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# Carbon steel and stainless steel bolted connections undergoing unloading and re-loading processes

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**Abstract:** A total of 50 bolted connections of carbon steel and stainless steel subjected to monotonic loading and cyclic loading conditions were investigated. The connection specimens were fabricated from carbon steel grades 1.20 mm G500 and 1.90 mm G450, as well as cold-formed stainless steel types EN 1.4301 and EN 1.4162 with nominal thickness 1.50 mm. In the monotonic tests, the specimens were tested under a constant loading rate by the displacement control test method, while in the cyclic tests, the specimens having the same dimensions as those in the monotonic tests were subjected to loading, unloading and re-loading processes, where displacement control and load control test methods were used. The results obtained from the cyclic tests were compared with those obtained from the monotonic tests. It was found that the ultimate loads obtained from the cyclic tests were, on average, larger than those obtained from the monotonic tests for carbon steel bolted connections; this was in contrast with the compared results for stainless steel bolted connections. The elongations corresponding to the ultimate loads obtained from the cyclic tests were, on average, larger than those obtained from the monotonic tests for both carbon steel and stainless steel, which may indicate that the loading processes in the cyclic tests generally delayed the bolted connection specimens from reaching the ultimate loads. Generally, the failure modes in the cyclic tests were consistent with those in the monotonic tests for the same specimen series, where the specimens mainly failed in the connection plate bearing.

**Keywords**: Bearing failure; bolted connection; carbon steel and stainless steel; cyclic loading; experimental investigation, monotonic loading.

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## 1. Introduction

Bolt connections are used commonly in cold-formed steel structures, including carbon steel and stainless steel. Experimental and numerical investigations have been conducted on the structural behavior of bolted connections subjected to monotonic tensile loading, where the connection specimens were fabricated by carbon steel [1-5] and stainless steel [6-10]. Design specifications are currently available for bolted connections of cold-formed carbon steel [11-13] and stainless steel [14-16] covering different failure modes, including bearing, net section tension (tension rupture), tearout (shear rupture) and bolt failure. It should be noted that these design rules are applicable for room temperature conditions, but not for conditions at elevated temperatures.

In the past few years, hundreds of experimental tests and numerical models of carbon steel bolted connections at elevated temperatures have been conducted by Yan and Young [17-19]. Subsequently, design rules were proposed for the carbon steel bolted connections subjected to steel plate bearing failure at elevated temperatures [19]. More recently, Cai and Young [20-24] investigated the effects of elevated temperatures on the behavior of cold-formed stainless steel bolted connections, where the steady state test method [20, 22], transient state test method [21-22] and numerical method [23-24] were used. These research outcomes with the proposed bearing resistance design rules were summarized and validated against results reported in the literature [25]. Investigations were extended into stainless steel bolted connections under post-fire conditions [26].

Steel bracings are commonly designed and constructed in steel structures to provide lateral stiffness. It is unavoidable that the brace members designed to provide tensile resistance will experience loading and unloading conditions under certain events during their lifetimes, such as wind loads and seismic effects. Bolt connections are commonly used at the end of brace members. Hence, the loadings are transferred by the bolted connections between the brace members and joints of beams and columns. The connections may also be subject to loading and unloading conditions. There have been investigations of the behavior of steel columns [27-29] and steel brace members [30-32] under cyclic loads for seismic effects, where the stainless steel columns [27] and carbon steel columns [29] were subjected to compressive loading, unloading and re-compressive loading processes. In addition, the responses of metal material subjected to tensile loading, unloading and re-tensile loading have been investigated, including carbon steel [33], stainless steel [34] and several metals [35]. However, it should be noted that investigation of the behavior of bolted connections of carbon steel and stainless steel subjected to tensile loading, unloading and re-tensile loading has been limited, which is the focus of this study.

In this study, an experimental investigation was conducted on bolted connections of carbon steel and stainless steel subjected to monotonic loading and cyclic loading conditions. The connection specimens were fabricated from carbon steel grades 1.20 mm G500 and 1.90 mm G450, as well as cold-formed stainless steel types EN 1.4301 and EN 1.4162 with nominal thickness 1.50 mm. In total, 50 bolted connection specimens in single shear and double shear were tested. The connection specimens covered 15 cases in carbon steel and 9 cases in stainless steel. In the monotonic tests, a series of specimens was tested under a constant loading rate by the displacement control test method; while in the cyclic tests, the specimens having the same dimensions as those in the monotonic tests were subjected to loading, unloading and re-loading processes, where displacement control and load control test methods were used. The results obtained from the monotonic tests were compared with those predicted by the carbon steel and stainless steel design specifications. The results obtained from the cyclic tests were compared with those obtained from the monotonic tests, in terms of ultimate load, elongation corresponding to ultimate load as well as failure mode. The purpose of this paper is to present the effects of loading processes on the structural behavior of carbon steel and stainless steel bolted connections subjected to tensile loading.

## 2. Material properties

Two grades of carbon steel and stainless steel were used to fabricate the bolted connection specimens. The carbon steel included the grades of G450 and G500, with the respective nominal thicknesses ($t$) of 1.90 mm and 1.20 mm. The stainless steel included austenitic stainless steel type EN 1.4301 and lean duplex stainless steel type EN 1.4162, with both $t$ = 1.50 mm. For simplicity, the stainless steel types EN 1.4301 and EN 1.4162 have been shortened as types A and L, respectively, hereafter in this paper. Material properties of the carbon steel and stainless steel were measured by tensile coupon tests. The coupon specimens, having the gauge length and width of 50 mm and 12.5 mm respectively, were designed according to the Australian Standard AS1391 [36]. The coupons were cut in the rolling direction of the carbon steel sheets and from the web centre of stainless steel tubes with nominal section dimensions of 50×20×1.5 (depth × width × thickness) in mm.

Two linear strain gauges were attached at the centers of two surfaces in each coupon. In addition, a calibrated extensometer was used to measure the longitudinal strain during the tests. The coupon tests were conducted in an MTS testing machine with 50 kN loading capacity. During the coupon tests, 90 seconds of pauses were made near the 0.2% proof stress ($f_{0.2}$), around the ultimate strength ($f_u$) and before the coupon fracture. This allowed the stress relaxation associated with plastic straining to take place. The initial average readings of the two strain gauges were used to determine the initial elastic Young's modulus ($E$). The material properties obtained from the stress-strain curves are shown in Table 1, including the strain at ultimate strength ($\varepsilon_u$) and strain at fracture ($\varepsilon_f$). Fig. 1 illustrates the completed test of the stainless steel coupon specimen Type A, where the extensometer was removed. Fig. 2 shows the test and static stress-strain curves of the coupon specimens.

## 3. Connection specimen design and labelling

### *3.1 Specimen design*

The aforementioned carbon steel and stainless steel were used to fabricate the bolted connection specimens. The carbon steel connection plates were machined from the thin sheets in the longitudinal direction, which were consistent with the coupon specimens. The stainless steel connection plates were cut from the tubes with nominal section dimensions of 50×20×1.5 in mm. The nominal width of the connection plates was kept as 50 mm.

The bolted connection specimens were designed in two types, single shear and double shear. The single shear specimens of were bolted with two steel plates and the double shear with three steel plates. Each connection type was designed by varying the material (steel grades), connection plate thickness ($t$), bolt diameters ($d$) and bolt numbers. For carbon steel, 15 series of bolted connection specimens were designed, with 9 series in single shear and 6 series in double shear, while for the stainless steel, 9 series were designed, with 4 in single shear and 5 in double shear. The connection plates were designed carefully such that the assembled connection specimens would fail mainly in the plate bearing by referring to the previous test results with carbon steel bolted connections conducted by Yan and Young [17-18] and stainless steel bolted connections conducted by Cai and Young [10]. It should be noted that this study focused mainly on the effects of loading conditions on the structural behavior of bolted connections.

Fig. 3 illustrates the dimensions and symbols for the bolted connection plates. It should be noted that, for stainless steel connection plates, the lip of 10 mm in height was designed in the overlapped connection region to prevent the out-of-plane curling [10], except for the middle plates in double shear connections. The length ($L$) of the connection plates was varied from 372 to 415 mm such that the assembled length of each bolted connection specimen was maintained at around 690 mm. High strength steel bolts with Grade 12.9 and stainless steel A4-80 bolts [10] were used to assemble the carbon steel and stainless steel plates, respectively. Standard steel washers on both sides and the corresponding nuts based on the bolt sizes were used in the connection specimens. The nominal diameter of the bolt hole ($d_o$) followed the carbon steel standards [11-12] and stainless steel standards [14-15], where $d_o = d + 1$ if $d$ is smaller than 12 mm, otherwise $d_o = d + 2$. The bolts were hand-tightened to a torque of approximately 10 Nm in the fabrication. Similar criteria were used by Rogers and Hancock [2], and Cai and Young [10]. The end distance, from the centre of the bolt hole to the end of the connection plate, was kept as $3d_o$ for the single shear and $5d_o$ for the double shear, so that the tearout failure could be avoided. The spacing between the centres of the two bolt holes was kept as $3d_o$. The spacing in the connected part of the carbon steel and stainless steel bolted connections could satisfy the requirements specified in the carbon steel standards [11-13] and the stainless steel specifications [14-16].

### *3.2 Specimen labeling*

Tables 2-6 show the labelling of the specimens in this study. The connection specimen was identified by the label indicating the connection type, material, bolt number and bolt diameter ($d$). The label of each connection specimen had four or five segments, depending on the connection types of single shear or double shear. It should be noted that the carbon steel of grades G450 and G500 having the nominal thicknesses of 1.90 mm and 1.20 mm, respectively, and the austenitic stainless steel EN 1.4301 and lean duplex stainless steel EN 1.4162 were shortened by A and L, respectively.

For examples of specimens “S-120-190-1-10”, “S-A-2-8” and “D-L-1-12”, the first segment indicates the connection type, “S” for single shear and “D” for double shear. The following segment shows the material of the connection specimen, where “120” and “190” mean the carbon steel 1.20 mm G500 and 1.90 mm G450, respectively; and the “A” and “L” are short for austenitic and lean duplex stainless steel, respectively. If it is a carbon steel connection specimen in single shear, there are two segments that indicate the material of the two connection plates; otherwise, there is only one segment indicating the material of the connection plates as they are identical. The following number indicates the bolt number used in the specimen, where “1” means one bolt, and “2” for two bolts arranged parallel to the loading direction; The last part of the label shows the nominal diameter ($d$) of the bolt, where “8” stands for $d$ = 8 mm, “10” means $d$ = 10 mm and “12” means $d$ = 12 mm.

## 4. Test rig and operation

### *4.1 General*

The carbon steel and stainless steel bolted connection specimens were tested in an MTS machine. The elongation of the specimen was captured by the average readings of the two linear variable displacement transducers (LVDTs) during the test. The LVDTs were assembled in a frame that covered a distance of 200 mm in the middle part of the specimen. A length of 65 mm at each end of the specimen was assembled into the gripping apparatus. The gripping apparatus was designed purposely such that the tensile loading was applied either through the shear plane of the specimens in single shear or concentrically loaded for the specimens in double shear [10]. The gripping apparatus was pinned to the steel blocks that were subsequently fixed to the grips of the testing machine. Clips linked with iron wire were used to prevent the extent of out-of-plane curling in the carbon steel bolted connection specimens [17]. Loading was applied onto the connection specimen by driving the actuator of the testing machine. The applied load and the readings of LVDTs were recorded regularly in a data acquisition system. The schematic views of the test setup are detailed in Cai and Young [10]. Fig. 4 illustrates a typical test setup for Specimen S-A-1-12.

*4.2 Monotonic Tests*

A series of monotonic tests on the carbon steel and stainless steel bolted connection specimens were conducted as a bench mark in this study. In the monotonic test, the bolted connection specimen was subjected to a constant specified loading rate throughout the test. The constant loading rates of 1.0 mm/min and 1.5 mm/min were used for the carbon steel and stainless steel bolted connections, respectively. A higher loading rate was applied to the stainless steel connection specimens due to the fact that the ductility of stainless steel is much higher than that of carbon steel, as reflected in the material properties shown in Table 1. The 15 monotonic tests of carbon steel bolted connections subjected to the constant loading rate of 1.0 mm/min and, 9 monotonic tests of stainless steel bolted connections subjected to the constant loading rate of 1.5 mm/min were conducted in this study.

*4.3 Loading, unloading and re-loading tests*

The carbon steel and stainless steel bolted connection specimens were subjected to the loading, unloading and re-loading processes. These processes are referred as cyclic loading processes in this paper. In each cycle, the specimen was first loaded using the displacement control method and then unloaded using the load control method. The specimen was loaded by driving the actuator of the testing machine for a pre-determined displacement ($\Delta_c$), e.g., 0.3 mm per cycle. In this step, the displacement control method was used with the same loading rate as that used in the monotonic test, i.e., 1.0 mm/min for the carbon steel specimens and 1.5 mm/min for the stainless steel specimens. After that, the specimen was unloaded to a small load level of 0.2 kN in 5 to 20 seconds using the load control method. A longer time was set to unload the specimen at a higher load level. This completed one cycle of the loading process in the cyclic test. It should be noted that there is no specified requirements for the value of $\Delta_c$. Generally, the values $\Delta_c$ of 0.3 mm and 0.5 mm were used for carbon steel and stainless steel in this study, respectively. The specimen was re-loaded by driving the actuator for another displacement ($\Delta_c$) for the next cycle, where the same loading rate as that in the previous step was used by displacement control. Generally, the test was conducted until the failure of the specimen or the load dropped over 10% of the ultimate load. The typical testing curves by the cyclic loading processes and by the monotonic test are illustrated in Fig. 5.

## 5. Connection test results

In total, 50 tests of carbon steel and stainless steel bolted connection specimens were conducted, including two repeated cyclic tests, where reduced pre-determined displacements ($\Delta_c$) were used (See Table 4). The bolted connection specimens were divided by the two connection types, i.e., single shear and double shear. The test results for the carbon steel bolted connections are shown in Tables 2 and 3, while those for the stainless steel bolted connections are presented in Tables 4 and 5. The $P_1$ and $u_1$ represent the ultimate loads and the elongation corresponding to ultimate loads obtained from the monotonic tests, while $P_2$ and $u_2$ are those obtained from the cyclic tests. In each table, the results obtained from the monotonic tests and cyclic tests (loading, reloading and un-loading processes) are presented, including the failure modes of the specimens. The connection elongation ($u$) was measured by the average readings from the two LVDTs. The measured thicknesses ($t_m$) of the bolted connection specimens are also reported, in Tables 2-5. For the bolted connection specimens in single shear, the measured smaller thicknesses of the connection plates are reported, while for those in double shear, the measurements refer to internal steel plates. Figs. 6-7 exemplify the load-elongation curves for the carbon steel single shear specimen series S-120-120-1-10 and S-120-120-2-6, respectively. Figs. 8-9 plot those of the carbon steel double shear specimen series D-190-1-8 and D-120-2-6, respectively. The tested curves for the stainless steel specimen series S-A-1-10 and S-A-1-12 are shown in Figs. 10-11, respectively. The vertical axes of the figures plots the loads applied on the specimens while the horizontal show the elongation of the specimen obtained from the two LVDTs.

## 6. Comparison of test results with design predictions

### *6.1 General*

Design rules for cold-formed carbon steel bolted connections are provided in the current specifications, including the Australian/New Zealand Standard (AS/NZS-4600) [11], Eurocode3 - Design of Steel Structures - Part 1.3 (EC3-1.3) [12] and the North American Specification (NAS) [13]. The design rules for stainless steel bolted connections are provided in the following specifications, i.e., the American Society of Civil Engineers Specification (ASCE) [14], the AS/NZS-4673 [15] and EC3-1.4 [16]. It should be noted that the EC3-1.4

[16] mainly refers to the design rules in EC3-1.8 [37]. The design equations for stainless steel bolted connection in the ASCE [14] are identical to those in the AS/NZS-4673 [15]. Hence, the predictions for stainless steel bolted connections by ASCE [14] and AS/NZS-4673 [15] are identical. The aforementioned design specifications were used to calculate the nominal strengths (unfactored design strengths) of the carbon steel and stainless steel bolted connection specimens in this study.

Different failure modes for carbon steel and stainless steel bolted connections are specified in the design specifications. Different failure modes are associated with the different design equations. Hence, the minimum nominal strength is taken as the predicted strength, and correspondingly the predicted failure mode for a connection specimen. The differences of the design equations for different failure modes and the differences among the design specifications are discussed by Yan and Young [17] for carbon steel bolted connections, and by Cai and Young [10] for stainless steel bolted connections. In this study, the results obtained from the monotonic tests were compared with those predicted by the aforementioned design codes for carbon steel [11-13] and stainless steel [14-16]. The monotonic test results serve as a bench mark for further analysis and discussions on the structural behavior of connections subjected to the loading, unloading and re-loading processes.

### *6.2 Ultimate loads*

The symbols of $P_{AS/NZS}$, $P_{EC3\text{-}1.3}$, $P_{NAS}$, $P_{ASCE}$ and $P_{EC3\text{-}1.4}$ represent the nominal strengths (unfactored design strengths) predicted by AS/NZS [11], EC3-1.3 [12], NAS [13], ASCE [14] and EC3-1.4 [16], respectively. The test strengths were compared with the predicted strengths. Noted that bolt shear failure (BS) was deliberately avoided in the specimen design, and this failure mode was not observed in the test results, except for specimen Series S-190-190-2-6 as shown in Table 2. The test strengths of the specimen Series S-190-190-2-6 were not included in the comparison due to the actual material properties of the bolts were not obtained.

Tables 6-7 show the comparisons between the test strengths and the predicted strengths for the carbon steel and stainless steel bolted connections, respectively. It is shown that the AS/NZS [11], EC3-1.3 [12] and NAS [13] generally provide conservative predictions for the carbon steel bolted connections, where the AS/NZS [11] and EC3-1.3 [12] provide the least conservative and most conservative predictions, respectively, with the mean values of $P_1/P_{AS/NZS}$ = 1.02 and $P_1/P_{EC3\text{-}1.3}$ = 1.31. However, the NAS (2016) provides the least scattered predictions, i.e., with the smallest value of coefficient of variation (COV), as shown in Table 6 for carbon steel bolted connections. It should be noted that predictions by EC3-1.3 [12] are conservative for all carbon steel bolted connections, as the values of $P_1/P_{EC3\text{-}1.3}$ are all larger than 1.00 (see Table 6). While for stainless steel bolted connections (see Table 7), both the ASCE [14] and EC3-1.4 [16] provide conservative predictions for all the connection tests. This may be due to the reason that the design rules in the current stainless steel design specifications [14-16] are mainly based on the rules of carbon steel with small modifications [8].

### *6.3 Failure modes*

The failure mode associated with the minimum nominal strength for each specimen was taken as the predicted failure mode. The predicted failure modes for the carbon steel and stainless steel bolted connections are shown in Tables 6-7, respectively.

For carbon steel bolted connections, the predicted failure mode by AS/NZS [11], EC3-1.3 [12] and NAS [13] was bearing failure (B) for all single shear connection specimens, which is consistent with the failure mode obtained from the tests (see Table 2), except for specimen Series S-190-190-2-6 that failed in BS and were not included in the comparison. The predicted bearing failure (B) mode by EC3-1.3 [12] is also consistent with the test results for double shear connection specimens, which is more accurate that those predicted by AS/NZS [11] and NAS [13]. While for stainless steel single shear and double shear bolted connections (see Table 7), the failure mode predicted by the ASCE [14] was net section tension (NS) failure for all the specimens, which are generally inconsistent with the failure modes obtained from the tests. The failure modes predicted by the EC3-1.4 [16] are more consistent with the test results compared with those predicted by the ASCE [14].

## 7. Discussions

### *7.1 General*

The structural behavior of the connection specimens subjected to the loading, unloading and re-loading processes, which is referred to as cyclic tests in this paper were discussed. The test results obtained from the monotonic tests were used as a bench mark. The results obtained from the cyclic tests were compared with those obtained from the monotonic tests, including $P_2/P_1$, $u_2/u_1$ and the failure modes. These will be discussed further in the following sections.

### *7.2 Ultimate loads*

The comparisons between the $P_2/P_1$ for the single shear and double shear bolted connections of carbon steel are shown in Tables 2 and 3, respectively. The single shear bolted connection specimen Series S-190-190-2-6 was not included in the comparison, as the failure mode was changed from failure of bolt in shear (BS) in the monotonic test to failure of connection plate in bearing (B) in cyclic test. The ratios of $P_2/P_1$ were within the range of 0.92 to 1.11 for the single shear specimens, and within the range of 0.98 to 1.03 for the double shear. The mean values of $P_2/P_1$ for the single shear and double shear were 1.03 and 1.02, respectively, with the corresponding coefficients of variation (COV) of 0.065 and 0.021. This may indicate that the carbon steel bolted connection specimens subjected to cyclic loading processes had higher ultimate loads than those subjected to the monotonic loading process. However, for the stainless steel bolted connections, the ratios of $P_2/P_1$ were smaller than 1.00 for the single shear and double shear specimens, except for specimen Series D-L-1-12 with $P_2/P_1$ = 1.03. The mean values of $P_2/P_1$ for the single shear and double shear were 0.98 and 0.99, respectively, with the corresponding COV of 0.010 and 0.027. This may have been because the unloading processes in the cyclic tests allowed the redistribution of critical regions within the grain of the material, which improved the load bearing capacity of the specimen of less ductile material properties. Note that the ductility of stainless steel was much higher than that of carbon steel, as mentioned in Section 4.2. The comparison of ultimate loads obtained from monotonic and cyclic tests for bolted connections of carbon steel and stainless steel are shown in Figs. 16 and 17, respectively.

### *7.3 Ultimate elongations*

The elongations ($u$) corresponding to the ultimate loads ($P$) for the carbon steel bolted connection specimens are presented in Table 2-5, where $u_1$ and $u_2$ indicate the results from the monotonic tests and cyclic tests, respectively. Similar to the discussions in Section 6.2, the specimen Series S-190-190-2-6 was not included in the comparison due to the change of failure modes. The ratios of $u_2/u_1$ are within the range of 0.87 to 1.26 for the single shear specimens, and within the range of 0.91 to 1.25 for the double shear. The mean values of $u_2/u_1$ were greater than 1.00 for both single shear and double shear bolted connections, e.g., 1.06 for the single shear with the corresponding COV of 0.121 as shown in Table 2. The values of COV for mean values of $u_2/u_1$ were much larger than those for the mean values of $P_2/P_1$, e.g., 0.121 compared with 0.065 for the single shear, as shown in Table 2.

Similarly, for stainless steel bolted connections, the mean values of $u_2/u_1$ are greater than 1.00 for both single shear and double shear bolted connections, e.g., 1.02 for single shear with the corresponding COV of 0.068 as shown in Table 4. The values of COV for the mean values of $u_2/u_1$ are also much larger than those for the mean values of $P_2/P_1$, e.g., 0.068 compared with 0.010 for the single shear, as shown in Table 4. However, the values of COV for stainless steel were smaller than those for the carbon steel in the bolted connections, e.g., 0.068 (See Table 4) compared with 0.121 (See Table 2) for the single shear. The mean values of $u_2/u_1$ were greater than 1.00 for both carbon steel and stainless steel bolted connections. This may indicate that the loading, unloading and re-loading processes in the cyclic tests generally delayed the bolted connection specimens of both carbon steel and stainless steel to reach the ultimate loads, when compared with those in the monotonic tests. This delayed ultimate loads may be due to the bolted connections were relaxed under the cyclic loading, i.e., at each un-loading process.

### *7.4 Failure modes*

The characteristics of different failure modes for carbon steel and stainless steel in monotonic tests are described by Yan and Young [17] and Cai and Young [18]. In this study, the failure modes of the carbon steel and stainless steel bolted connections obtained from the monotonic tests and cyclic tests are correspondingly presented in Tables 2-5. As mentioned in Section 3.1, the connection plates were designed carefully such that the assembled bolted connection specimens were mainly failed in plate bearing. Generally, bearing failure (B) of the connection plates was observed in all the bolted connection specimens. The specimen Series S-190-190-2-6 changed the failure modes from bolt shear (BS) failure to connection plate bearing failure (B). The specimen Series D-190-2-6 changed the failure modes from bearing failure (B) to net section tension failure (NS) of the connection plates. It may be concluded that the loading, unloading and re-loading processes in the cyclic tests had little effect on the failure mode of the carbon steel and stainless steel bolted connection specimens that were subjected to connection plate bearing failure in the monotonic tests. The bearing failure modes of the carbon steel specimen series D-120-1-8, D-190-1-10 are shown in Figs 12-13. The failure modes of the specimen Series D-190-2-6 are illustrated in Fig. 14. Fig. 15(a)-(b) shows the bearing failure mode of the stainless steel specimen Series D-A-1-10.

## 8. Conclusions

In this study, an experimental investigation was conducted on bolted connections of carbon steel and stainless steel subjected to monotonic loading and cyclic loading conditions. The connection specimens were fabricated from carbon steel grades 1.20 mm G500 and 1.90 mm G450, as well as cold-formed stainless steel types EN 1.4301 and EN 1.4162 with nominal thickness 1.50 mm. In total, 50 bolted connection specimens in single shear and double shear were tested. The connection specimens covered 15 cases in carbon steel and 9 cases in stainless steel. In the monotonic tests, a series of specimens was tested under a constant loading rate, while in the cyclic tests, the specimens having the same dimensions as those in the monotonic tests were subjected to loading, unloading and re-loading processes.

The results obtained from the monotonic tests were compared with those predictions calculated by using the carbon steel and stainless steel design specifications. Generally, it is shown that the ultimate loads predicted by the carbon steel and stainless steel design specifications are conservative, where the predictions by the stainless steel design specification are more conservative. The failure modes predicted by the carbon steel and stainless steel design specifications are generally in consistent with those obtained from the tests.

In addition, the results obtained from the cyclic tests were compared with those obtained from the monotonic tests, in terms of ultimate load, elongation corresponding to ultimate load as well as failure mode. It was found that the ultimate loads obtained from the cyclic tests were, on average, larger than those obtained from the monotonic tests for carbon steel bolted connections. This was in contrast to the compared results for stainless steel bolted connections. It was also found that the elongations corresponding to the ultimate loads obtained from the cyclic tests were, on average, larger than those obtained from the monotonic tests for both the carbon steel and stainless steel, which may indicate that the loading, unloading and re-loading processes in the cyclic tests generally delayed the bolted connection specimens to reach the ultimate loads. This may be due to the bolted connections were relaxed at each un-loading process. Generally, the failure modes in the cyclic tests were consistent with those in the monotonic tests for the same specimen series, where the specimens mainly failed in connection plate bearing.

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| Material | Type | Thickness | | Test curve | | Static curve | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $t$ (mm) | $t_m$ (mm) | $f_{0.2}$ MPa | $f_u$ MPa | $E$ GPa | $f_{0.2}$ MPa | $f_u$ MPa | $\varepsilon_u$ % | $\varepsilon_f$ % | $n$ |
| Carbon steel | G500 | 1.20 | 1.18 | 648 | 657 | 214 | 622 | 630 | 5.8 | 8.9 | 15 |
| | G450 | 1.90 | 1.85 | 502 | 534 | 212 | 486 | 511 | 8.2 | 13.9 | 14 |
| Stainless steel | EN 1.4301 | 1.50 | 1.46 | 437 | 692 | 199 | 403 | 647 | 50.4 | 56.9 | 6 |
| | EN 1.4162 | 1.50 | 1.45 | 714 | 858 | 200 | 681 | 800 | 19.5 | 38.6 | 10 |

**Table 1:** Material properties of carbon steel and stainless steel

| Specimen labelling | Monotonic | | | | Cyclic | | | | | Comparisons | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $t_m$ (mm) | $P_1$ (kN) | $u_1$ (mm) | Failure | $t_m$ (mm) | $\Delta_c$ (mm) | $P_2$ (kN) | $u_2$ (mm) | Failure | $P_2/P_1$ | $u_2/u_1$ |
| S-120-120-1-8 | 1.24 | 18.52 | 11.55 | B | 1.25 | 1.5 | 19.47 | 12.27 | B | 1.05 | 1.06 |
| S-120-120-1-10 | 1.22 | 19.72 | 9.42 | B | 1.24 | 1.5 | 21.21 | 11.88 | B | 1.08 | 1.26 |
| S-120-190-1-8 | 1.23 | 20.48 | 10.55 | B | 1.25 | 1.0 | 18.81 | 11.88 | B | 0.92 | 1.13 |
| S-120-190-1-10 | 1.24 | 22.15 | 11.25 | B | 1.24 | 0.3 | 24.60 | 11.26 | B | 1.11 | 1.00 |
| S-190-190-1-8 | 1.92 | 25.47 | 12.54 | B | 1.92 | 0.3 | 25.53 | 14.86 | B | 1.00 | 1.19 |
| S-190-190-1-10 | 1.91 | 27.74 | 12.34 | B | 1.91 | 0.3 | 30.48 | 11.91 | B | 1.10 | 0.97 |
| S-120-120-2-6 | 1.22 | 27.47 | 9.73 | B | 1.24 | 0.3 | 26.95 | 9.53 | B | 0.98 | 0.98 |
| S-120-190-2-6 | 1.22 | 28.70 | 8.55 | B | 1.24 | 0.3 | 28.23 | 7.48 | B | 0.98 | 0.87 |
| S-190-190-2-6 | 1.92 | 31.70 | 5.80 | BS | 1.92 | 0.3 | 35.34 | 14.47 | B | - | - |
| | | | | | | | | | Mean | 1.03 | 1.06 |
| | | | | | | | | | COV. | 0.065 | 0.121 |

**Table 2:** Test results and comparisons of carbon steel single shear bolted connections

| Specimen labelling | Monotonic | | | | Cyclic | | | | | Comparisons | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $t_m$ (mm) | $P_1$ (kN) | $u_1$ (mm) | Failure | $t_m$ (mm) | $\Delta_c$ (mm) | $P_2$ (kN) | $u_2$ (mm) | Failure | $P_2/P_1$ | $u_2/u_1$ |
| D-120-1-8 | 1.22 | 21.91 | 8.68 | B | 1.23 | 0.3 | 21.84 | 10.89 | B | 1.00 | 1.25 |
| D-120-1-10 | 1.23 | 24.79 | 10.18 | B | 1.23 | 0.3 | 25.28 | 10.48 | B | 1.02 | 1.03 |
| D-190-1-8 | 1.92 | 33.54 | 12.97 | B | 1.92 | 0.3 | 34.36 | 13.85 | B | 1.02 | 1.07 |
| D-190-1-10 | 1.92 | 38.39 | 14.01 | B | 1.93 | 0.3 | 37.65 | 12.72 | B | 0.98 | 0.91 |
| D-120-2-6 | 1.23 | 30.25 | 7.54 | B | 1.24 | 0.3 | 31.29 | 7.23 | B | 1.03 | 0.96 |
| D-190-2-6 | 1.91 | 41.51 | 7.67 | B | 1.93 | 0.3 | 42.92 | 8.99 | NS | 1.03 | 1.17 |
| | | | | | | | | | Mean | 1.02 | 1.07 |
| | | | | | | | | | COV. | 0.021 | 0.122 |

**Table 3:** Test results and comparisons of carbon steel double shear bolted connections

| Specimen labelling | Monotonic | | | | Cyclic | | | | | Comparisons | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $t_m$ | $P_1$ | $u_1$ | Failure | $t_m$ | $\Delta_c$ | $P_2$ | $u_2$ | Failure | $P_2/P_1$ | $u_2/u_1$ |
| | (mm) | (kN) | (mm) | | (mm) | (mm) | (kN) | (mm) | | | |
| S-A-1-10 | 1.44 | 29.94 | 18.09 | B | 1.42 | 2.0 | 29.53 | 19.46 | B | 0.99 | 1.08 |
| S-A-1-10# | - | - | - | - | 1.41 | 0.7 | 29.12 | 17.98 | B | 0.97 | 0.99 |
| S-A-1-12 | 1.45 | 34.75 | 20.47 | B | 1.40 | 2.0 | 33.99 | 19.83 | B | 0.98 | 0.97 |
| S-A-1-12# | - | - | - | - | 1.42 | 0.5 | 33.44 | 19.74 | B | 0.96 | 0.96 |
| S-L-1-12 | 1.47 | 41.24 | 15.64 | B | 1.46 | 2.0 | 40.76 | 17.67 | B | 0.99 | 1.13 |
| S-A-2-8 | 1.46 | 38.24 | 19.27 | B | 1.42 | 0.5 | 37.03 | 18.66 | B | 0.97 | 0.97 |
| | | | | | | | | | Mean | 0.98 | 1.02 |
| | | | | | | | | | COV. | 0.010 | 0.068 |

Note: # Repeated test.

**Table 4:** Test results and comparisons of stainless steel single shear bolted connections

| Specimen labelling | Monotonic | | | | Cyclic | | | | | Comparisons | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $t_m$ | $P_1$ | $u_1$ | Failure | $t_m$ | $\Delta_c$ | $P_2$ | $u_2$ | Failure | $P_2/P_1$ | $u_2/u_1$ |
| | (mm) | (kN) | (mm) | | (mm) | (mm) | (kN) | (mm) | | | |
| D-A-1-10 | 1.42 | 34.52 | 18.34 | B | 1.41 | 0.5 | 34.29 | 19.60 | B | 0.99 | 1.07 |
| D-A-1-12 | 1.41 | 37.86 | 19.37 | B | 1.41 | 0.5 | 36.94 | 18.58 | B | 0.98 | 0.96 |
| D-L-1-12 | 1.46 | 44.38 | 10.33 | B | 1.44 | 0.5 | 45.57 | 11.45 | B | 1.03 | 1.11 |
| D-A-2-8 | 1.43 | 42.08 | 16.25 | B | 1.44 | 0.5 | 40.13 | 14.73 | B | 0.95 | 0.91 |
| D-L-2-8 | 1.45 | 52.96 | 7.52 | NS | 1.46 | 0.5 | 51.88 | 7.88 | NS | 0.98 | 1.05 |
| | | | | | | | | | Mean | 0.99 | 1.02 |
| | | | | | | | | | COV. | 0.027 | 0.081 |

**Table 5:** Test results and comparisons of stainless steel double shear bolted connections

| Specimen labelling | AS/NZS [11] | | EC3-1.3 [12] | | NAS [13] | |
|---|---|---|---|---|---|---|
| | $P_1/P_{AS/NZS}$ | Failure | $P_1/P_{EC3\text{-}1.3}$ | Failure | $P_1/P_{NAS}$ | Failure |
| S-120-120-1-8 | 0.99 | B | 1.19 | B | 1.10 | B |
| S-120-120-1-10 | 0.86 | B | 1.04 | B | 0.95 | B |
| S-120-190-1-8 | 1.10 | B | 1.33 | B | 1.22 | B |
| S-120-190-1-10 | 0.95 | B | 1.14 | B | 1.05 | B |
| S-190-190-1-8 | 1.08 | B | 1.30 | B | 1.08 | B |
| S-190-190-1-10 | 0.95 | B | 1.14 | B | 0.95 | B |
| S-120-120-2-6 | 0.99 | B | 1.20 | B | 1.10 | B |
| S-120-190-2-6 | 1.04 | B | 1.26 | B | 1.15 | B |
| S-190-190-2-6 | - | - | - | - | - | - |
| D-120-1-8 | 0.89 | B | 1.44 | B | 0.99 | B |
| D-120-1-10 | 0.97 | NS | 1.29 | B | 0.99 | NS |
| D-190-1-8 | 1.07 | B | 1.71 | B | 1.07 | B |
| D-190-1-10 | 1.18 | NS | 1.57 | B | 1.09 | NS |
| D-120-2-6 | 1.07 | NS | 1.31 | B | 1.11 | NS |
| D-190-2-6 | 1.16 | NS | 1.42 | B | 1.08 | NS |
| Mean | 1.02 | | 1.31 | | 1.07 | |
| COV | 0.094 | | 0.137 | | 0.072 | |

**Table 6:** Comparison of test strengths with predictions for carbon steel bolted connections

| Specimen labelling | ASCE [14] | | EC3-1.4 [16] | |
|---|---|---|---|---|
| | $P_1/P_{ASCE}$ | Failure | $P_1/P_{EC3\text{-}1.4}$ | Failure |
| S-A-1-10 | 1.65 | NS | 2.35 | B |
| S-A-1-12 | 1.71 | NS | 2.26 | B |
| S-L-1-12 | 1.62 | NS | 1.95 | B |
| S-A-2-8 | 1.59 | NS | 1.30 | NS |
| D-A-1-10 | 1.55 | NS | 1.65 | B |
| D-A-1-12 | 1.85 | NS | 1.52 | B |
| D-L-1-12 | 1.29 | NS | 1.27 | B |
| D-A-2-8 | 1.78 | NS | 1.46 | NS |
| D-L-2-8 | 1.31 | NS | 1.36 | NS |
| Mean | 1.59 | | 1.68 | |
| COV | 0.121 | | 0.245 | |

**Table 7:** Comparison of test strengths with predictions for stainless steel bolted connections

**Fig. 1:** Coupon test of stainless steel Type A (EN 1.4301)

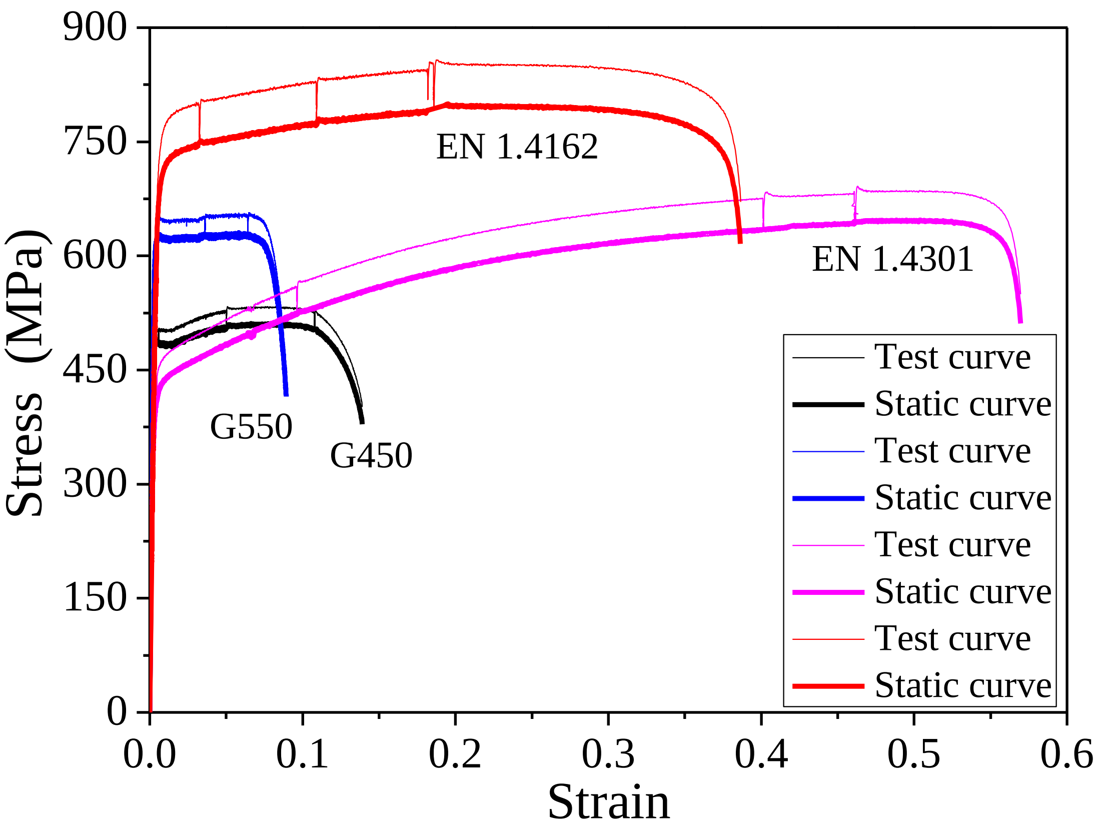
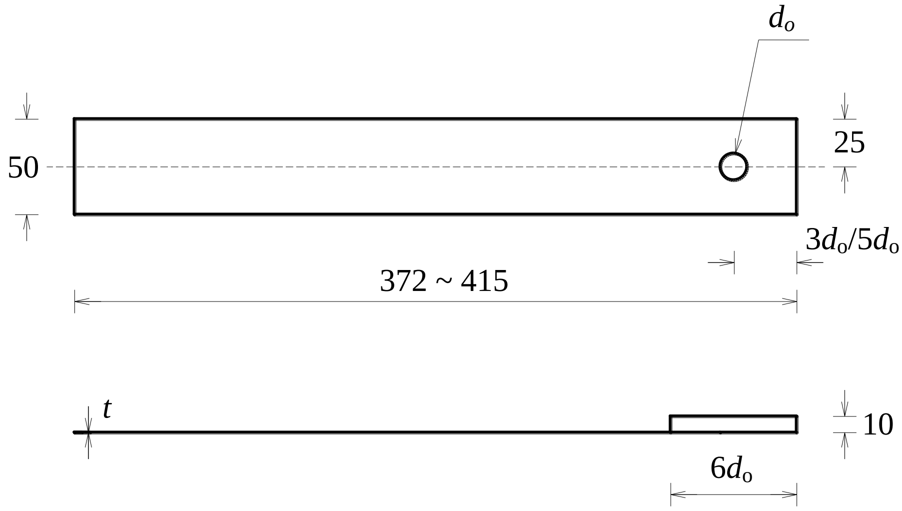
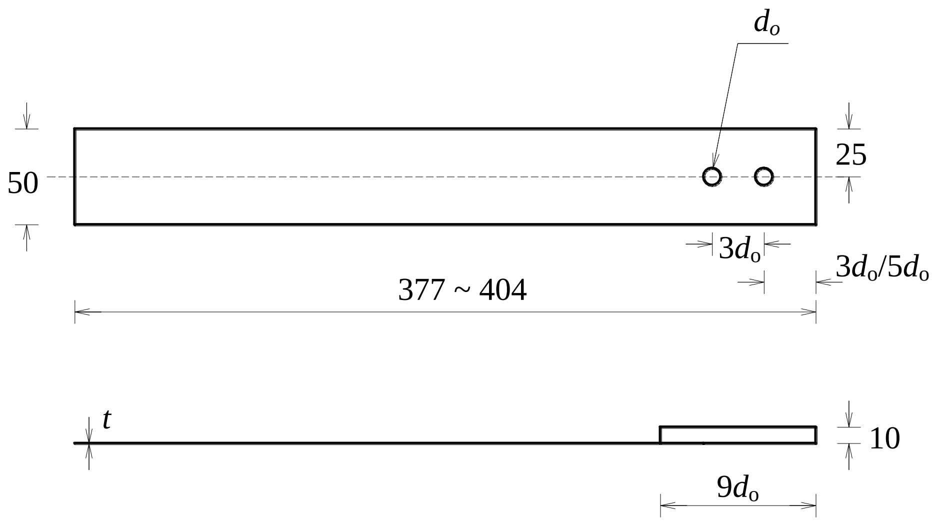



**Fig. 2:** Stress-strain curves of coupon tests




(a) Plate with one bolt hole




(b) Plate with two bolt holes

**Fig. 3**: Dimensions (mm) and symbols for bolted connection plates

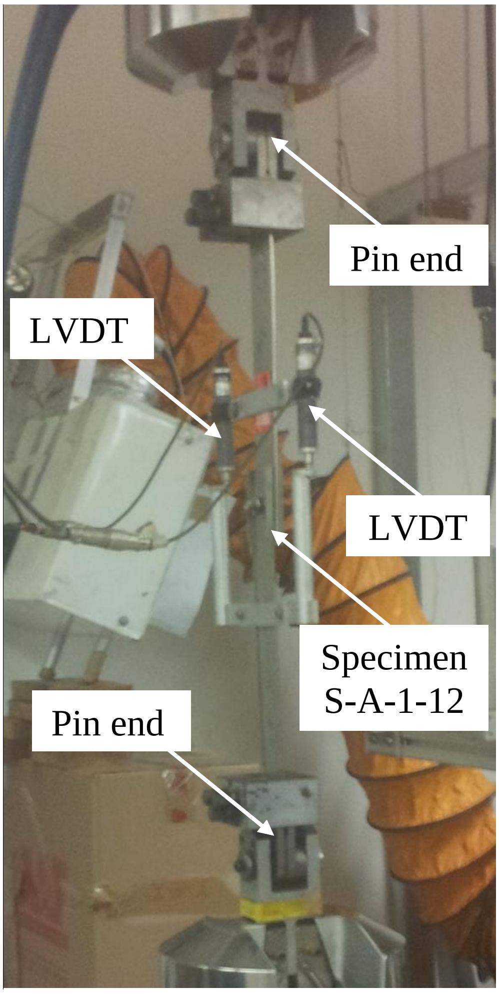



**Fig. 4:** Test setup of stainless steel single shear bolted connection specimen

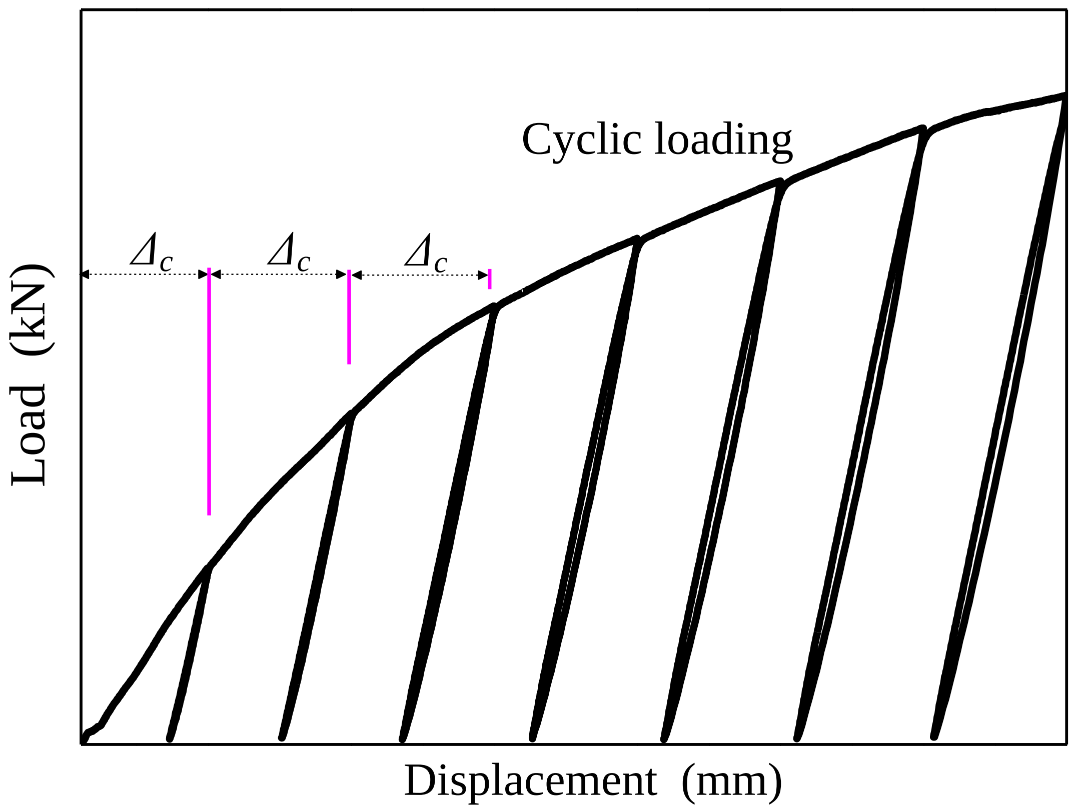



**Fig. 5:** Typical testing curve of cyclic loading

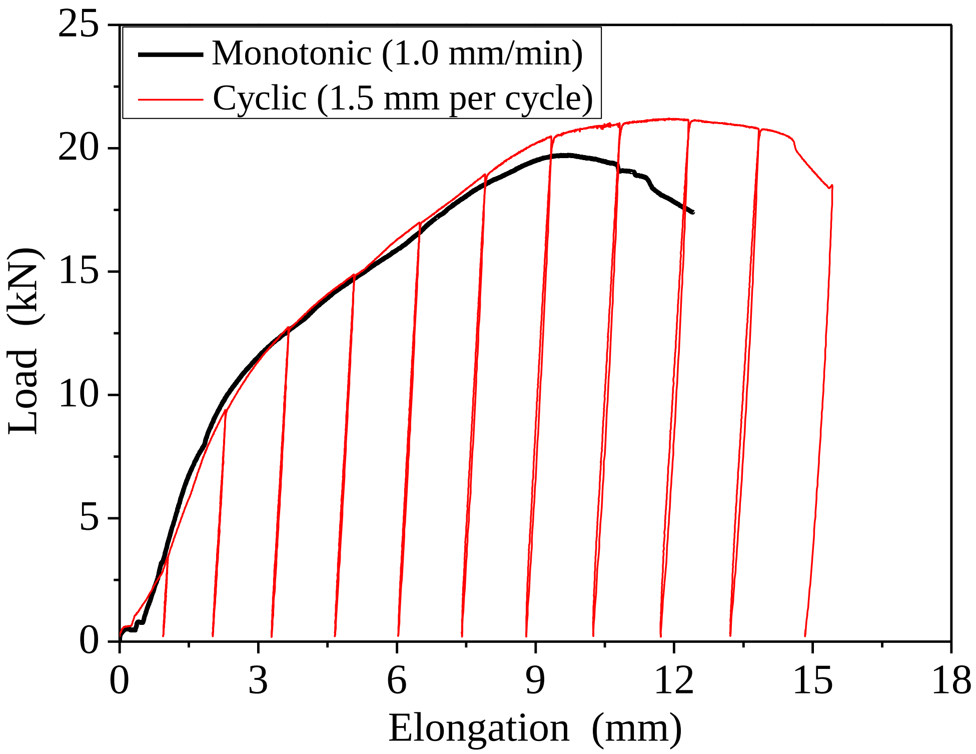



**Fig. 6:** Load-elongation curves for specimen Series S-120-120-1-10

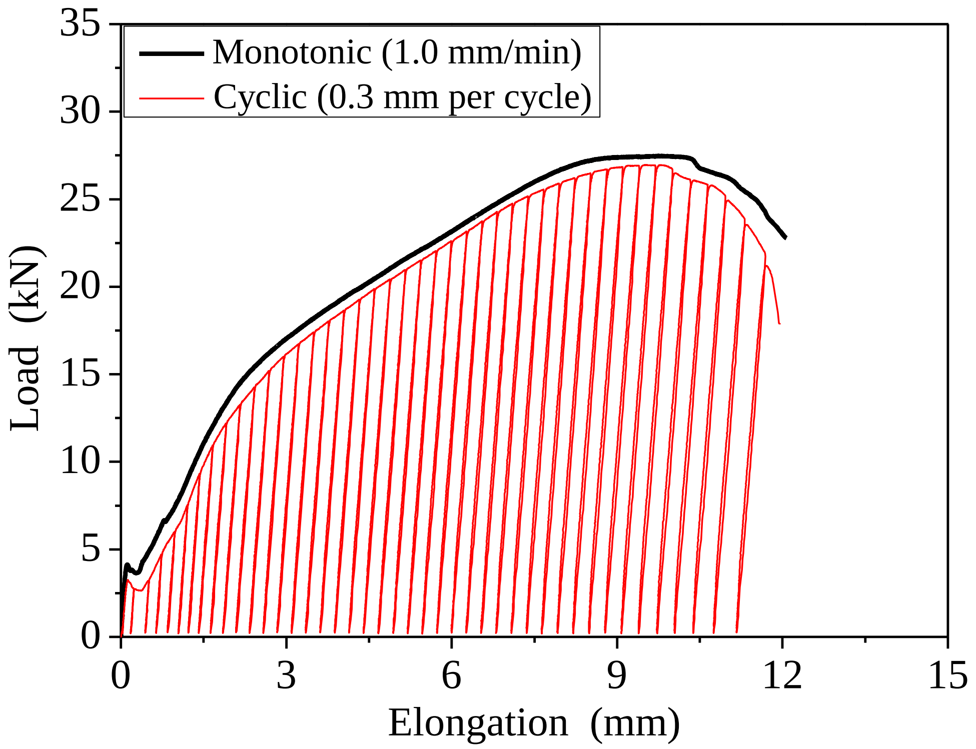



**Fig. 7:** Load-elongation curves for specimen Series S-120-120-2-6

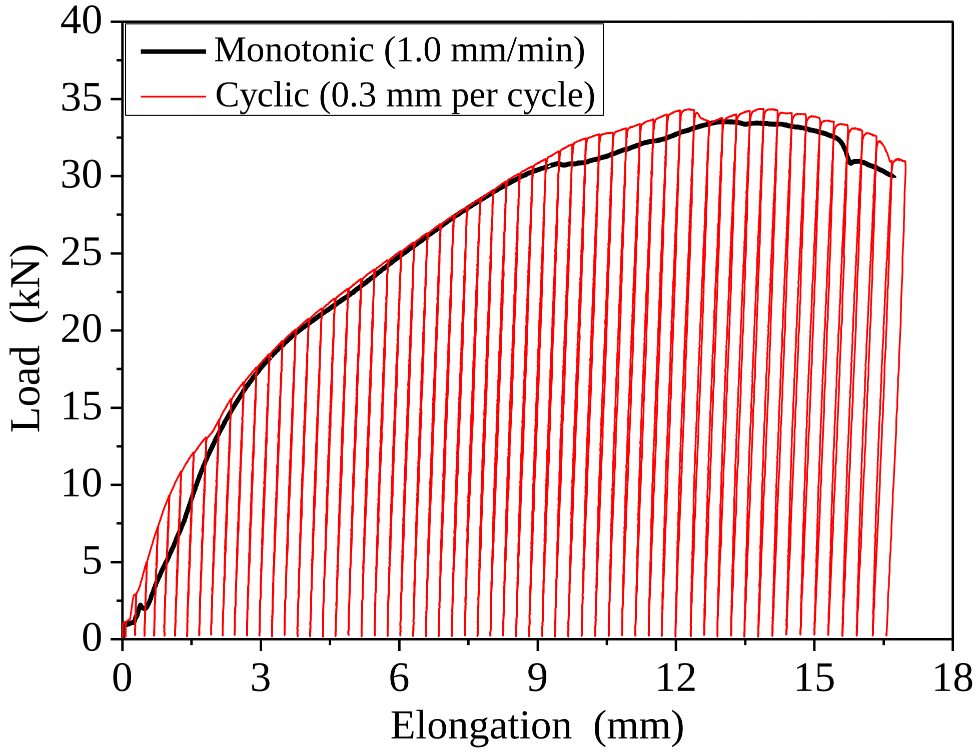



**Fig. 8:** Load-elongation curves for specimen Series D-190-1-8

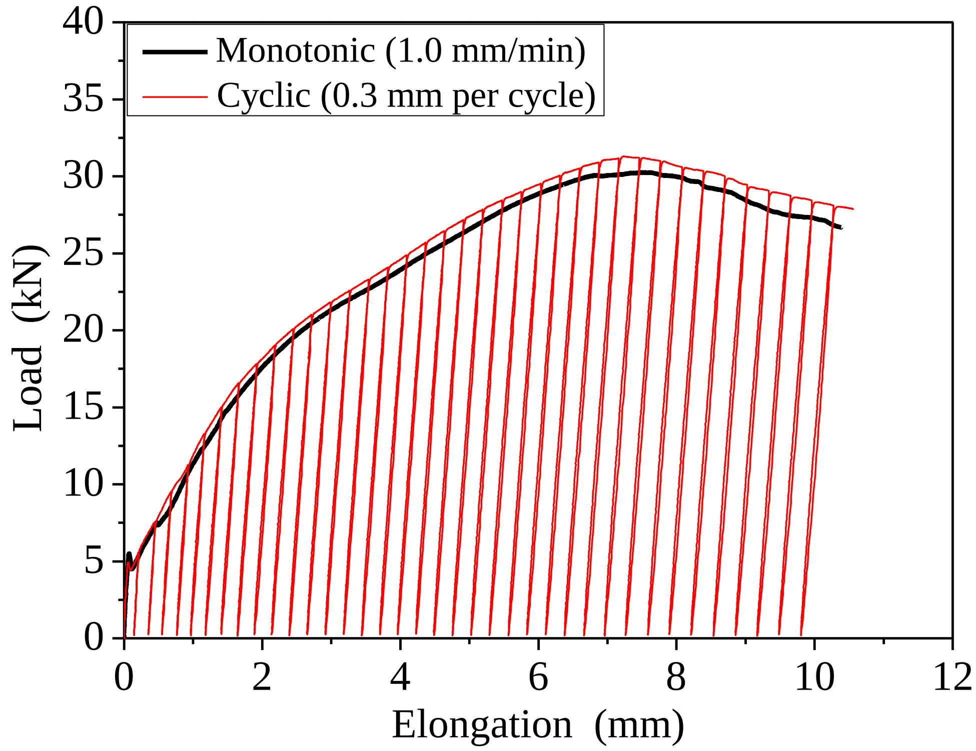



**Fig. 9:** Load-elongation curves for specimen Series D-120-2-6

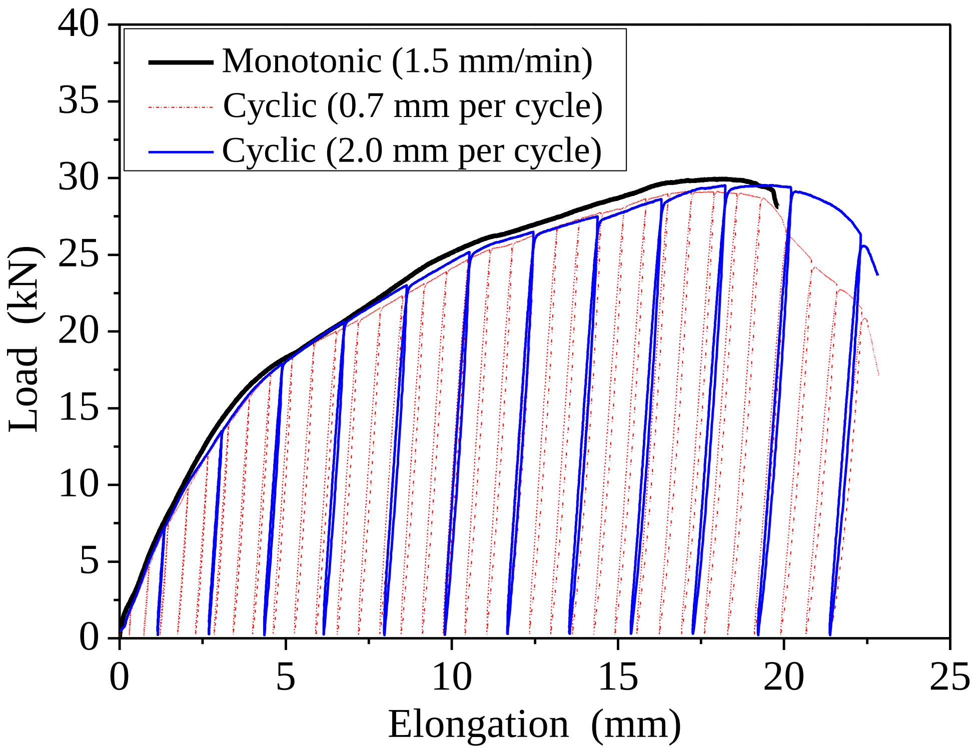



**Fig. 10:** Load-elongation curves for specimen Series S-A-1-10

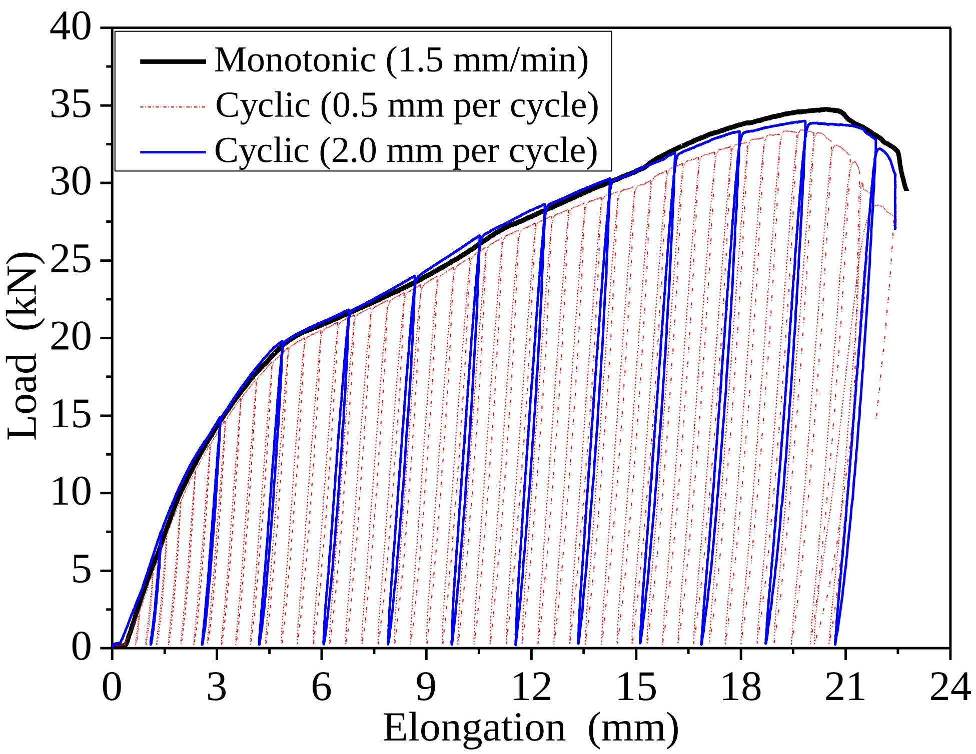



**Fig. 11:** Load-elongation curves for specimen Series S-A-1-12

(a) Monotonic test (1.0 mm/min)

(b) Cyclic test ($\Delta_c$ = 0.3 mm)

**Fig. 12:** Bearing failure mode of specimen Series D-120-1-8

(a) Monotonic test (1.0 mm/min)

(b) Cyclic test ($\Delta_c$ = 0.3 mm)

**Fig. 13:** Bearing failure mode of specimen Series D-190-1-10

(a) Monotonic test (1.0 mm/min)

(b) Cyclic test ($\Delta_c$ = 0.3 mm)

**Fig. 14:** Bearing and net section tension failure modes of specimen Series D-190-2-6

(a) Monotonic test (1.5 mm/min)

(b) Cyclic tests ($\Delta_c$ = 0.3 mm)

**Fig. 15:** Bearing failure mode of specimen Series D-A-1-10

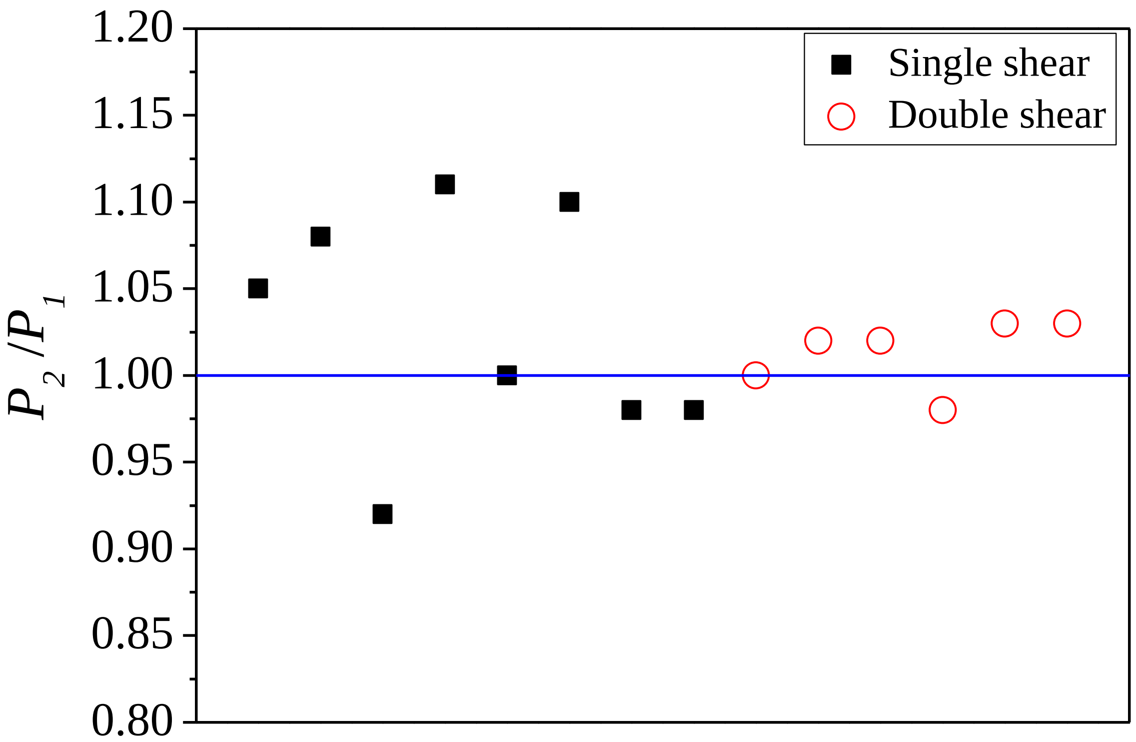



**Fig. 16:** Comparison of ultimate loads obtained from monotonic and cyclic tests for carbon steel bolted connections

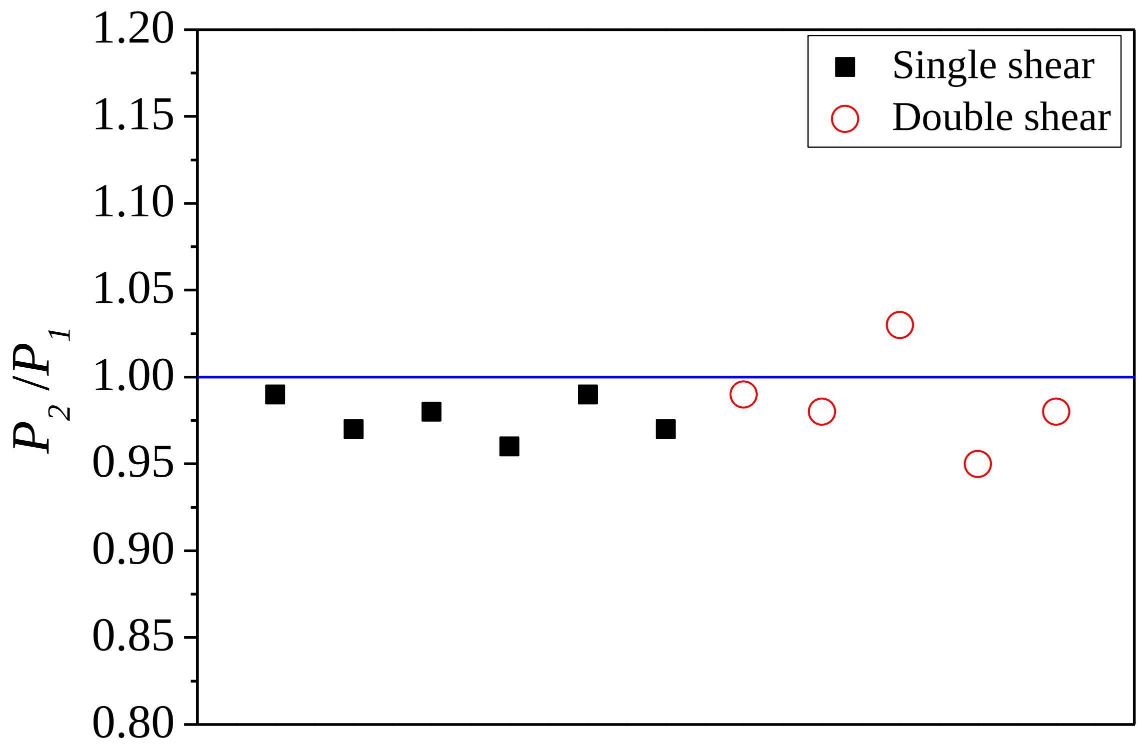



**Fig. 17:** Comparison of ultimate loads obtained from monotonic and cyclic tests for stainless steel bolted connections