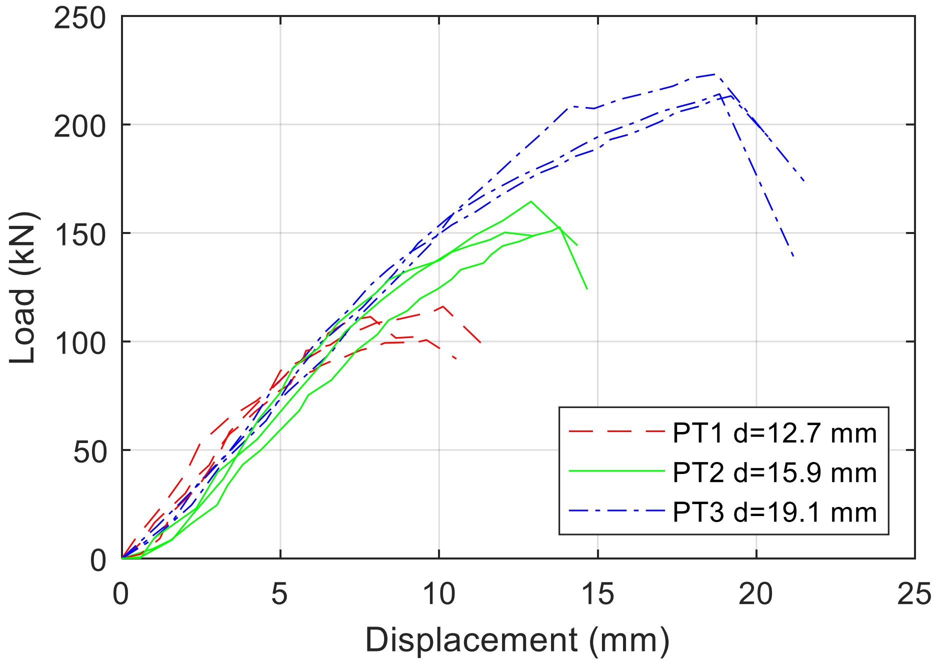

Figure 3. Load-displacement curves for monotonic tests

Table 3 summarizes the results of the experimental cyclic tests. This table contains the maximum load reached in both compression and tension, the value of the failure load, and the cycle in which failure occurs. Figure 4 shows the behavior from cyclic push-out tests compared to maximum monotonic mean load (Figure 4a-4c). Most of the specimens subjected to reversal cyclic loading did not reach the maximum monotonic loading as seen in these figures. The failure occurred before reaching the maximum monotonic capacity in 8 of the 9 cyclic tests. Figure 4d shows typical behavior for cyclic loading. A decrease in load for each cycle can be clearly seen. This decrease starts at the first phase, i.e., at displacements of ±20% of the ultimate displacement Δ_m. As seen in Figure 4d, the specimen PT1-RC-1 reached a displacement of ±80% Δ_m (±8.8 mm) in the first cycle and fails in the second cycle in tension load (-48.4 kN) as indicated in the "failure cycle" column in Table 3. In the first cycle of 80% $\Delta_{m,}$ the specimen reached 75.8 kN in compression and 72.8 kN in tension. At the second cycle of 80% Δ_m, the specimen reached 59.8 kN in compression and failed with 48.4 kN in tension.

Figure 5 shows the comparison between the envelope curves of the cyclic tests with the monotonic curves. As general trend, cyclic specimens have shown a reduction in strength capacity. Figure 6 shows the percentage reduction due to the cyclic loading effect. The reduction of the compression load with respect to the monotonic loading reaches 34% for the PT1 specimens (d = 12.7 mm), 23% for the PT2 specimens (d = 15.9 mm), and 30% for the PT3 specimens (d = 19.1 mm), while the tension load reaches 35% for the PT1 and PT2 specimens, and 41% for the PT3 specimens. The reduction in failure load was even greater, reaching 56% for the PT1 and PT3 specimens, and 57% for the PT2 specimens. In 6 of 9 cyclic tests, the failure load was below the maximum load achieved in early cycles of the series due to low-cycle fatigue in the steel or degradation in the concrete.

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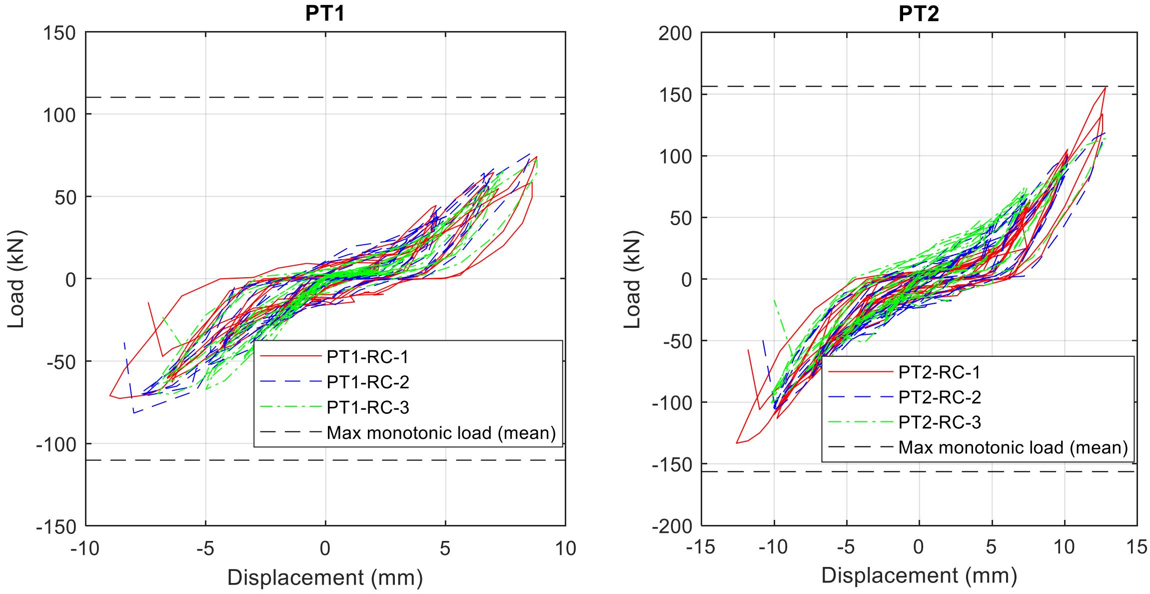
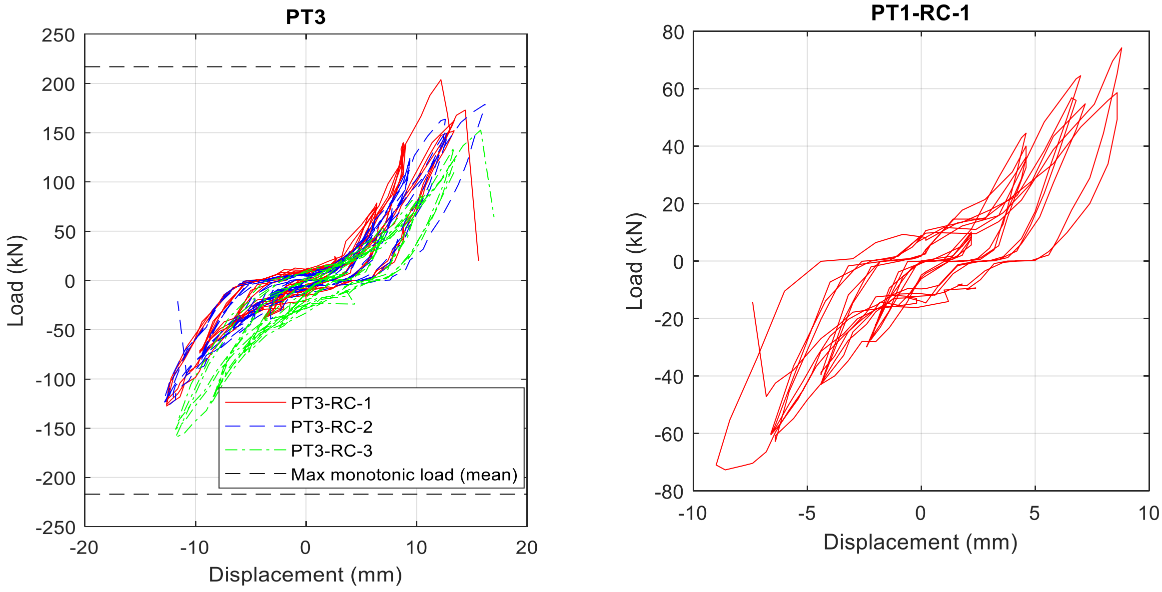

a) Diameter 12.7 mm

b) Diameter 15.9 mm


c) Diameter 19.1 mm

d) Typical cyclic load-displacement curves

Figure 4. Load-displacement curves for cyclic tests

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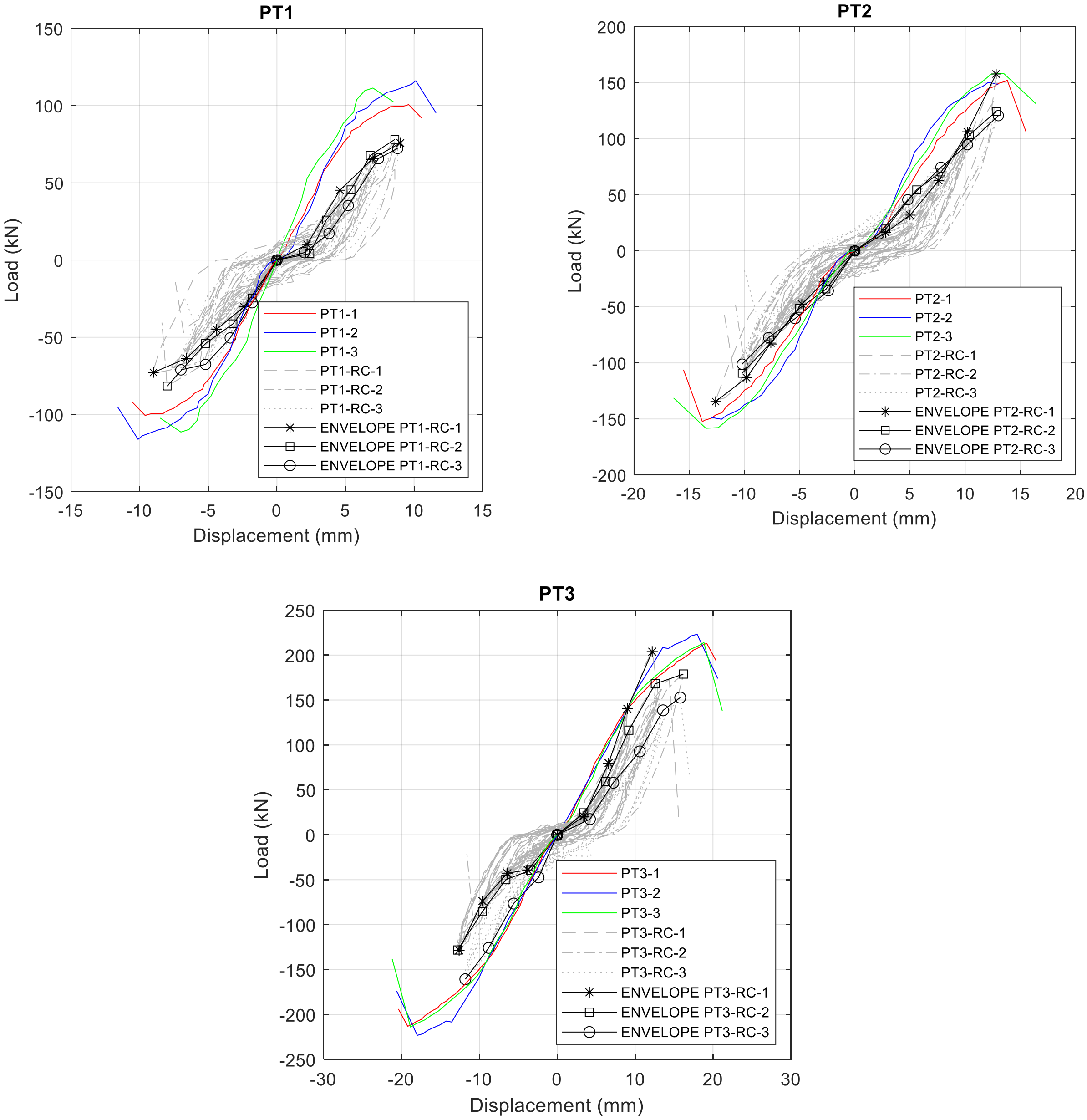

Figure 5. Comparison between envelopes of the cyclic test with the monotonic curves

Figure 7 shows the typical failure modes for the three diameters with both monotonic and cyclic loading. As seen in this figure, two failures modes occurred, where one mode of failure was shear rupture between the threads at the bolt shank at the top of the welding, and the other mode was welding failure. Except for the PT2-RC-2 and PT2-RC-3 specimens, all series of tests have the same shear failure at the bolt shank (see Table 2 and Table 3). There is no evidence of concrete crushing, except for the concrete located at the base of the bolt. Inspection after the tests revealed that the maximum bolt slip in monotonic loading was around 4 mm for the PT1 specimens, around 5 mm for the PT2 specimens, and around 6 mm for the PT3 specimens. An evident reduction of slip capacity of bolt due to cyclic loading for all diameters can be observed in Figure 7. Inspection after the tests revealed that the slip achieved in cyclic loading was around 2 mm for all the specimens.

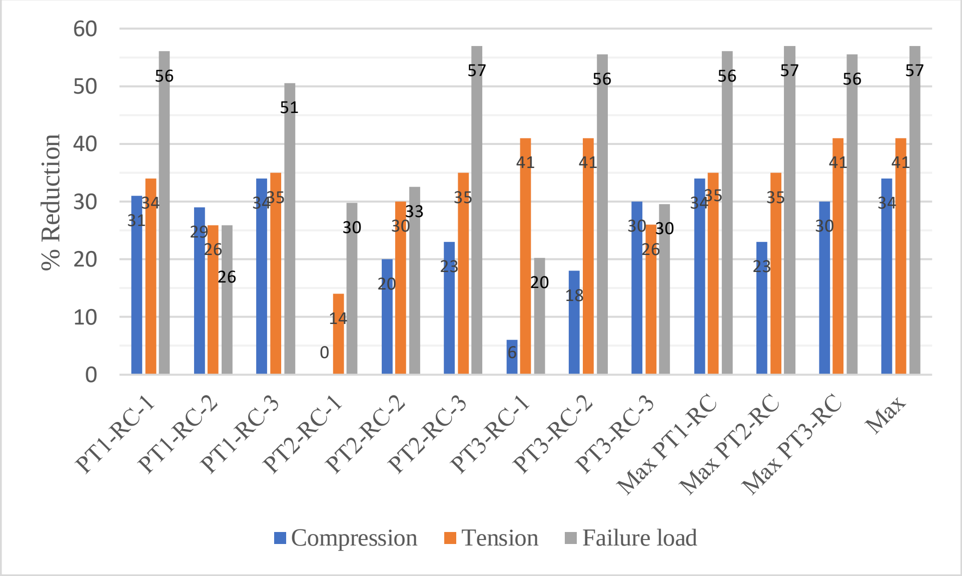

Figure 6. Percentage reduction in capacity due to cyclic loading

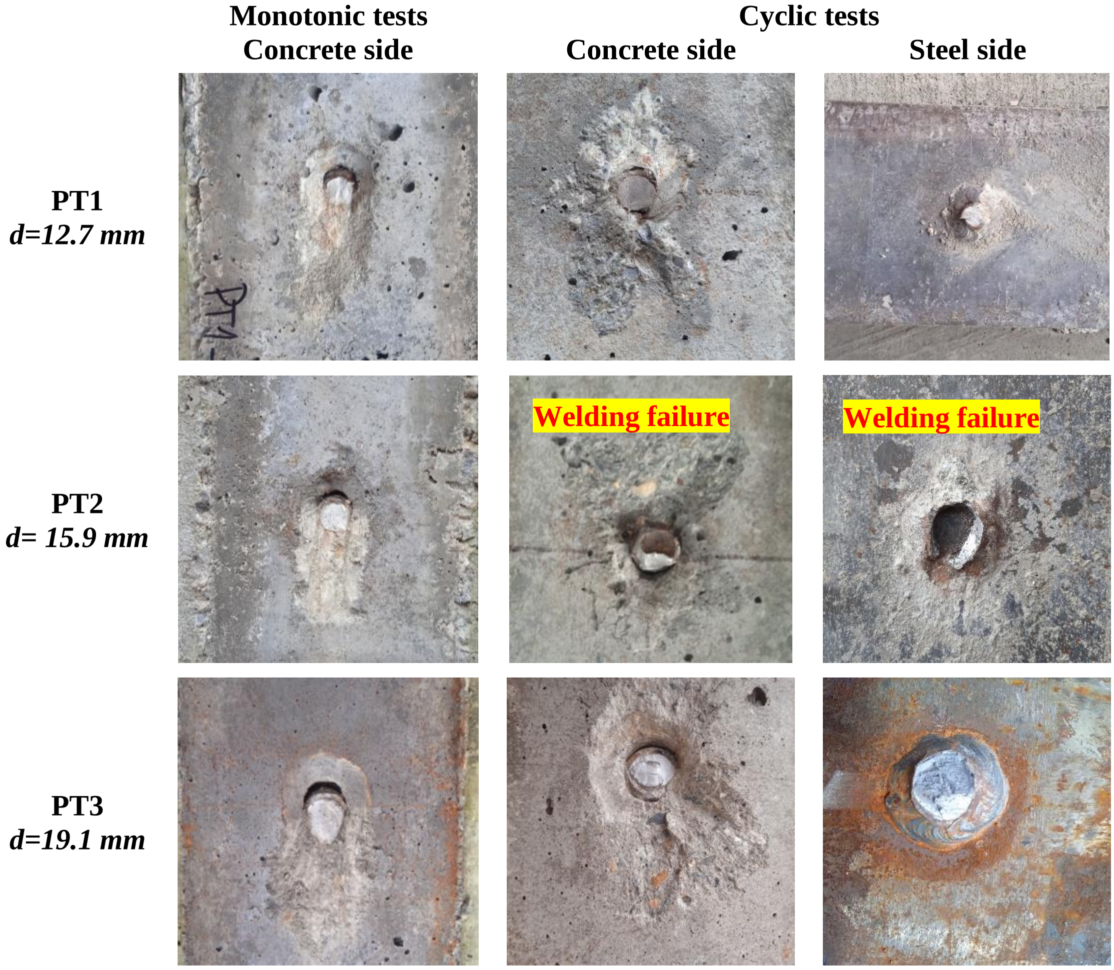

Figure 7. Typical failure modes

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4. Conclusions

A series of experimental tests on push-out specimens with variable bolt diameter were performed to investigate the behavior of welded bolts shear connectors subjected to fully reversed cyclic loading. The obtained results showed that the diameter is a significant variable to increase the shear capacity of welded bolts in both monotonic and cyclic loading. The load capacity and slip capacity increased with the increased of diameter. When welded bolts were subjected to fully reversal cyclic loading, a significant reduction in shear capacity was observed. This reduction was up to 57% of the failure load. Therefore, it is recommended that a reduction factor less than or equal to 0.43 be applied to the monotonic shear capacity of welded bolts when considering low-cycle fatigue. This factor may need to be reviewed when applied to prediction models of capacity.

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