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Measurement of Slip Coefficient for Grade ASTM A588 Steel

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ABSTRACT

An investigation of the slip coefficient of Grade ASTM A588 steel was carried out using a total of 99 tension double lap splice joints. The test parameters included the effect of steel heat, faying surface condition, level of bolt pretension, bolt hole diameter (regular size and oversize) and bolt hole fabrication method on the slip coefficient. The test specimens consisted of 1/2-in. or 5/8-in. main plates with double splice plates of the same thickness as the main plates. One end of the test specimens was prepared with a one-bolt joint and the other end with two bolts. Pre-calibrated centre-hole load cells were used to measure the bolt pretension directly, which was introduced by turning the nut. The double lap splice joints were loaded in axial tension and the load and deformation were continuously monitored in the test until either bolt shear failure or plate bearing failure took place.

The test results showed no significant effect of the level of bolt pretension *per se*, bolt hole fabrication, or bolt hole diameter on the slip coefficient. However, the test results suggest that the preparation of the faying surface has a significant effect on the slip coefficient; as-received faying surfaces with loose particles removed before joint assembly showed a lower slip coefficient than degreased faying surfaces. The steel heat also seems to affect the slip coefficient.

The results were close to the mean slip coefficient proposed in *Specification for Structural Joints Using ASTM A325 or A490 Bolts* [RCSC 2004] for clean mill scale faying surfaces, but showed a substantially higher slip coefficient than determined in another study on A588 steel [Yura *et al.* 1981].

ACKNOWLEDGEMENTS

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

AISC	American Institute of Steel Construction INC.
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CISC	Canadian Institute of Steel Construction
CSA	Canadian Standards Association
DOF	Degrees of Freedom
LVDT	Linear Variable Differential Transformer
RCSC	Research Council on Structural Connections
U of A	University of Alberta
UTM	Universal Testing Machine

SYMBOLS

A_b	nominal cross sectional area of a bolt
B_r	factored bearing resistance
$B_{r,predicted}$	predicted bearing failure load
C	resistance adjustment factor
D	dead load
d	diameter of the bolt(s)
E	modulus of elasticity
F_u	ultimate strength
F_u	specified minimum tensile strength of the bolt(s) or connected material
F_y	yield strength
h_{sc}	oversize hole reduction factor
L	live load
m	number of shear planes
N_b	number of bolts

N_s	number of slip planes
P_{slip}	slip load determined as outlined in Section 3.2
$\overline{Q}$	mean value of total load effect
$\tilde{Q}$	nominal total load effect
$\overline{R}$	mean resistance value
$\tilde{R}$	nominal resistance value
R_{slip}	slip resistance
T_b	total bolt pretension
$T_{b,i}$	pretension in bolt *i*
V_A	bolt area coefficient of variation
V_D	dimension coefficient of variation
V_Q	coefficient of variation of the total load effect
V_R	coefficient of variation of the resistance
V_d	bolt diameter coefficient of variation
V_m	material property coefficient of variation
V_p	design equation coefficient of variation
V_r	factored bolt shear resistance of the connection
$V_{r,predicted}$	predicted bolt shear failure load
V_t	specimen thickness coefficient of variation
t	thickness of the connected material
α	level of significance; separation factor in reliability analysis
α'	load factor
α_Q	load effect separation factor
α_R	resistance separation factor
β	safety index
ε_{SH}	strain at beginning of strain hardening

ε_r	strain at failure
μ	slip coefficient between the faying surfaces
μ_{av}	mean slip coefficient
ρ_A	bolt area bias coefficient
ρ_D	dimension bias coefficient
ρ_Q	load effect bias coefficient
ρ_R	resistance bias coefficient
ρ_d	bolt diameter bias coefficient
ρ_m	material property bias coefficient
ρ_p	bias coefficient or professional factor
ρ_t	specimen thickness bias coefficient
σ	standard deviation
$\sigma_c^{\ 2}$	combined population variance of two samples
ϕ	resistance factor
ϕ_b	resistance factor for bolts
ϕ_{br}	resistance factor for bearing of bolts on steel

1. INTRODUCTION

The slip resistance of bolted connections is a function of the slip coefficient of the faying surfaces, the number of slip planes, and the total clamping force on the joint, which is equal to the sum of the pretension in all the bolts. These parameters appear directly in the following equation used to calculate the slip resistance of a bolted joint:

$$R_{slip} = \mu \, N_s \sum_{i=1}^{N_b} T_{b,i} \tag{1}$$

where R_{slip} : slip resistance

μ : slip coefficient for the faying surfaces

N_s : number of slip planes

N_b : number of bolts

$T_{b,i}$: pretension in bolt *i*

The bolt pretension is usually assumed to be identical in all bolts, which allows Equation (1) to be simplified to

$$R_{slip} = \mu \, N_s \, N_b \, T_b \tag{2}$$

Equation (2) shows that for a given joint geometry, i.e., number of slip planes and bolts are known, the slip resistance of the joint depends solely on the slip coefficient, μ, and the bolt pretension, T_b. The *Specification for Structural Joints Using ASTM A325 or A490 Bolts* [RCSC 2004], subsequently referred to as the RCSC Specification, requires that the minimum bolt pretension, T_b, be equal to at least 70% of the minimum tensile strength of the bolt. The slip coefficient, μ, is provided in the RCSC Specification for three faying surface conditions: 1) uncoated clean mill scale steel surfaces or surfaces with Class A coatings on blast-cleaned steel, for which $\mu = 0.33$; 2) uncoated blast-cleaned steel surfaces or surfaces with Class B coatings on blast-cleaned steel, for which $\mu = 0.50$; and 3) roughened hot-dip galvanized surfaces, for which $\mu = 0.35$. These values have been adopted in the current edition of CAN/CSA–S16–01 [CSA 2001], whereas the AISC Specification [AISC 2005] has grouped Class A and Class C surfaces together and uses a slip coefficient of 0.35 for both types of surfaces. These slip coefficients were determined through statistical analyses on a large number of slip test results, as summarized in Kulak *et al.* [1987].

According to the RCSC Specification, the slip coefficient is not a function of the type of steel. However, in one test program on ASTM Grade A588 steel with clean mill scale surfaces the mean slip coefficient obtained was only 0.23 [Yura *et al.* 1981]. This is substantially lower than the value of 0.33 specified in the current RCSC Specification. A588 steel is an atmospheric corrosion resistant steel (weathering steel), widely used in highway and railway bridges, where, because of fatigue considerations, bolted connections have to be designed as slip-critical. Furthermore, A588 steel satisfies the chemical and mechanical requirements of other structural steels, making A588 steel a logical substitute for other steels. Since A588 steel is used as a substitute to other structural grade steels without notice, it is implied that slip-critical connections with clean mill-scale should be designed with a slip coefficient of 0.23. This lower slip coefficient results in approximately 30% more bolts if the slip resistance governs the design. However, because only one set of A588 tests has been conducted, it was deemed necessary to carry out more slip tests on plates with A588 clean mill scale faying surfaces. Since the tests by Yura *et al.* [1981] on blast-cleaned A588 steel surfaces resulted in slip coefficients similar to those for other steel grades, no tests on blast-cleaned surfaces with other steels were carried out in the present study.

The current report presents additional slip tests on A588 steel plates carried out in the Structures Laboratory at the University of Alberta. Chapter 2 of the report outlines the experimental program. This is followed by a presentation of the test results in Chapter 3, which are then analyzed in Chapter 4. A summary with conclusions and recommendations for future work are presented in Chapter 5.

2. EXPERIMENTAL PROGRAM

2.1 Introduction

The experimental program was designed to provide a statistically significant data set from which a statistical analysis could be conducted. Several parameters that might affect the slip coefficient of A588 steel faying surfaces were investigated. These are outlined in Section 2.2. Section 2.3 presents a description of the test set up used for all tests. The test matrix is presented in Section 2.4 and Section 2.5 describes the instrumentation used to determine the slip load and the bolt pretension.

2.2 Parameters Investigated

2.2.1 Introduction

According to the RCSC Specification, the slip resistance of a bolted connection with clean mill scale faying surfaces and a given geometry (number of slip planes and number and type of bolts and bolt hole clearance) is uniquely defined by equation (2). However, several investigations, summarized in Kulak *et al.* [1987], have shown that other parameters might affect the slip behaviour of a joint. Several of the more controversial ones were examined in this study and they are as follows:

- Steel heat (for a given grade);
- Condition of the so-called clean mill scale faying surfaces;
- Effect of level of bolt pretension on surface roughness;
- Bolt hole clearance;
- Fabrication method used for the bolt hole, i.e., drilled versus punched.

2.2.2 Steel Heat

Vasarhelyi and Chiang [1967] have shown that the slip coefficient varies slightly for different steels and steel heats. This has been attributed to the condition under which the mill scale forms and the chemical composition of the steel, which varies between heats. However, it does not seem to have any simple relation to the mechanical properties of the steel. Rather, it is affected by the steel making process, which is controlled by the individual mill. In order to include the possibility that the condition of the mill scale might affect the test results, in this program two sets of plates were ordered, each from a different mill. These two sets are differentiated by their respective plate thicknesses of 1/2-in. and 5/8-in.

2.2.3 Condition of Faying Surfaces

Most tests used to determine the slip coefficient presented in the RCSC Specification were conducted with surfaces wherein the loose mill scale and dirt was removed by light hand wire brushing and the grease was dispersed with a solvent [Kulak and Fisher 1985]. However, consultation with local steel fabricators revealed that often only light wire brushing is applied, which does not remove the water soluble oil used for hole drilling. It is often assumed that the oil-laden cutting fluid used in the drilling process will evaporate before the joints are assembled. For the tests conducted in the present study, the fabricator was instructed to deliver the plates as they would be prepared for any slip-critical connection, with the exception that any fabrication burrs be left in place. These were removed by the researchers once the plates were delivered. The researchers made sure that burr removal was done without damaging the condition of the mill-scale around the bolt holes. As was expected, the oil on the as-received plates was still present, especially around the bolt holes. In order to obtain consistent test results, it was decided to remove the oil using a solvent (a common glass cleaner), with the exception of some plates that were left in the as-received condition.

The plates were stored in stacks in the laboratory and tested within one month of delivery. No information concerning the storage before delivery could be retrieved.

2.2.4 Bolt Pretension

It is evident from equation (2) that the level of bolt pretension affects the slip resistance, R_{slip}, of a joint. Furthermore, it is conjectured that the slip coefficient, μ, may decrease for bolt pretension higher than 70% of the tensile strength of the bolts [Barakat *et al.* 1984]. This has been attributed to local deformations around the bolt holes, which reduce the roughness of the faying surface. The 70% of tensile strength requirement of the RCSC Specification is a minimum requirement. It is well known that most pretension methods result in a higher average pretension, almost reaching the tensile strength of the bolt for the turn-of-nut method [Kulak *et al.* 1987]. Since the RCSC Specification does not make an allowance for a reduction in slip coefficient because of higher pretension, the finding by Barakat *et al.* [1984] was investigated in the present study by performing several tests in which the pretension was 90% of the bolt nominal tensile strength.

2.2.5 Bolt Hole Clearance

In order to facilitate erection, holes are often oversized. The RCSC Specification gives maximum clearances for oversized holes as a function of the bolt diameter. If oversized holes are used, a reduction factor of 0.85 must be applied to the slip resistance. This reduction in slip resistance is partly attributed to a possible reduction in bolt pretension if the turn-of-nut method of installation is used, or to a change in contact surface stresses around the bolt hole. However, several studies have shown that when the requirements for oversize in the RCSC Specification are respected, no reduction in slip coefficient is observed [Chesson and Munse 1964; Allan and Fisher 1968; Frank and Yura 1981]. In order to confirm these observations, tests specimens were prepared with oversized holes. It must be noted that since bolt pretension was measured directly (see Section 2.5) only the possible effect of local conditions around the bolt holes was investigated here.

2.2.6 Bolt Hole Fabrication

Bolt holes are either drilled or punched. (In some situations, holes can be sub-punched and reamed, but this is not common practice today.) The slip coefficients in the RCSC

Specification do not account for the method of hole fabrication. To explore the relationship between the method of bolt hole fabrication and the slip coefficient, ten specimens for each plate thickness were prepared with punched holes. Normally, a higher slip coefficient is expected for these specimens compared to the specimens with drilled holes. The reasons for this are the absence of cutting fluid around the bolt holes and the presence of a shear lip around the perimeter of the punched hole, which could provide some interlock between the faying surfaces. For the present study, drilled holes were deburred in the Laboratory using a countersink tool and the oil was removed from the test specimens. The punched holes were lightly touched with the countersink tool to ensure that any small burrs were removed, but leaving the shear lip intact.

2.3 Test Setup, Specimen Preparation and Assembly

All tests were carried out on double lap joints loaded in tension. The specimen geometry is shown in Figure 1. The thickness of the main and splice plates, t, was either 1/2-in. or 5/8-in. (see Section 2.4).

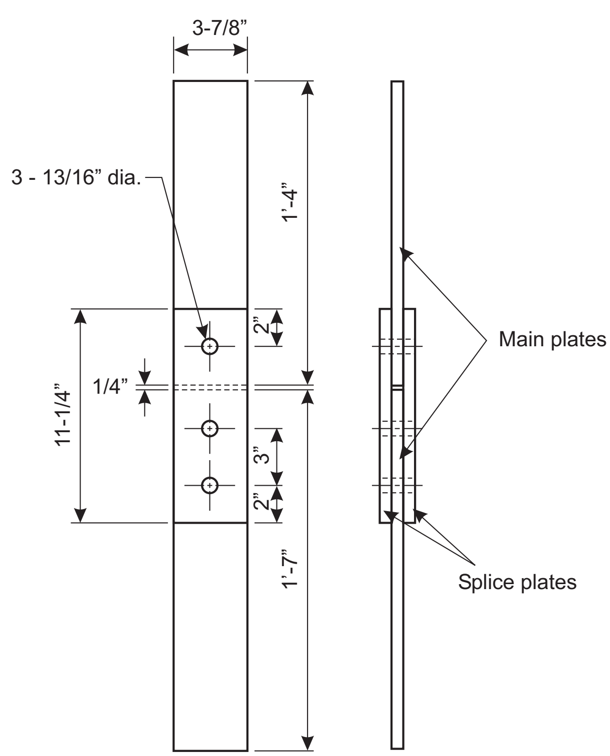

Figure 1 *– Specimen geometry.*

The specimens consisted of a one-bolt joint on one end and a two-bolt joint on the other end. This arrangement was chosen in order to be able to identify two distinct slip loads and thus two results for the slip coefficient evaluation in a single test. The tests were carried out in a universal testing machine (UTM) with a maximum static capacity of 1000 kN (see Figure 2).

The first 11 tests were conducted under stroke control for the entire duration of the tests. However, this resulted in gradual slips, which made the determination of the slip load difficult. Subsequent tests were conducted under load control up to the slip of the two–bolt joint. The tests were then completed in stroke control up to failure of the specimens, either by bolt shear or plate bearing failure. This procedure showed a much more sudden slip for most of the tests and still produced valid results for the ultimate strength of the specimens.

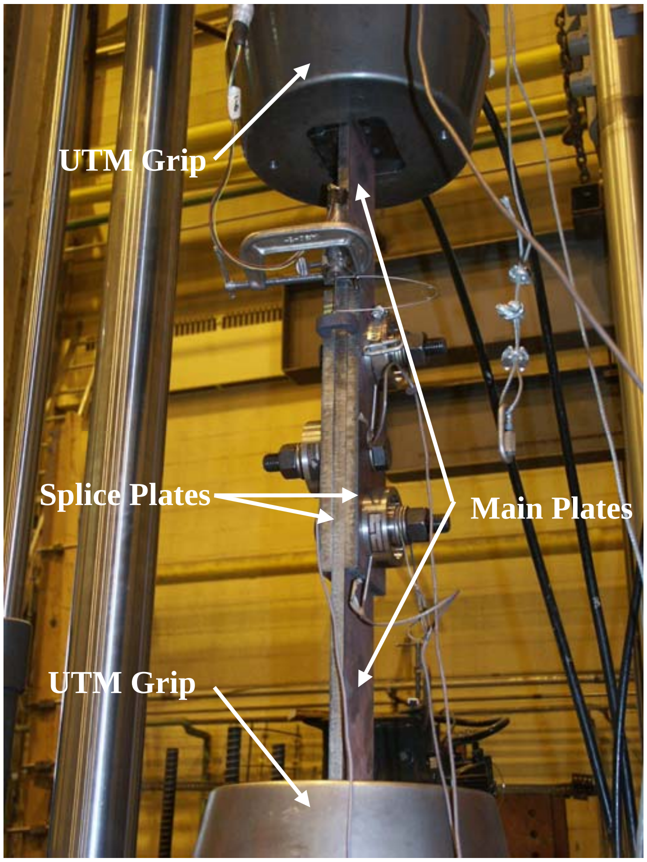

Figure 2 *– Test set-up.*

All plates were cut and the holes drilled or punched by a local fabricator. The fabricator was instructed to prepare the plates as they would be prepared for any slip-critical joint with clean mill scale faying surface, with the exception that no deburring was to be done in the shop. Deburring in a fabricating shop is usually done by light grinding around the bolt holes, which can remove the mill scale around the holes. Once the plates were delivered to the I. F. Morrison Structures Laboratory, the burrs from cutting of the plates and drilling or punching were carefully removed by light grinding around the perimeter of the plates and by using a countersink tool for the bolt holes. The plates were then cleaned with a glass cleaner to remove any oil and grease on the faying surfaces before the test specimens were assembled, except for the plates being tested in the as-received condition.

The bolts used for all the test specimens were 3/4 in. dia. A325. Before the bolts were tightened to the required pretension, the specimens were set up such that all bolts were in negative bearing (bearing with the plates in the direction opposite to the applied load). This ensured that significant displacement would take place in the joint when slip took place, making slip detection easier.

Tension coupons and material samples for chemical analyses were obtained from plates of the same heat as the test specimens in order to confirm that the steel plates were ASTM Grade A588. Figure 3 shows the engineering stress vs. strain curve for the three tested tension coupons of each plate. The mechanical properties (static yield strength, F_y, static ultimate strength, F_u, modulus of elasticity, E, strain at onset of strain hardening, ε_{SH}, and strain at rupture, ε_r) obtained from these curves are summarized in Table 1. The minimum required strength properties specified by ASTM A588 [ASTM 2005b] for F_y and F_u are listed in the last row of the table. The results of the chemical analysis for the two plates are presented in Table 2. The table also shows the required limits from the ASTM Standard for A588 Grade B steel.

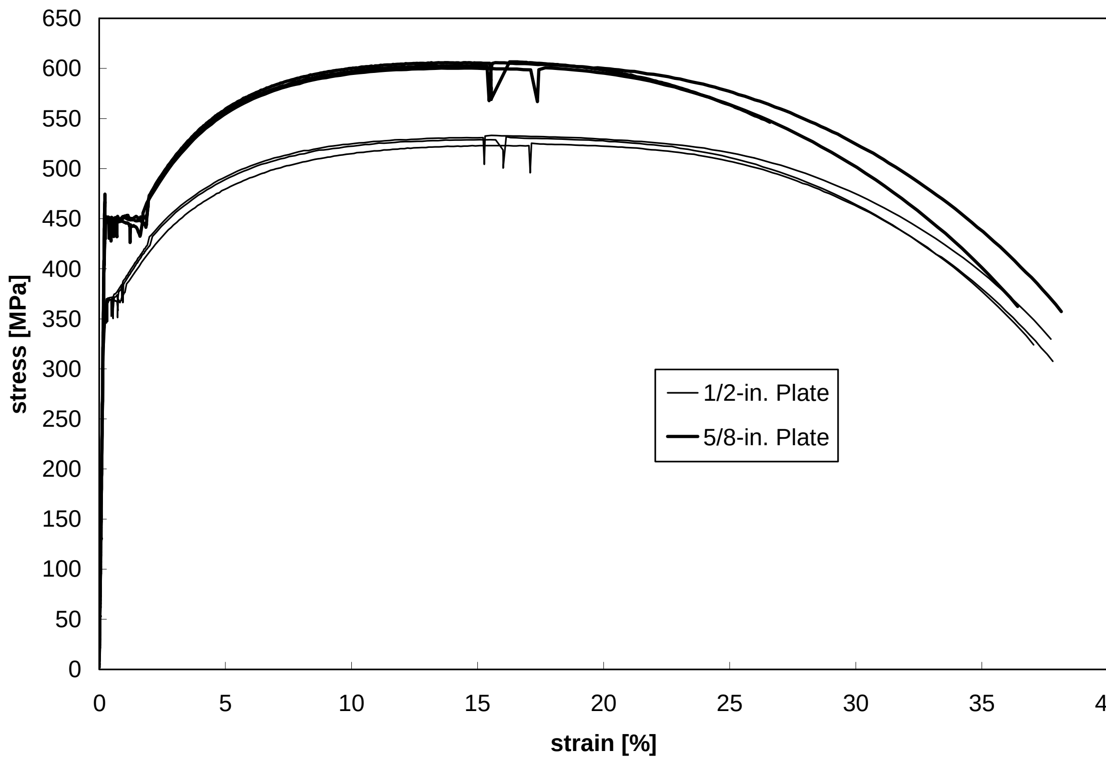

Figure 3 *– Engineering stress vs. strain curve for the tested tension coupons.*

Table 1 *– Results of tension coupon tests of the two plates.*

Plate	Tension Coupon	σ_y [MPa]	σ_u [MPa]	*E* [MPa]	ε_{SH} [%]	ε_r [%]
1/2-in.	4.1	355	504	211,000	0.5	38
	4.2	350	501	209,000	0.6	37
	4.3	354	496	214,000	0.8	38
5/8-in.	5.1	431	569	216,000	1.9	—
	5.2	428	567	214,000	1.7	36
	5.3	430	568	211,000	1.9	38
ASTM A588	Min. req.	345	485	—	—	—

From a comparison of the measured strengths and chemical compositions with the required values in ASTM A588, it can be concluded that both plates meet the requirements for Grade ASTM A588 steel. Furthermore, the measured properties correspond to the mill test certificates that were provided with the plates by the fabricator.

***Table 2** – Results of chemical analyses of the two plates (in % wt).*

Element	ASTM A588 Requirements	1/2-in. Plates	5/8-in. Plates
Carbon	0.20 max	1)	1)
Manganese	0.75 – 1.35	1.06	0.94
Phosphorus	0.04 max	0.015	0.013
Sulfur	0.05 max	0.022	0.023
Silicon	0.15 – 0.50	0.35	0.23
Nickel	0.50 max	0.19	0.16
Chromium	0.40 – 0.70	0.50	0.43
Copper	0.20 – 0.40	0.28	0.26
Vanadium	0.01 – 0.10	0.035	0.037

1) Due to contamination resulting from inadequate storage of the samples the carbon content could not be determined from the samples.

2.4 Test Matrix

Plates for 100 specimens were fabricated. One test specimen was damaged during setup and could not be tested, leaving 99 tests to be analyzed. The test program started with 1/2-in. plate specimens with degreased faying surfaces, 70% bolt pretension and regular size drilled holes (diameter 1/16-in. larger than the bolt diameter). These tests were carried out until the problem of slip detection was resolved by changing from stroke control to load control during testing. This resulted in a total of 14 tests with the same preparation parameters on the 1/2-in. plates. All other series of tests consisted of 10 replicate tests with the same combination of test parameters, with the exception of the higher pretension tests on the 1/2-in. plates, which were only repeated five times. The test matrix is shown in Table 3. All tests on the 1/2-in. plates were designated with the number 4 (= 4/8-in.) and all tests with the 5/8-in. plates with the number 5 as the first digit. The letter used in the series designation refers to the investigated parameter: N for normal, or reference, test; S for specimens with as-received faying surfaces; T for specimens with bolts with higher pretension; D for specimens with oversized holes; and P for specimens with punched holes. Since no cutting fluid was used on the plate specimens with punched holes, no degreasing of these surfaces was performed.

***Table 3** – Test matrix.*

Series	No. of Tests	Plate Thickness	Faying Surface	Bolt Pretension	Hole Clearance	Hole Fabrication
4N	14	1/2-in.	degreased	70%	1/16-in.	drilled
4S	10	1/2-in.	as-received	70%	1/16-in.	drilled
4T	5	1/2-in.	degreased	90%	1/16-in.	drilled
4D	10	1/2-in.	degreased	70%	3/16-in.	drilled
4P	10	1/2-in.	as-received	70%	1/16-in.	punched
5N	10	5/8-in.	degreased	70%	1/16-in.	drilled
5S	10	5/8-in.	as-received	70%	1/16-in.	drilled
5T	10	5/8-in.	degreased	90%	1/16-in.	drilled
5D	10	5/8-in.	degreased	70%	3/16-in.	drilled
5P	10	5/8-in.	as-received	70%	1/16-in.	punched

2.5 Instrumentation

In order to calculate the slip coefficient the total bolt pretension and the slip load must be measured accurately. Bolt pretension was measured directly with calibrated load cells. These load cells were inserted between the nut and the plates at each bolt location, as illustrated in Figure 4.

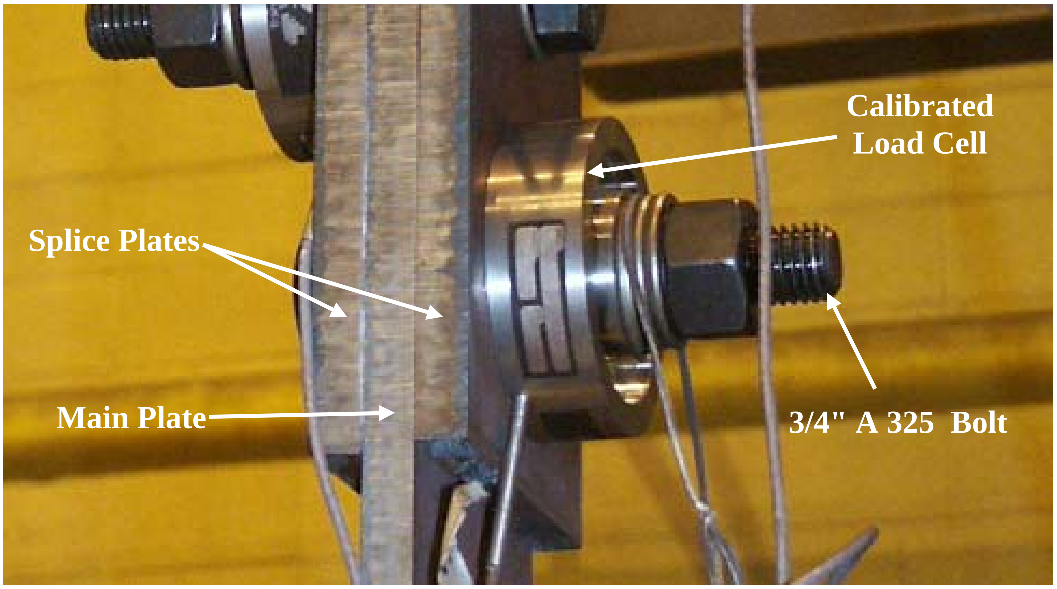

Figure 4 *– Detail of an installed load cell.*

The stroke and load from the universal testing machine (UTM) were recorded using a data acquisition system. Pilot tests showed that it was possible to determine the slip, and thus the slip load, of the one-bolt joint from these readings. However, the observation of the slip on the two-bolt joint was not as obvious and it was decided to monitor the displacement of the joint with a variable differential transformer (LVDT) on one side of the joint, as is illustrated in Figure 5.

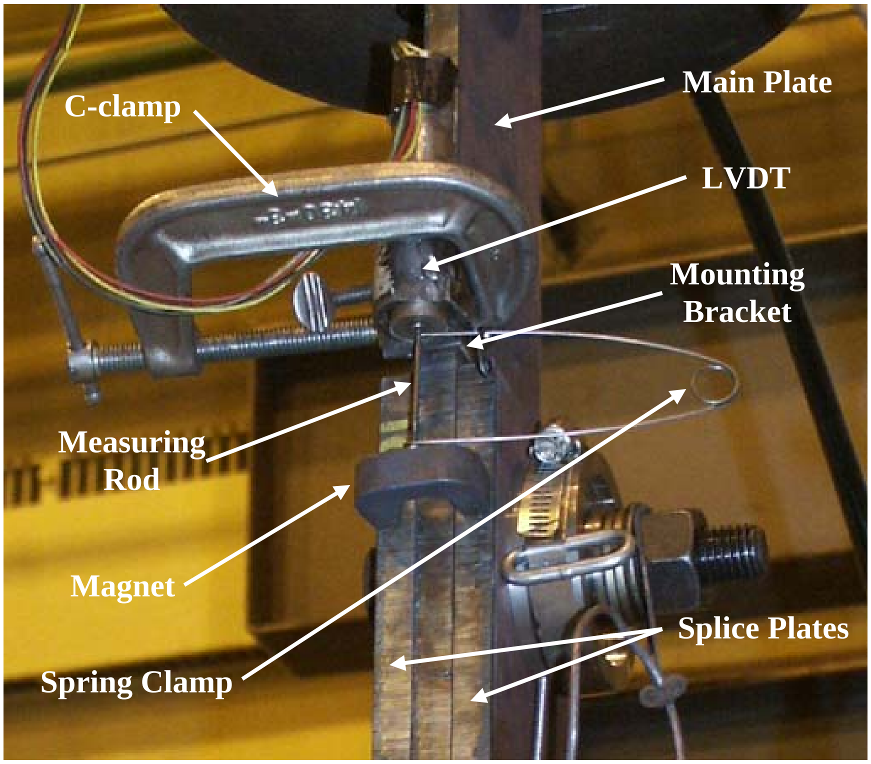

Figure 5 *– Detail of the LVDT used on the two–bolt joint to determine the slip.*

3. TEST RESULTS

3.1 Introduction

The slip coefficient was obtained from the measurements of the slip load and the total bolt pretension. The bolt pretension was readily attainable from the load cell data. However, the definition of the slip load was not always straightforward because in some tests a gradual slip occurred instead of a sudden slip. Furthermore, some specimens showed more than two significant slips. Thus a consistent definition of the slip load had to be established. This is discussed in Section 3.2. The test results, i.e., the calculated mean values and standard deviations of the slip coefficient for each test series, are presented in Section 3.3.

3.2 Definition of Slip Load

Figure 6 illustrates three representative displacement vs. load curves. Curve 1 shows sudden slip at two load levels, the lower one for the one-bolt joint and the higher one for the two-bolt joint. In this case, the slip loads are clearly P_1 for the one-bolt joint and P_2 for the two-bolt joint.

Curve 2 shows two gradual slips. The following procedure was used to establish the slip load. The linear part of the curve before slip occurs was extended (lines 1A and 2A) and a line tangent to the part where the curve becomes quasi linear again, but is still slipping (lines 1B and 2B), was drawn. The intersection points of the two lines (1A – 1B and 2A – 2B, respectively) was taken as the slip loads P_1 for the one–bolt joint and P_2 for the two–bolt joint. This procedure ensured a consistent definition of the slip load for both joints of the connection and for specimens with and without oversized holes. Furthermore, checks showed that the same slip loads were obtained when the LVDT vs. UTM load curves were used instead of the UTM displacement vs. UTM load curves, therefore confirming the validity of the approach used to determine the slip load from load curves similar to curve 2.

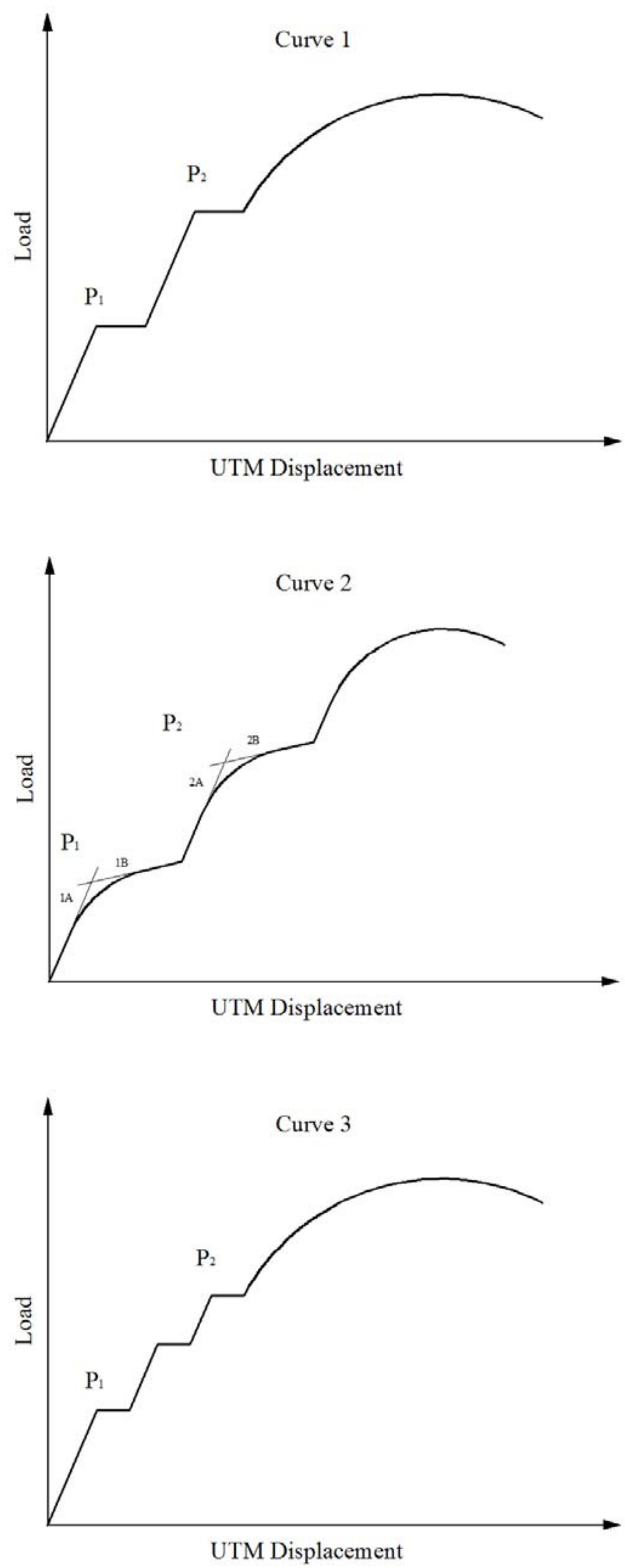

Figure 6 *– Definition of slip load from UTM displacement vs. UTM load curves.*

Curve 3 shows three slips. The most probable explanation for this behaviour is illustrated in Figure 7, which shows the one-bolt joint. Initially, the load is entirely transferred through friction between the main plate and the splice plates and the bolt in negative bearing on all three plates (Figure 7a). As the load exceeds the slip resistance of the main plate against the splice plates, the main plate moves by an amount $slip_{1,1}$ in the direction of loading (Figure 7b). At this point the main plate slips into bearing while the position of the splice plates relative to the bolt remains the same since the friction between the splice plates and the washer and load cell prevents slip between the splice plates and the bolt. Slippage stops once the main plate comes into positive bearing with the bolt. At this stage the slip resistance between the three plates has been overcome and the slip load of the one-bolt connection, P_1, is reached. Upon further loading, the slip resistance between the splice plates and the washer and load cell is overcome and the main plate moves with the bolt by an amount $slip_{1,2}$ in the direction of loading (Figure 7c), resulting in positive bearing of all three plates. This stage does not correspond to a relevant slip load. The two-bolt joint only slips at a higher load, P_2. It would be expected that the same phenomenon as for the one-bolt joint, i.e., first a slip between the main plate and the splice plates, followed by a slip between the splice plates and the washer and load cell should occur. However, at the load P_2 the one-bolt joint is stressed to such an extent that local plastic deformations in the bolt and main plate have started to take place, resulting in a reduction of the overall stiffness of the specimen. This reduction becomes so pronounced that the slip between the splice plates and the washer and load cell, respectively, can no longer be detected.

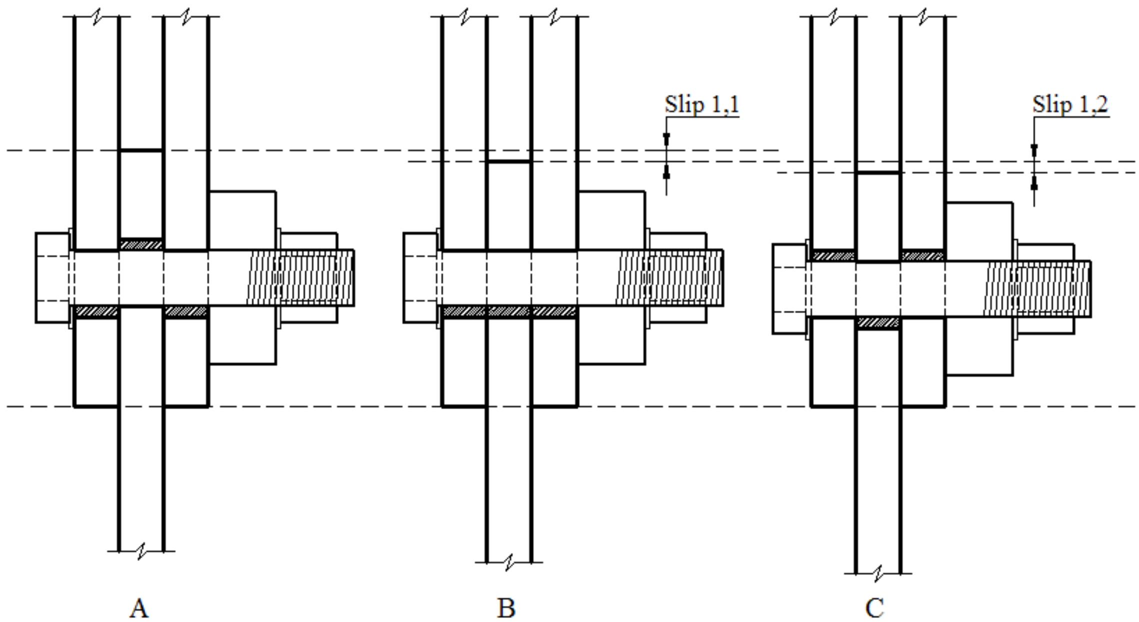

Figure 7 *– Illustration of slip sequence on one–bolt joint.*

Using the definitions of the slip loads described above, it was possible to determine all 99 slip loads on the one-bolt joint. However, no clear slip could be defined in eight cases of the two-bolt joints, therefore yielding only 91 test results for this configuration.

3.3 Results

From equation (2) the slip coefficient, μ, can be calculated as follows:

$$\mu = \frac{P_{slip}}{N_s T_b} \tag{3}$$

where P_{slip} : slip load determined as outlined in Section 3.2

N_s : number of slip planes, $N_s = 2$

T_b : total bolt pretension (bolt 1 for one–bolt joint, bolt 2 + bolt 3 for two–bolt joint)

The bolt pretension was determined from the initial readings at the start of the test. Although bolt pretension decreased over the entire test, it remained relatively constant until slip took place. Therefore, only the initial pretension is relevant in the calculation of the slip coefficient. As expected, all bolts showed a marked drop in pretension once they were in bearing. Furthermore, the one–bolt pretension decreased substantially because of the plastic deformations that took place prior to failure of the connection.

The mean value of the slip coefficient, μ_{av}, and the standard deviations, σ, for each test series are summarized in Table 4. The individual load vs. deformation curves for all 99 tests are presented in Appendix A. The individual test results are presented in Appendix B. The results and analyses of the failure loads (governed by either shearing of the bolt or bearing failure of the main plate) are presented in Appendix D.

***Table 4** – Mean, μ_{av}, and standard deviation, σ, of the slip coefficient, μ, for each test series.*

Series	1-Bolt Joint			2-Bolt Joint			Parameter Investigated
	results	μ_{av}	σ	results	μ_{av}	σ	
4N	14	0.40	0.056	8	0.35	0.018	Regular size drilled holes with degreased faying surfaces and 0.7 F_u pretension
4S	10	0.32	0.022	10	0.29	0.028	As-received faying surfaces
4T	5	0.39	0.039	5	0.31	0.031	Bolt pretension of 0.9 F_u
4D	10	0.35	0.060	10	0.31	0.030	Oversized holes
4P	10	0.35	0.016	10	0.38	0.038	Punched holes
5N	10	0.40	0.049	9	0.47	0.061	Regular size drilled holes with degreased faying surfaces and 0.7 F_u pretension
5S	10	0.37	0.054	10	0.37	0.034	As-received faying surfaces
5T	10	0.45	0.061	9	0.45	0.039	Bolt pretension of 0.9 F_u
5D	10	0.43	0.052	10	0.47	0.059	Oversized holes
5P	10	0.40	0.036	10	0.47	0.066	Punched holes

The mean slip coefficient and standard deviation for all 190 test results are 0.39 and 0.0071, respectively.

4. ANALYSIS OF TEST RESULTS

4.1 Introduction

A statistical analysis of the test results was conducted in order to determine whether they could be grouped into one sample or whether some of the results needed to be treated separately. For this analysis it is assumed that the data from each test series follow a normal distribution. The two-sided Student *t*–Test and the two-sided *F*–Test were used to compare the mean values and the standard deviations, respectively [Kennedy & Neville 1986]. From the results of each of the two tests a so-called level of significance, α, is obtained. If this level of significance is smaller than a reference level of significance, the hypothesis that the compared mean values (in the case of the Student *t*–Test) or standard deviations (in the case of the *F*–Test) of the two samples are significantly different has to be rejected. In other words, if the level of significance is large enough, the difference between the two samples is statistically insignificant. Since the variability in test results for the slip coefficient of clean mill scale faying surfaces is usually large [Kulak *et al.* 1987], the boundary between insignificant and significant statistical differences is difficult to define. Therefore four degrees of difference as a function of the obtained levels of significance, α, are assigned here:

- Significant for $\alpha < 1.0\%$
- Moderate for $1.0\% \leq \alpha < 2.5\%$
- Small for $2.5\% \leq \alpha < 5.0\%$
- Insignificant for $\alpha \geq 5.0\%$

It is important to recall that a perfect match in a two-sided test leads to a level of significance $\alpha = 100\%$.

Based on the results from the *t*– and *F*–tests, the following sections compare the results from the one-bolt joints to the two-bolt joints (Section 4.2) and the two steel heats (Section 4.3). Furthermore the effects of the faying surface preparation (Section 4.4), the amount of pretension (Section 4.5), the hole clearance (Section 4.6), and the method of hole fabrication (Section 4.7) are assessed. Finally, the results are compared to the data reported by Yura *et al.* [1981] and data obtained from other steel types reported by Kulak *et al.* [1987] (Section 4.8). The comparisons are presented in tabulated form, listing the calculated *F*– (for the standard deviations) and *t*–value (for the means), the obtained level of significance, α, and the assigned degree of difference between the two compared samples.

More details about the two statistical tests and a sample calculation are presented in Appendix C.

4.2 Comparison between One-Bolt and Two-Bolt Joint Test Results

Each set of the one-bolt and the two-bolt connections having the same parameters were compared. Table 5 presents the results of the statistical tests.

***Table 5** – Comparison between the one–bolt and two–bolt joint test results.*

Comparison Between	**Standard Deviation**			**Mean Value**		
	F	**α (%)**	**Level**	***t***	**α (%)**	**Level**
One– and Two –Bolt	1.97	0.11	Significant	0.48	63.2	Insignificant

Based on the t–test it can be concluded that the mean values of the two sets of results do not show a significant difference. However, their standard deviations are significantly different.

4.3 Comparison between the Two Steel Heats

Each set of the 1/2-in. and 5/8-in. plate specimens having the same parameters were compared to assess the effect of the two different heats. Table 6 presents the results of the statistical tests.

***Table 6** – Comparison between each set of the 1/2-in. and 5/8-in. plate specimens.*

Comp. Between	**Standard Deviation**			**Mean Value**		
	F	**α (%)**	**Level**	***t***	**α (%)**	**Level**
4N One and 5N One	1.27	73.4	Insignificant	0.28	78.0	Insignificant
4N Two and 5N Two	11.1	0.48	Significant	5.75	3.8×10^{-3}	Significant
4R One and 5R One	6.05	1.31	Moderate	2.82	1.13	Moderate
4R Two and 5R Two	1.44	59.9	Insignificant	5.58	2.7×10^{-3}	Significant
4T One and 5T One	2.42	40.9	Insignificant	1.70	11.3	Insignificant
4T Two and 5T Two	1.54	71.3	Insignificant	7.09	1.3×10^{-3}	Significant
4D One and 5D One	1.32	68.4	Insignificant	3.00	0.77	Significant
4D Two and 5D Two	3.92	5.4	Insignificant	7.89	3.0×10^{-5}	Significant
4P One and 5P One	5.17	2.2	Moderate	3.91	0.10	Significant
4P Two and 5P Two	3.01	11.6	Insignificant	3.63	0.19	Significant

Although a few comparisons show that the mean values do not differ significantly, examination of the test data shows a clear tendency for the 5/8-in. plates to have a significantly higher slip coefficient than the 1/2-in. plates. The standard deviations generally correspond well.

4.4 Effect of Faying Surface Preparation

The effect of the faying surface preparation, i.e. degreased clean mill scale versus as-received clean mill scale, was assessed by comparing the N–Series to the S–Series. Table 7 presents the results of the statistical tests.

***Table 7** – Statistical evaluation of the effect of faying surface preparation.*

Comp. Between	**Standard Deviation**			**Mean Value**		
	F	**α (%)**	**Level**	***t***	**α (%)**	**Level**
4N One and 4R One	6.5	0.82	Significant	4.64	1.3×10^{-2}	Significant
4N Two and 4R Two	2.43	25.4	Insignificant	4.99	1.3×10^{-2}	Significant
5N One and 5R One	1.18	80.7	Insignificant	1.23	23.3	Insignificant
5N Two and 5R Two	3.16	10.6	Insignificant	4.86	1.5×10^{-2}	Significant

With the exception of the one–bolt joints with 5/8-in. plates, all joints show a significant difference in mean slip coefficient between the degreased and the as-received plates. For all samples the degreased specimens show a higher mean slip coefficient. Therefore, the present investigation indicates that the surface preparation has a rather strong effect on the slip coefficient. With the exception of the one-bolt 1/2-in. plate joints, the standard deviations show insignificant difference at a level of confidence of 5%.

4.5 Effect of Level of Bolt Pretension

The effect of the level of bolt pretension was assessed by comparing the N–Series to the T–Series. Table 8 presents the results of the statistical tests.

None of the comparisons show a significant difference between the mean slip coefficients of the investigated samples. Contrary to the conclusions drawn by Barakat *et al.* [1984], the present investigation indicates that the level of pretension does not significantly affect the slip coefficient. All standard deviations were found to be similar. The result reported herein is what would be expected.

***Table 8** – Statistical evaluation of the effect of level of bolt pretension.*

Comp. Between	**Standard Deviation**			**Mean Value**		
	F	**α (%)**	**Level**	***t***	**α (%)**	**Level**
4N One and 4T One	2.03	51.6	Insignificant	0.25	80.3	Insignificant
4N Two and 4T Two	2.97	19.9	Insignificant	2.60	2.5	Small
5N One and 5T One	1.51	54.7	Insignificant	2.04	5.6	Insignificant
5N Two and 5T Two	2.42	23.4	Insignificant	0.79	44.0	Insignificant

4.6 Effect of Bolt Hole Size

The effect of bolt hole size, i.e. normal versus oversized clearance, was assessed by comparing the N–Series to the D–Series. Table 9 presents the results of the statistical tests.

With the exception of the two–bolt joints of the 1/2-in. plates, the comparisons show a good agreement between the normal and oversized holes. This supports the conclusions drawn by Chesson and Munse [1964], Allan and Fisher [1968], and Frank and Yura [1981] that as long as the maximum clearance for oversized holes as stated in the RCSC Specification is respected, no reduction in slip is observed. However, it should be noted that the present results were obtained with measured pretensions and therefore do not account for a potential reduction in pretension when the turn-of-nut method is used to tighten the bolts. All calculated standard deviations are similar.

Table 9 – Statistical evaluation of the effect of bolt hole size.

Comp. Between	Standard Deviation			Mean Value		
	F	α (%)	Level	t	α (%)	Level
4N One and 4D One	1.18	76.5	Insignificant	1.97	6.2	Insignificant
4N Two and 4D Two	2.66	21.1	Insignificant	2.97	0.90	Significant
5N One and 5D One	1.13	85.8	Insignificant	1.55	13.9	Insignificant
5N Two and 5D Two	1.06	92.2	Insignificant	0.01	99.1	Insignificant

4.7 Effect of Bolt Hole Fabrication Process

The effect of the bolt hole fabrication process, i.e., drilled versus punched holes, was also investigated in the present study. Table 10 presents the results of the statistical tests.

Table 10 – Statistical evaluation of the effect of bolt hole fabrication.

Comp. Between	Standard Deviation			Mean Value		
	F	α (%)	Level	t	α (%)	Level
4N One and 4P One	12.46	6.7×10^{-2}	Significant	2.73	1.21	Moderate
4N Two and 4P Two	4.35	6.5	Insignificant	2.42	2.8	Small
5N One and 5P One	0.26	80.1	Insignificant	1.90	35.4	Insignificant
5N Two and 5P Two	0.19	85.4	Insignificant	1.19	81.9	Insignificant

None of the comparisons of the mean slip values shows a significant difference. Although the difference between the two sets of 1/2-in. plates was assigned to be moderate and small, they do not allow any conclusion as to which of the two hole fabrication methods results in a higher slip coefficient since the mean slip coefficient is higher for the drilled one-bolt joints, but lower for the drilled two-bolt joints. Therefore, it can be concluded that as long as the grease on drilled plates and all burrs are properly removed, the hole fabrication method does not significantly affect the slip coefficient. With the exception of the one-bolt 1/2-in. plate joints, the standard deviations correspond well.

4.8 Comparison with Other Test Results

Although not all samples show an insignificant difference in mean slip coefficient and the standard deviations of the one-bolt and two-bolt joints do not correspond well, all the test results obtained in the present investigation (called the U of A test results herein) are grouped into one sample. This sample is then compared to the test results obtained by Yura *et al.* [1981] on the same steel grade, namely ASTM Grade A588. Furthermore, the U of A sample is compared to the sample reported in Kulak *et al.* [1987], which summarizes the test results on clean mill scale faying surfaces for different steel types (A7, A36, A440, Fe37 and Fe52) from several research projects carried out in North America and Europe.

The total number of the U of A test results is 190, with a mean slip coefficient $\mu_{av} = 0.39$ and a standard deviation $\sigma = 0.071$. The Yura *et al.* [1981] test series on clean mill scale yielded 31 test results, with $\mu_{av} = 0.23$ and $\sigma = 0.034$. Kulak *et al.* [1987] analysed 327 test results and obtained a mean slip coefficient $\mu_{av} = 0.33$ with a standard deviation $\sigma = 0.070$. Table 11 presents the results of the statistical tests.

It is obvious that the U of A test results are significantly different from the ones obtained by Yura *et al.* [1981]. In fact, the level of significance between the two studies for both the mean slip coefficient and its standard deviation is much lower than any level of significance obtained for comparisons within the U of A test results.

***Table 11** – Statistical comparison of U of A test results with data reported in Yura et al. [1981] and Kulak et al. [1987].*

Comp. Between	Standard Deviation			Mean Value		
	F	***α* (%)**	**Level**	***t***	***α* (%)**	**Level**
U of A and Yura	4.37	$1.3x10^{-3}$	Significant	11.8	$4x10^{-23}$	Significant
U of A and Kulak	1.03	80.2	Insignificant	8.96	$6x10^{-16}$	Significant

The mean slip coefficients of the U of A test results and the ones reported by Kulak *et al.* [1987] also show a significant difference, which is a reflection of the substantially higher mean slip coefficient obtained in the U of A study. However, the difference is not as marked as compared to the Yura *et al.* [1981] test results. Furthermore, the two standard deviations are close and not significantly different.

4.9 Summary

Statistical tests were conducted to assess the effect of different parameters on the slip coefficient of ASTM Grade A588 steel with clean mill scale tested in the present study. Good agreement between the mean values of the one-bolt and the two-bolt joint results was observed. However, their standard deviations were found to be significantly different. No significant effect of level of bolt pretension or bolt hole clearance could be detected. Conversely, the test results suggest that the preparation of the faying surfaces, i.e., if the surfaces are degreased or not, has a marked influence on the slip coefficient. The influence of the two steel heats cannot be conclusively assessed, but a clear tendency for the 5/8-in. plates to display a higher slip coefficient than the 1/2-in. plates was observed. No significant difference was observed between punched and drilled holes.

A comparison with the results obtained by Yura *et al.* [1981] shows a significant difference in both the mean values and standard deviations. With respect to other steel types, the slip coefficient measured in the present study is significantly higher, although its standard deviation is similar to that observed on other steel grades as presented by Kulak *et al*. [1987].

Although some of the U of A test series resulted in significantly different mean slip coefficients, they all fall within tolerable limits, as is illustrated in the histogram of Figure 8. Therefore it is reasonable to group all results into one sample having a size of 190 with a mean slip coefficient $\mu_{av} = 0.39$ and a standard deviation $\sigma = 0.071$.

Figure 8 also shows the histograms for the test results obtained by [Yura *et al.* 1981] on ASTM Grade A588 clean mill scale faying surfaces and the data reported in [Kulak *et al.* 1987] on other structural steel grades with clean mill scale faying surfaces. It is apparent from Figure 8 that there is a marked difference between the U of A and the [Yura *et al.* 1981] test results, confirming the findings of the statistical analysis. The difference does not seem to be as marked for the [Kulak *et al.* 1987] data, but a shift to the left with respect to the U of A results is discernible, indicating the lower mean slip coefficient.

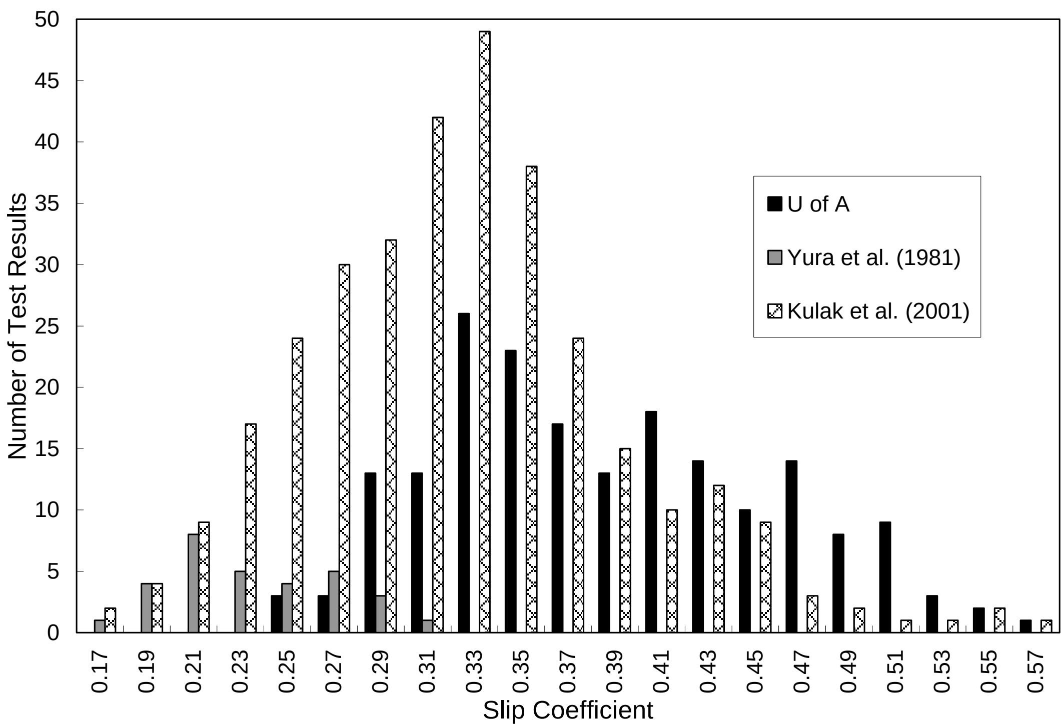

***Figure 8** – Histogram with* U of A *test results and data from Yura et al. [1981] and Kulak et al. [1987].*

5. SUMMARY, CONCLUSIONS, AND FUTURE WORK

5.1 Summary and Conclusions

A total of 99 slip-critical double lap splice specimens made of ASTM Grade A588 plates with clean mill scale faying surfaces were tested to determine the slip coefficient, μ. The test specimens were unsymmetrical: one end of the joint consisted of a one-bolt joint and the other end consisted of a two-bolt joint. The test program yielded 99 valid test results on one-bolt joints and 90 valid test results on two-bolt joints. Statistical analyses showed good agreement between the mean values of the one-bolt and two-bolt joints. The effect of bolt pretension and hole oversize, given that these are within the requirements of the RCSC Specification, were not found to be significant. However, a marked reduction in slip coefficient was detected when the faying surfaces were not degreased. Although the statistical analyses are not conclusive, the test results suggest that the steel heat might have an appreciable effect on the slip coefficient. For punched holes the data suggest that no significant difference with respect to drilled holes should be expected as long as the faying surfaces are deburred.

A comparison with test results obtained by Yura *et al.* [1981] on clean mill scale ASTM Grade A588 steel showed a substantially higher slip coefficient for the plates tested at the U of A. Although the difference was not as pronounced, the U of A tests showed a higher slip coefficient compared to tests carried out on clean mill scale surfaces of other steel types investigated in North America and Europe.

Although some of the U of A test results showed a significantly different mean slip coefficient than the basic series, the overall scatter falls within reasonable limits and all test results can be grouped into one sample. The sample size for the U of A test program on A588 steel faying surfaces is 190, with mean slip coefficient $\mu_{av} = 0.39$ and standard deviation $\sigma = 0.071$.

If all test results from the present study, from Yura *et al.* [1981], and from Kulak *et al.* [1987] are grouped into one sample with size 548, a mean slip coefficient $\mu_{av} = 0.34$ and a standard deviation $\sigma = 0.079$ is obtained.

5.2 Future Work

The slip coefficient does not seem to be influenced by oversized holes which are within the limits set out in the RCSC Specification. However, the effect of oversized holes on the level of pretension was not investigated in the present study. This should be further analyzed in order to assess the reduction factor, $\phi = 0.85$, proposed in the RCSC Specification for oversized holes.

The higher slip coefficient obtained in the present study might be coincidental or a consequence of different mill scale characteristics in newer steels. If the latter were true, then a new database of test results on clean mill scale would have to be obtained by a suitable test program. The suitability of the current database of test results on clean mill scale should be investigated.

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APPENDIX A

LOAD VS. DEFORMATION CURVES

The load vs. stroke (UTM displacement) and the load vs. LVDT displacement up to the slip of the two-bolt joint for each test are presented in the following. For the first 55 tests, the LVDT was mounted only on the two-bolt joint of the specimen. For the remaining 44 tests the LVDT was first installed on the one-bolt joint and then switched to the two-bolt joint after the first slip. Therefore, the first 55 LVDT curves just show the second slip. For the remaining tests both slips can be observed on the LVDT curves.

The overall joint behaviour up to failure is presented for each specimen at the bottom half of the following pages. In addition to the load vs. UTM displacement curve (overall joint behaviour), the load vs. LVDT displacement and the individual bolt pretensions vs. the UTM displacement are also shown. “Single Bolt” refers to the one-bolt joint, and “Top Bolt” and “Bottom Bolt” refer to the bolts on the two-bolt joint, where the top bolt is the one farther from the joint between the two main plates (see Figure 2).

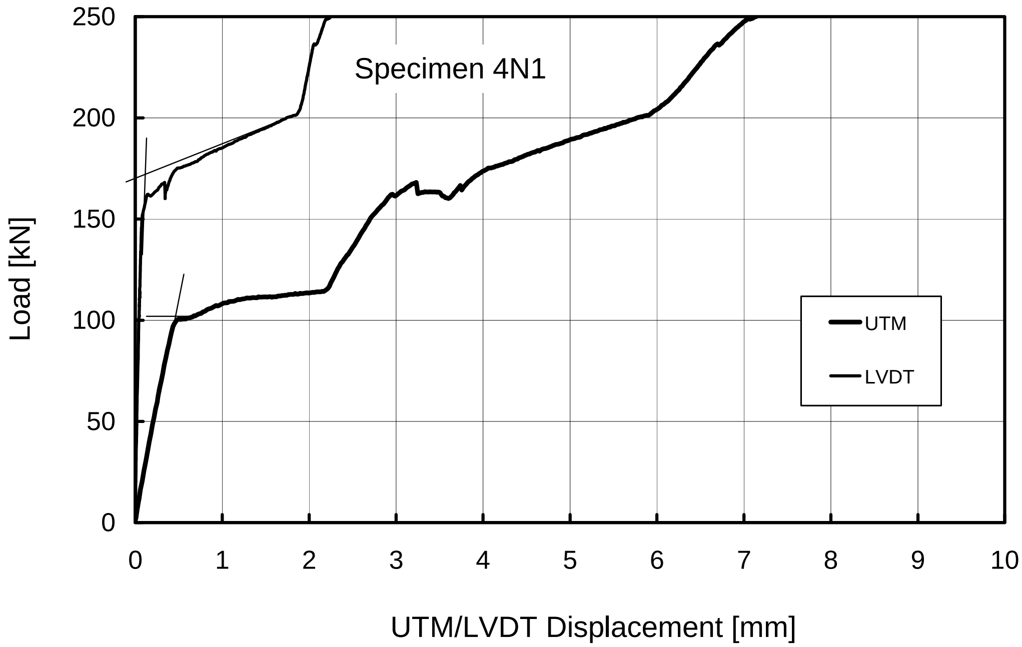

Figure 9 *– Load vs. displacement, 4N1.*

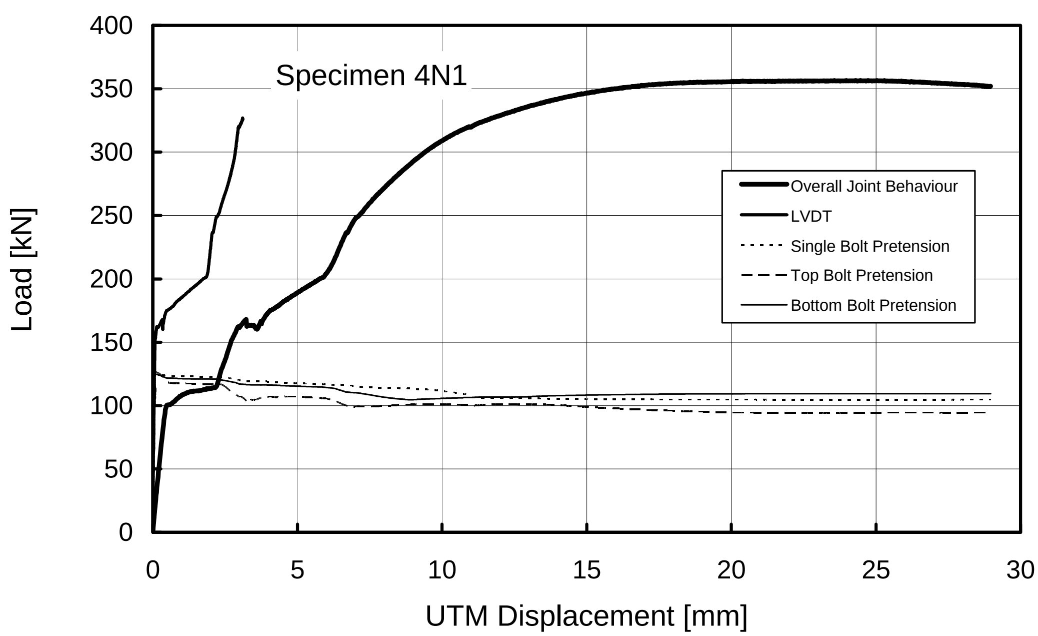

Figure 10 *– Load vs. displacement, 4N1.*

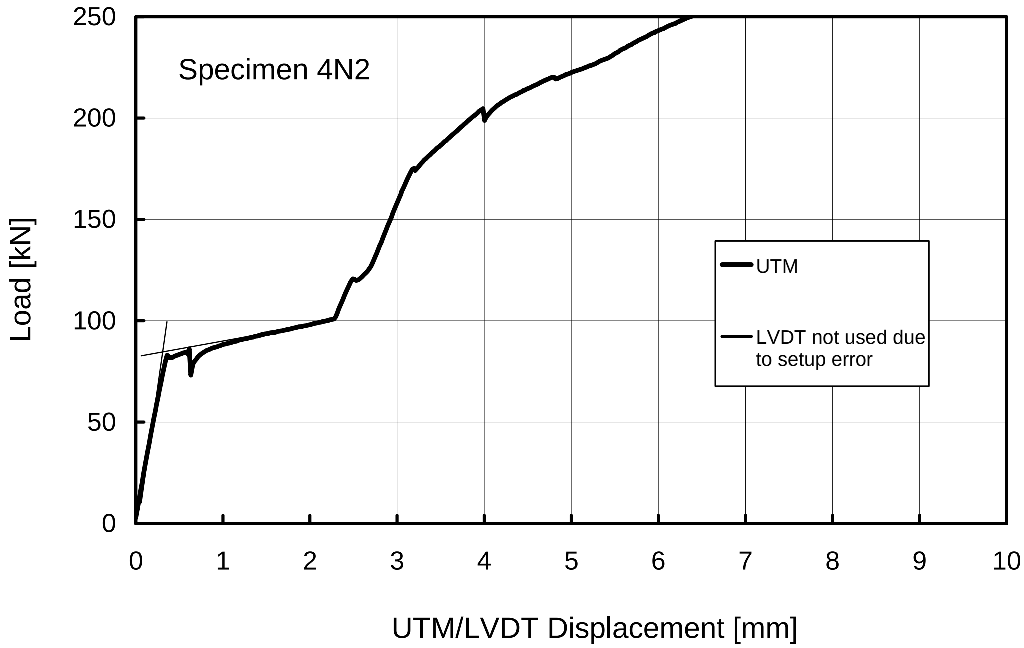

Figure 11 – *Load vs. displacement, 4N2.*

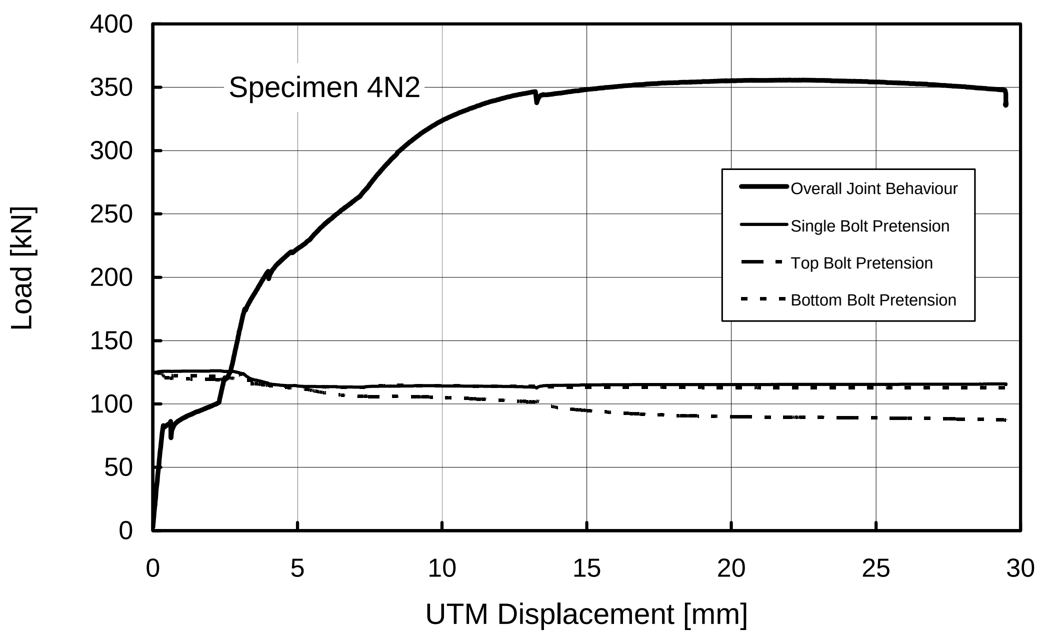

Figure 12 – *Load vs. displacement, 4N2.*

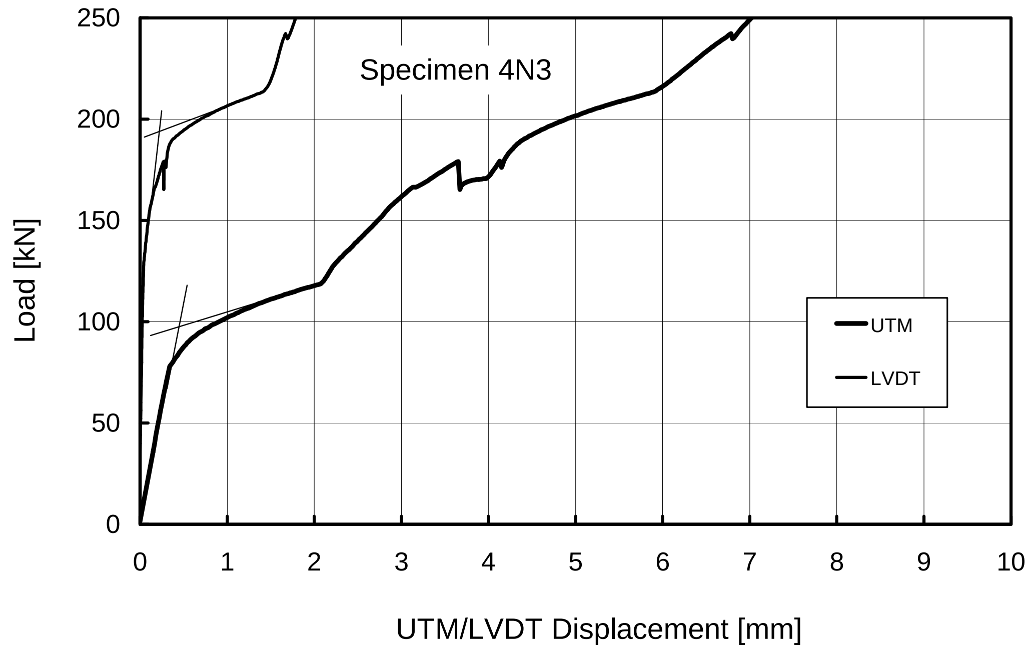

***Figure 13** – Load vs. displacement, 4N3.*

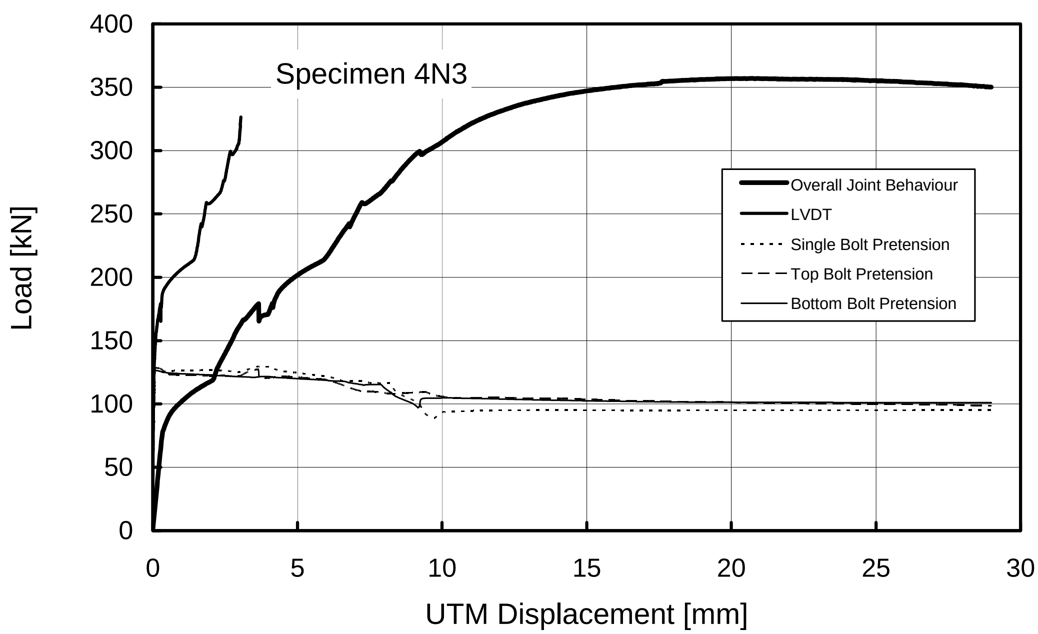

***Figure 14** – Load vs. displacement, 4N3.*

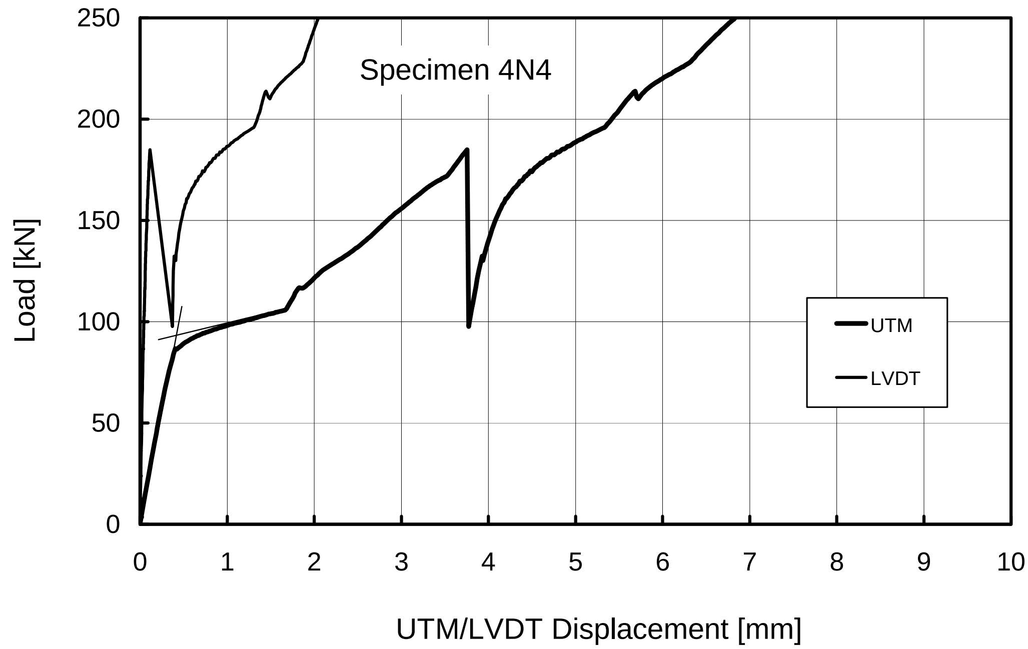

***Figure 15** – Load vs. displacement, 4N4.*

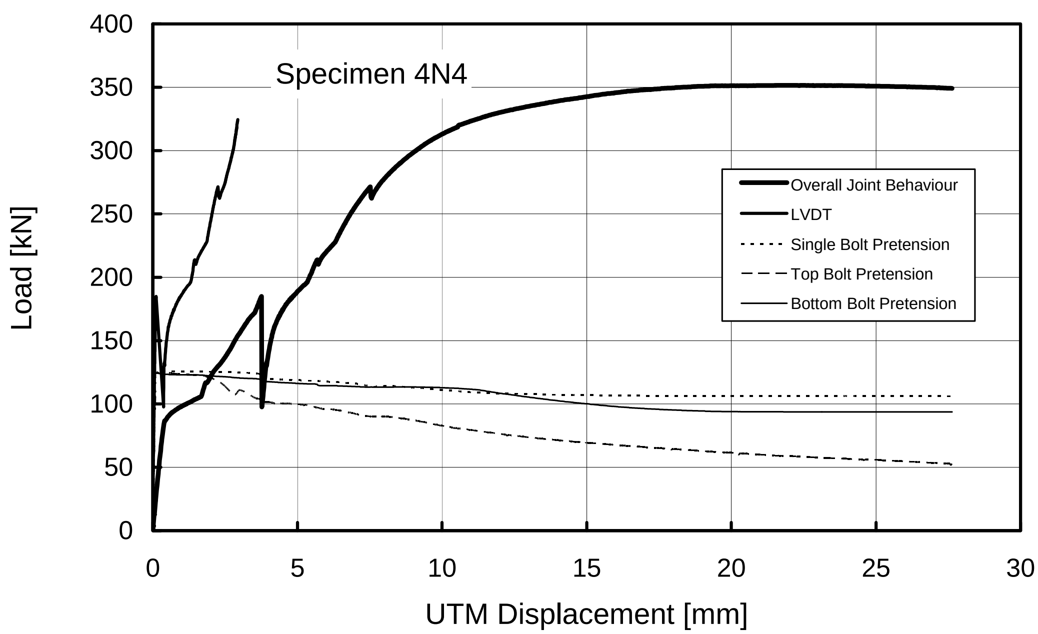

***Figure 16** – Load vs. displacement, 4N4.*

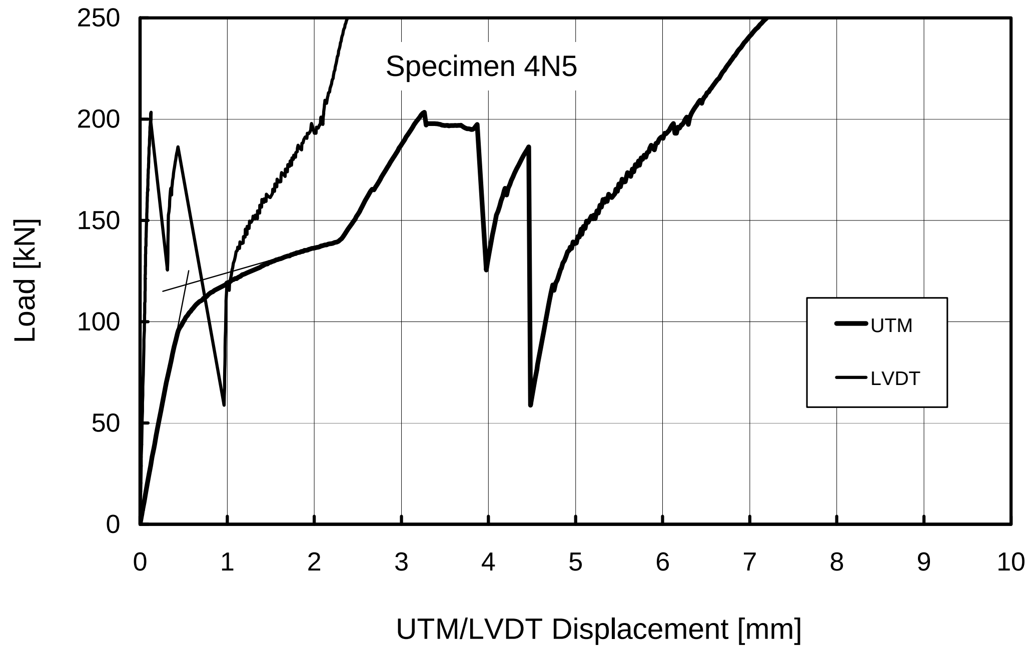

Figure 17 *– Load vs. displacement, 4N5.*

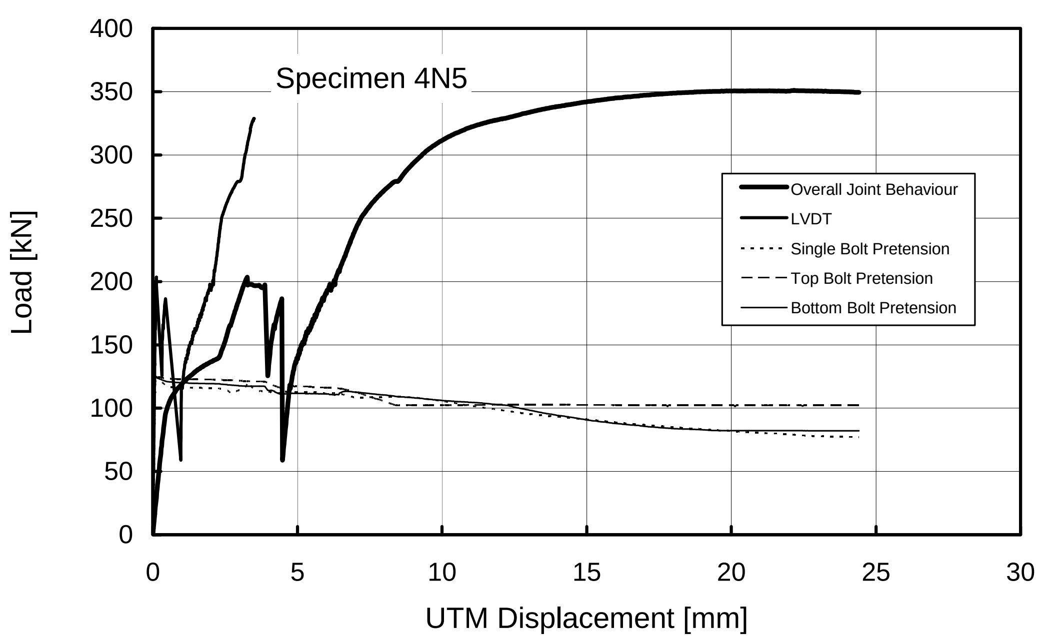

Figure 18 *– Load vs. displacement, 4N5.*

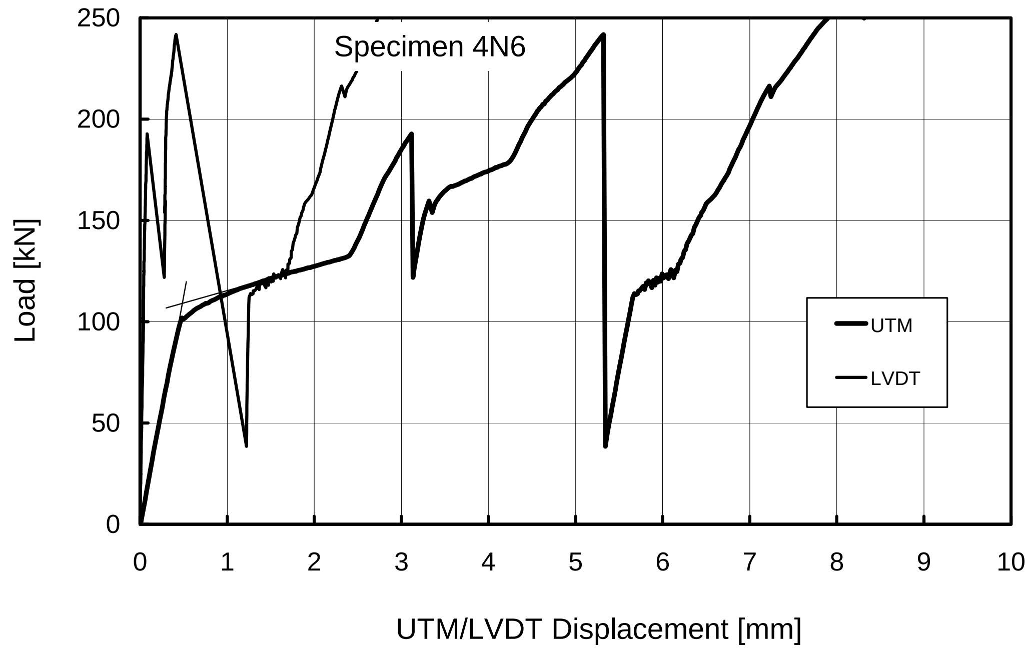

Figure 19 – *Load vs. displacement, 4N6.*

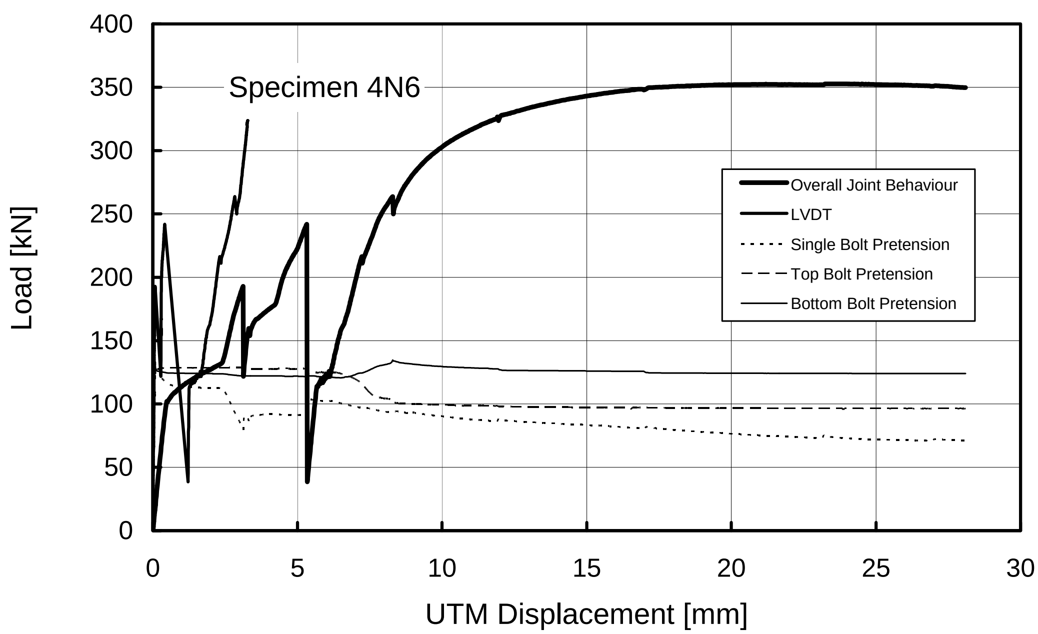

Figure 20 – *Load vs. displacement, 4N6.*

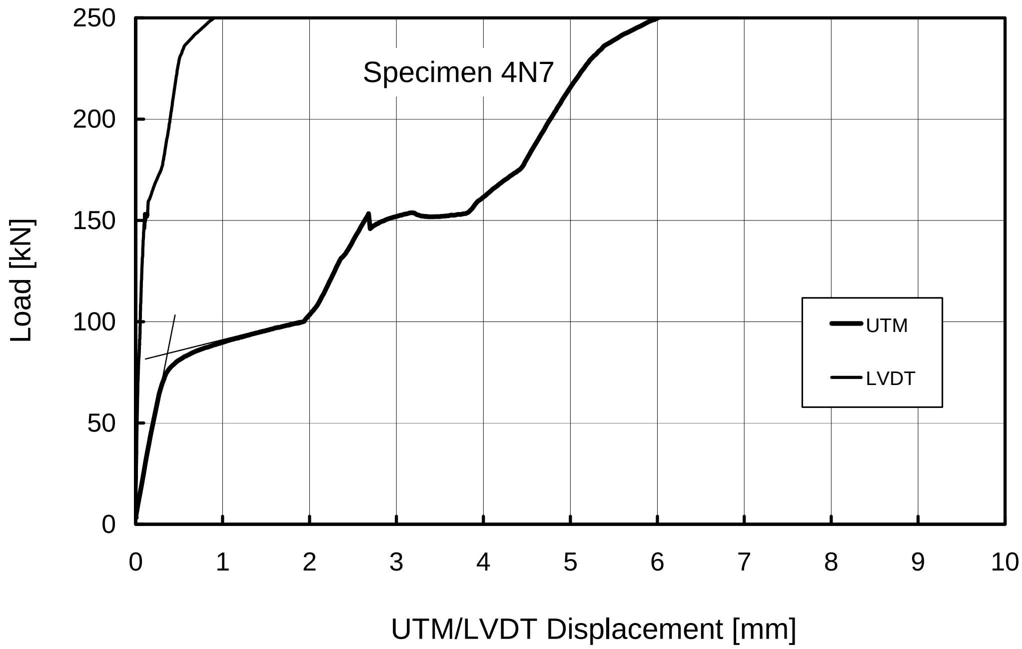

Figure 21 *– Load vs. displacement, 4N7.*

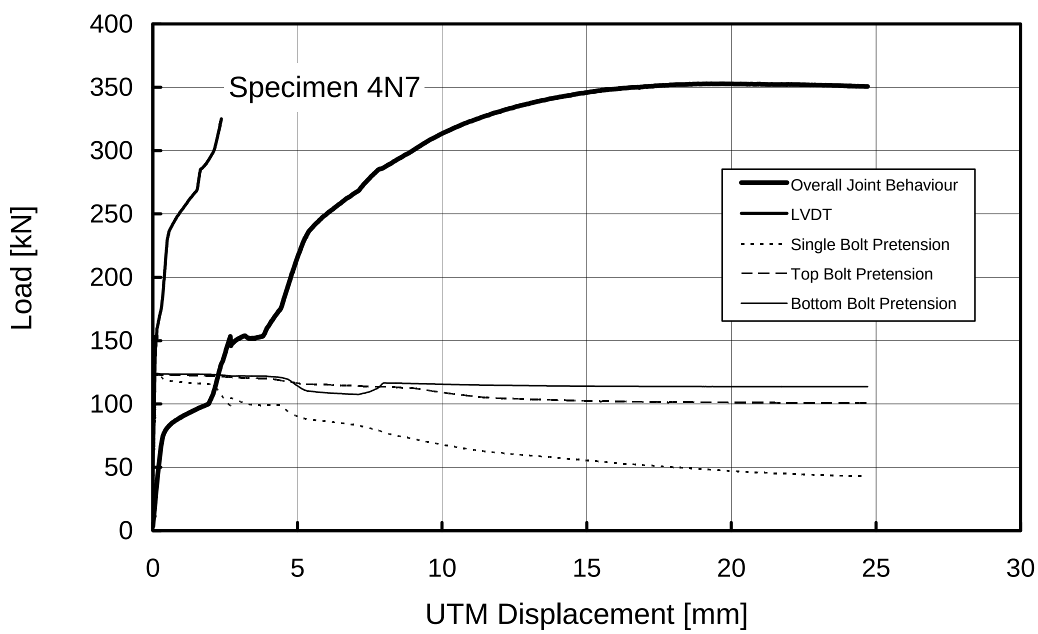

Figure 22 *– Load vs. displacement, 4N7.*

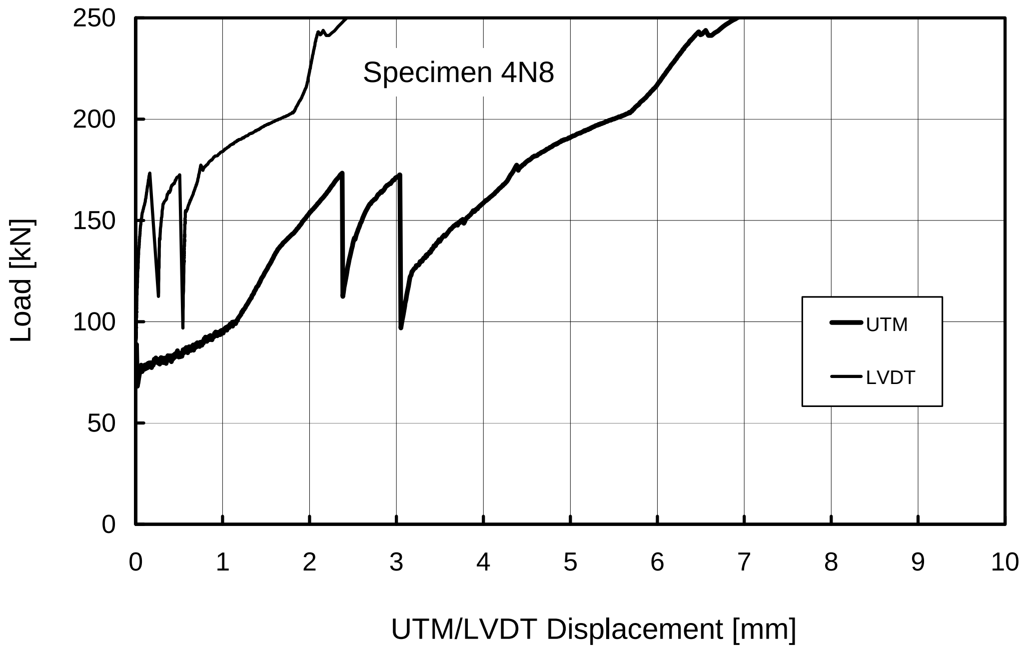

***Figure 23** – Load vs. displacement, 4N8.*

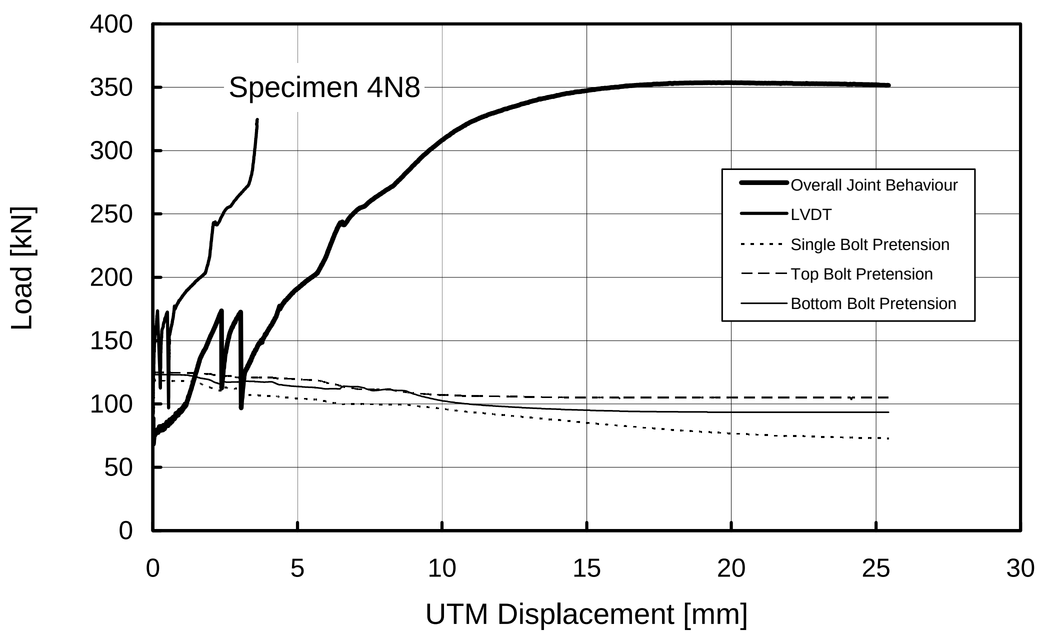

***Figure 24** – Load vs. displacement, 4N8.*

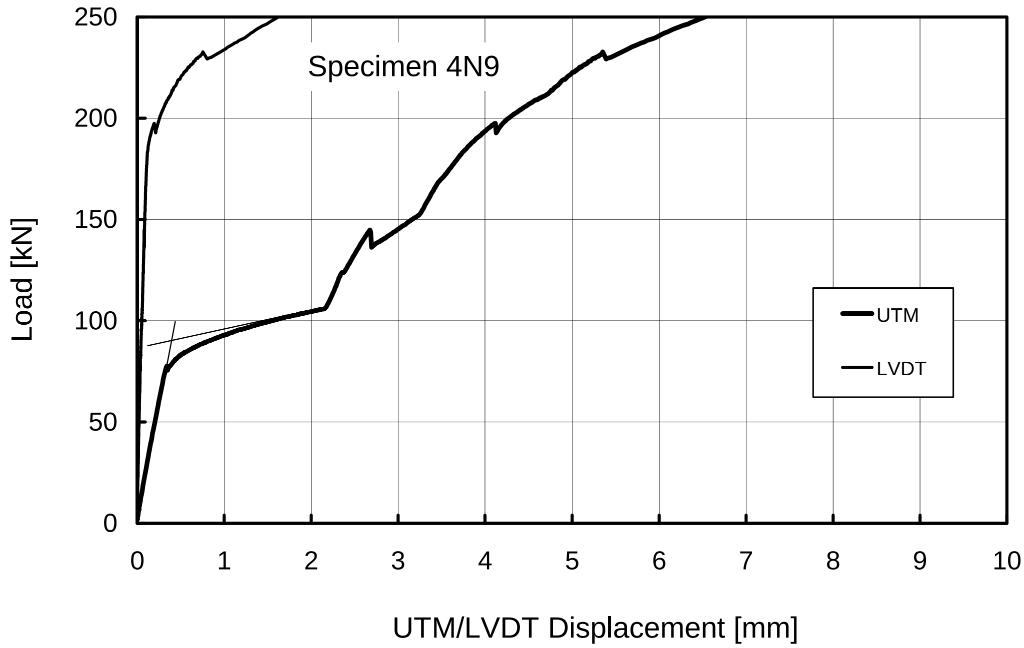

***Figure 25** – Load vs. displacement, 4N9.*

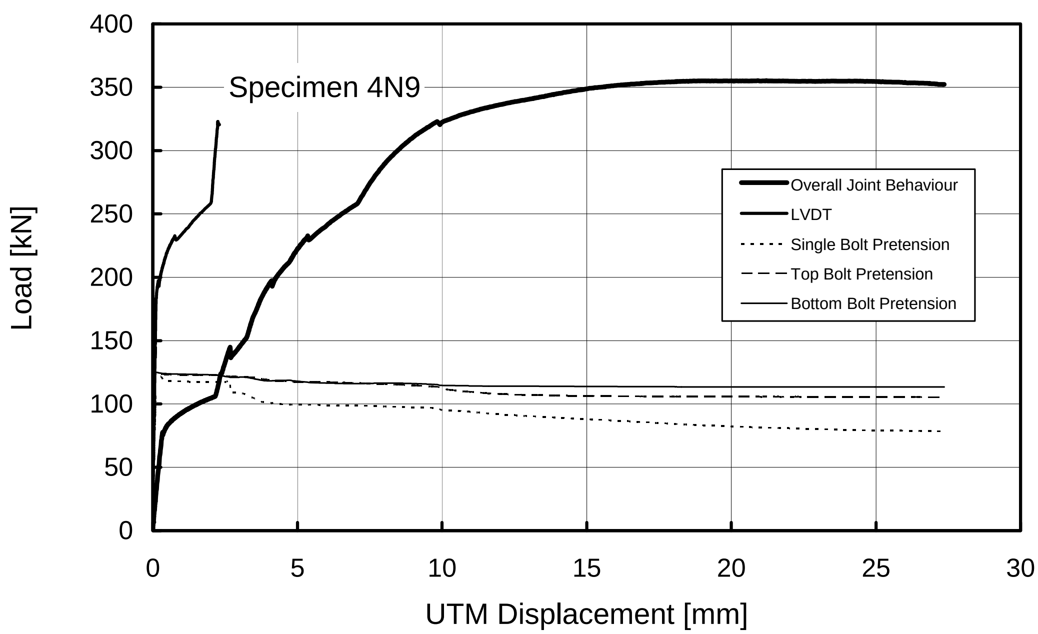

***Figure 26** – Load vs. displacement, 4N9.*

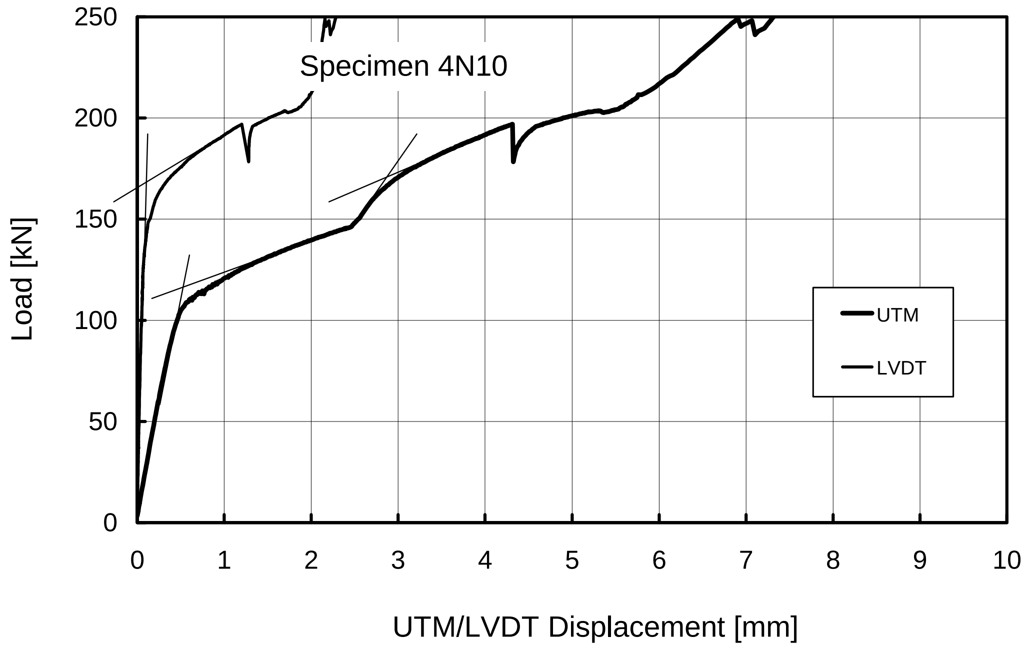

Figure 27 *– Load vs. displacement, 4N10.*

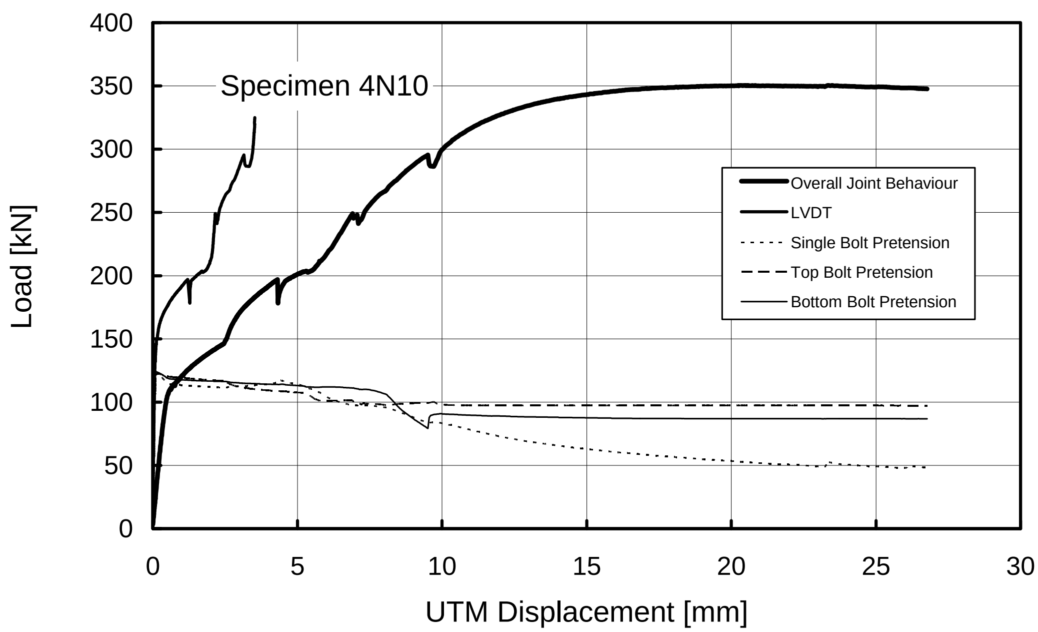

Figure 28 *– Load vs. displacement, 4N10.*

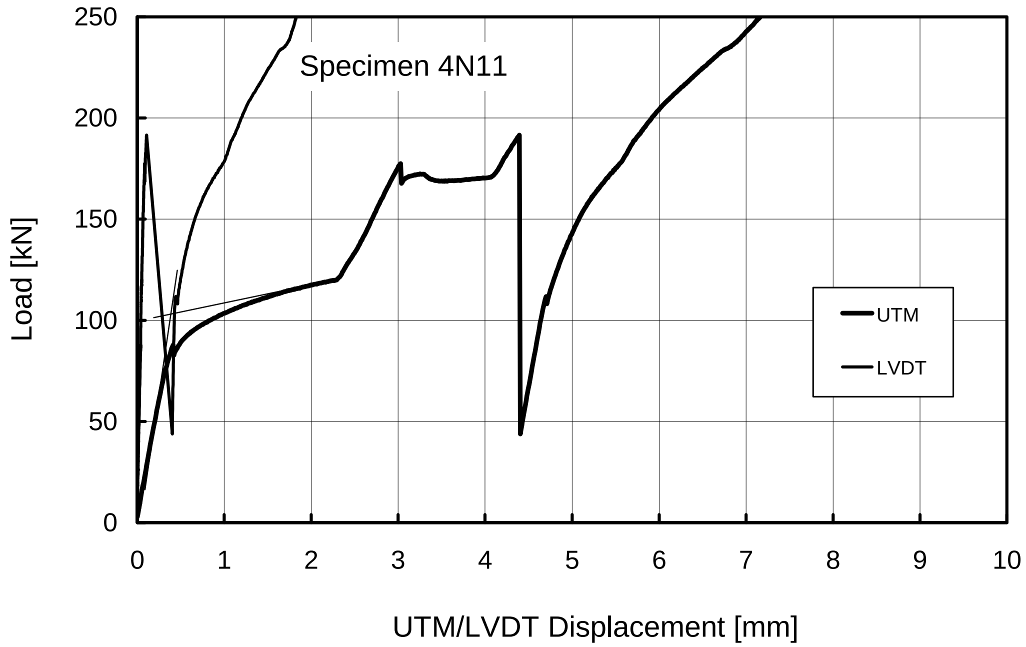

Figure 29 *– Load vs. displacement, 4N11.*

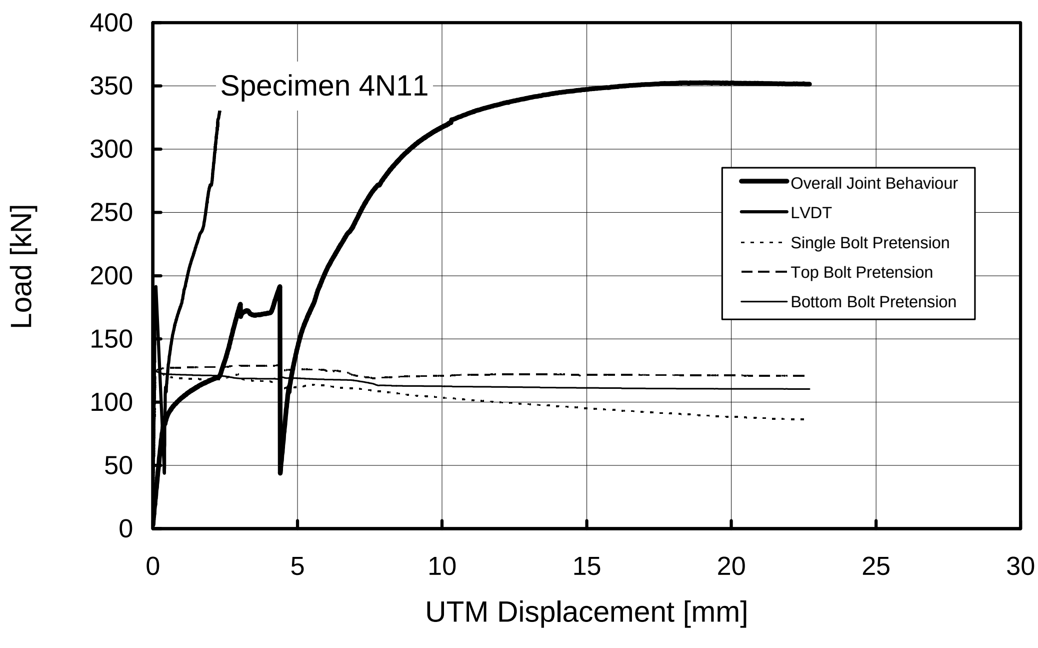

Figure 30 *– Load vs. displacement, 4N11.*

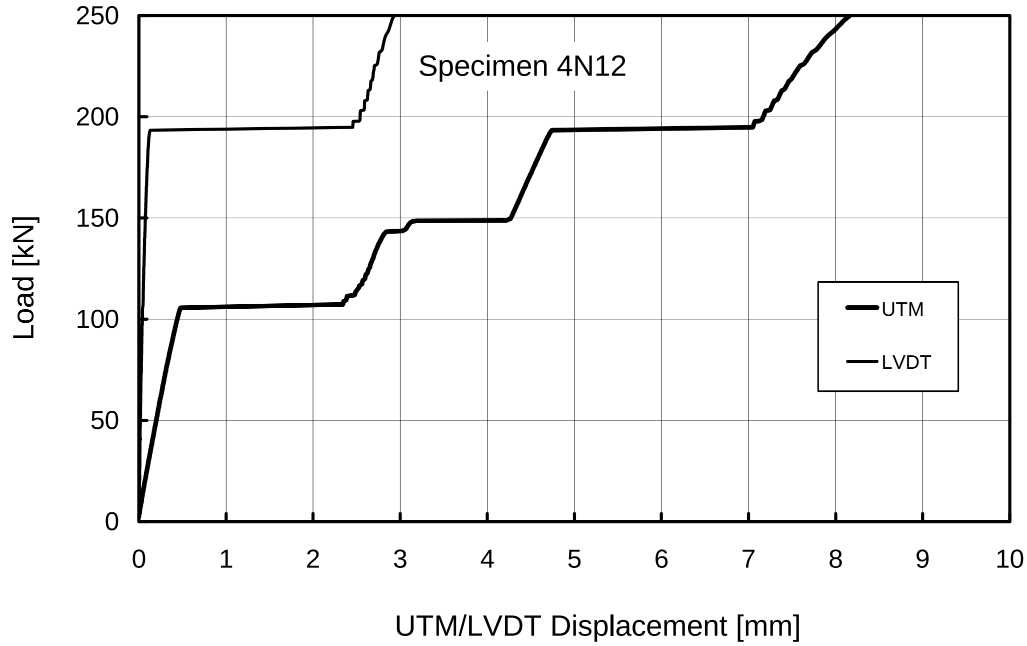

Figure 31 *– Load vs. displacement, 4N12.*

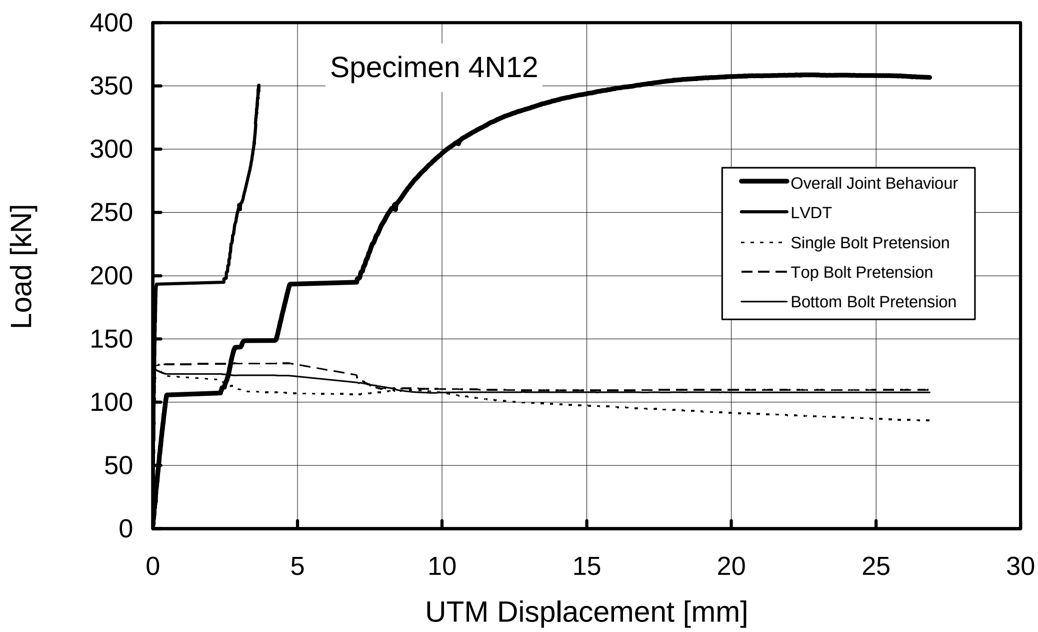

Figure 32 *– Load vs. displacement, 4N12.*

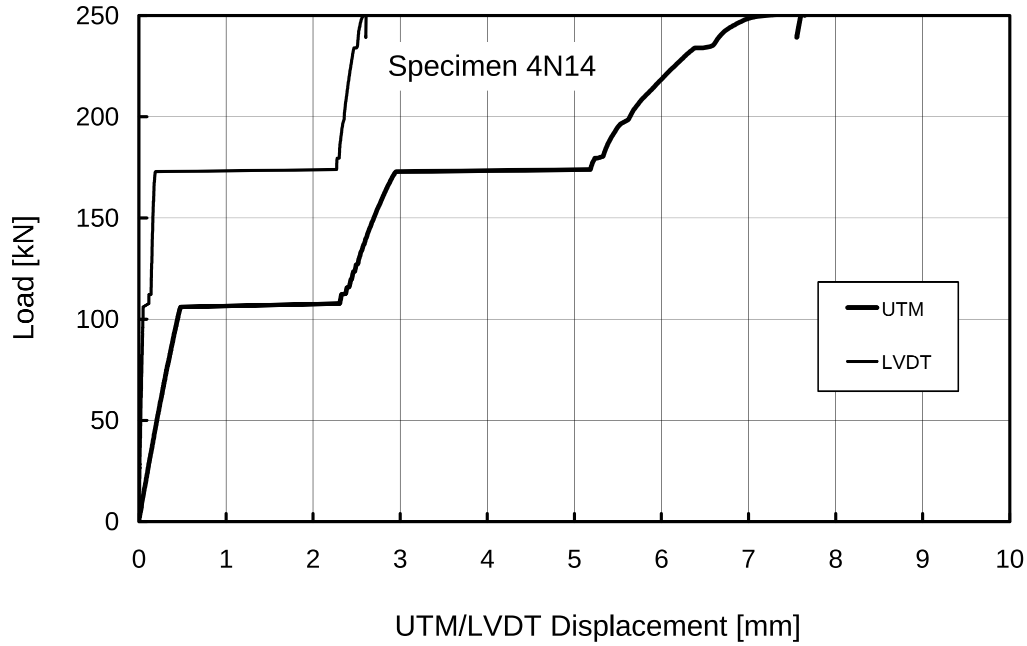

Figure 33 *– Load vs. displacement, 4N14.*

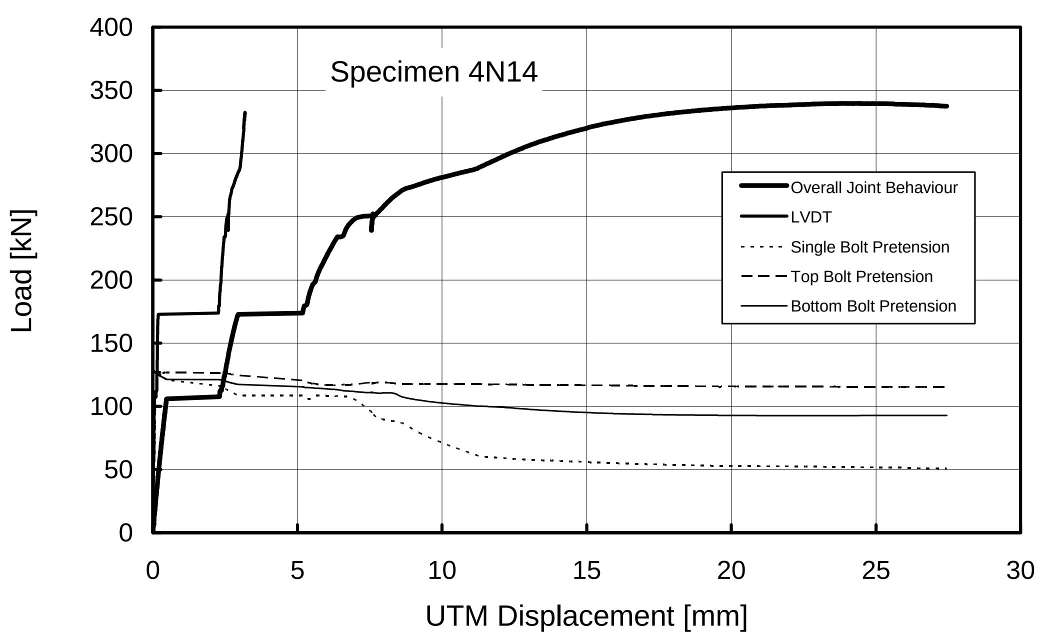

Figure 34 *– Load vs. displacement, 4N14.*

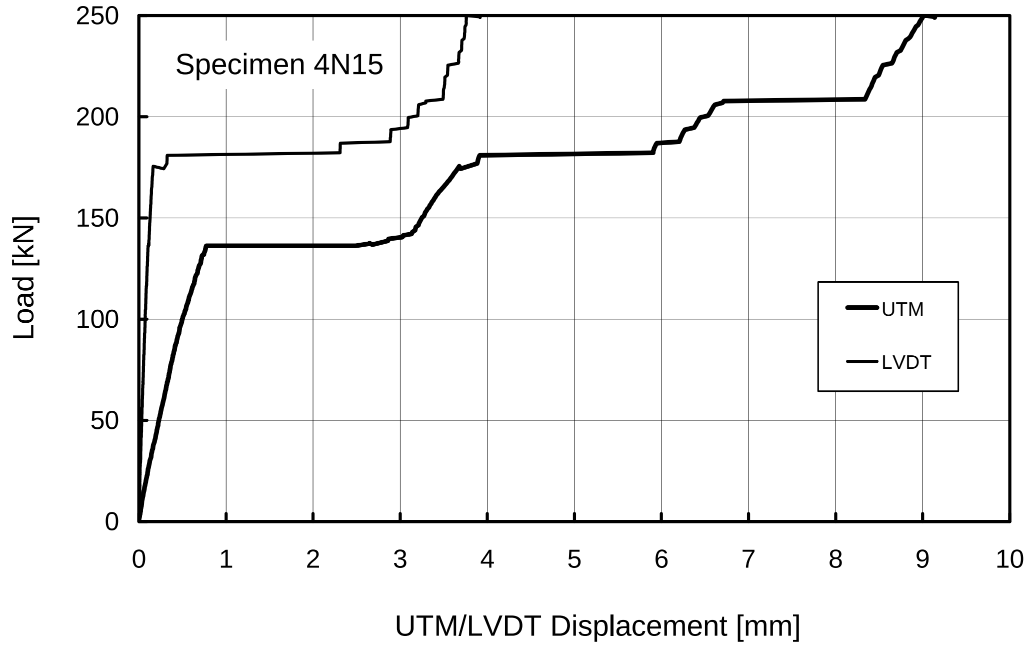

***Figure 35** – Load vs. displacement, 4N15.*

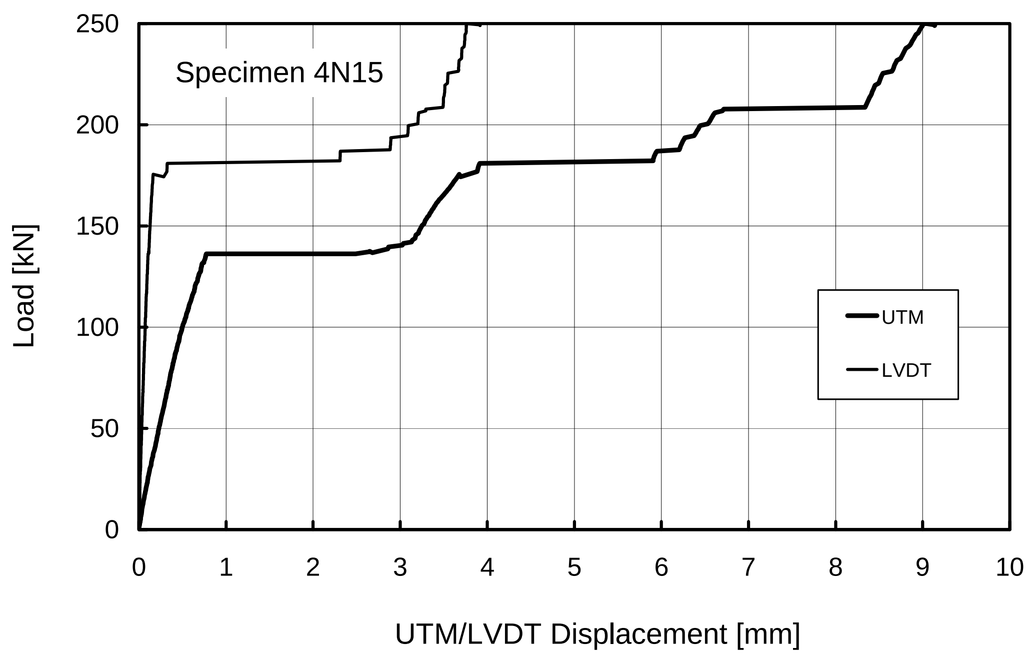

***Figure 36** – Load vs. displacement, 4N15.*

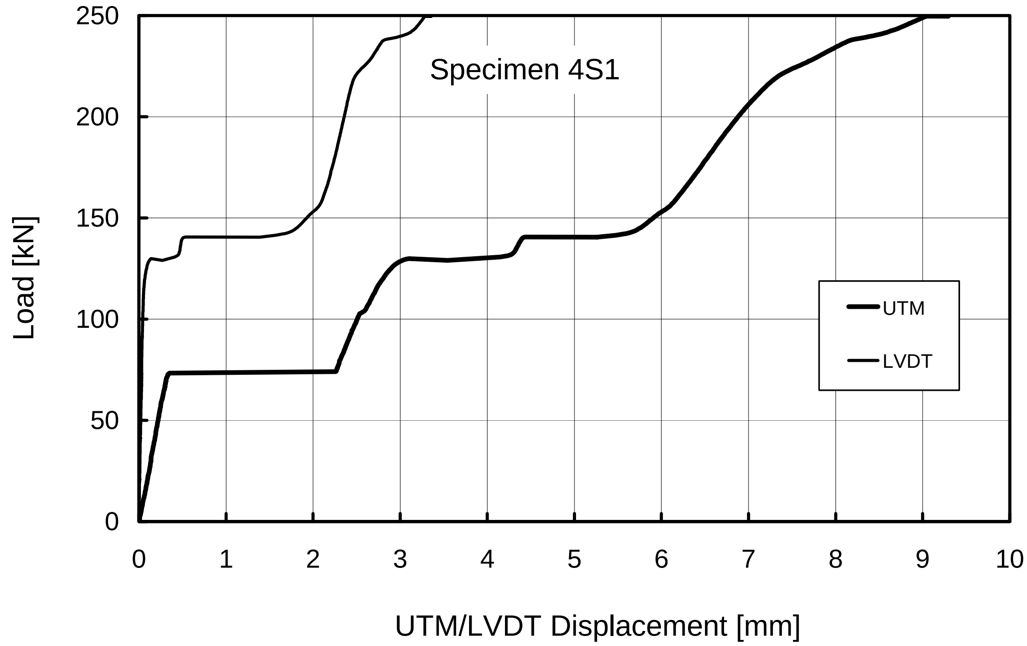

***Figure 37** – Load vs. displacement, 4S1.*

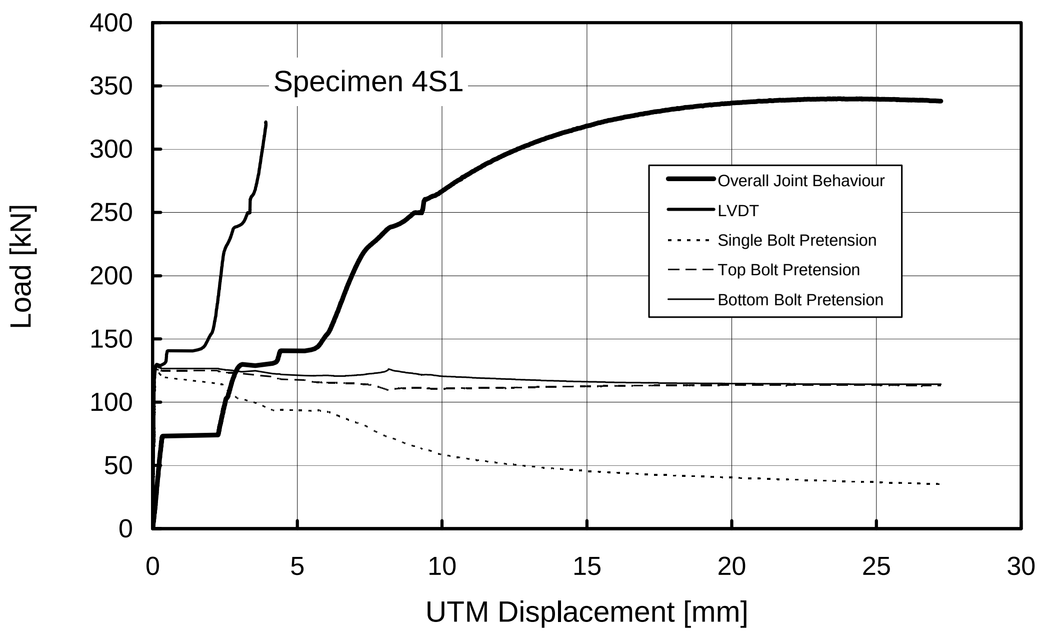

***Figure 38** – Load vs. displacement, 4S1.*

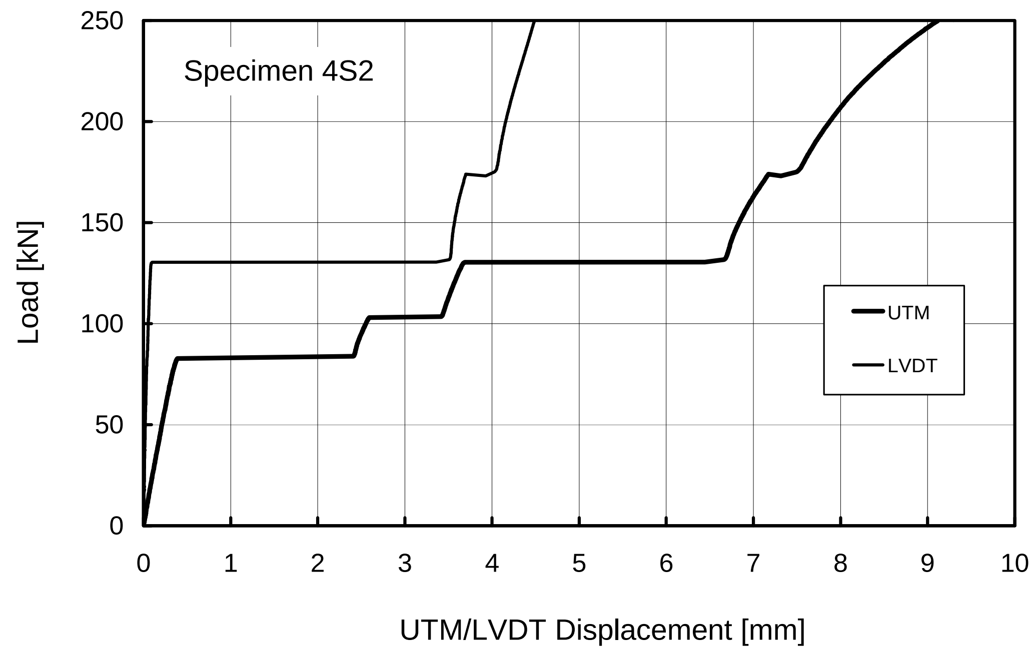

***Figure 39** – Load vs. displacement, 4S2.*

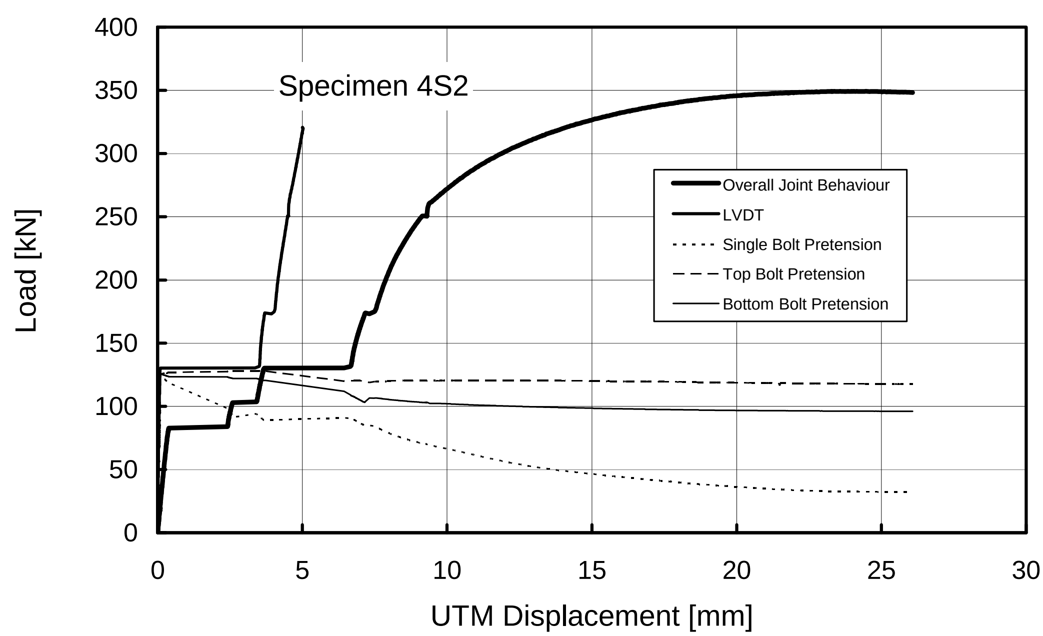

***Figure 40** – Load vs. displacement, 4S2.*

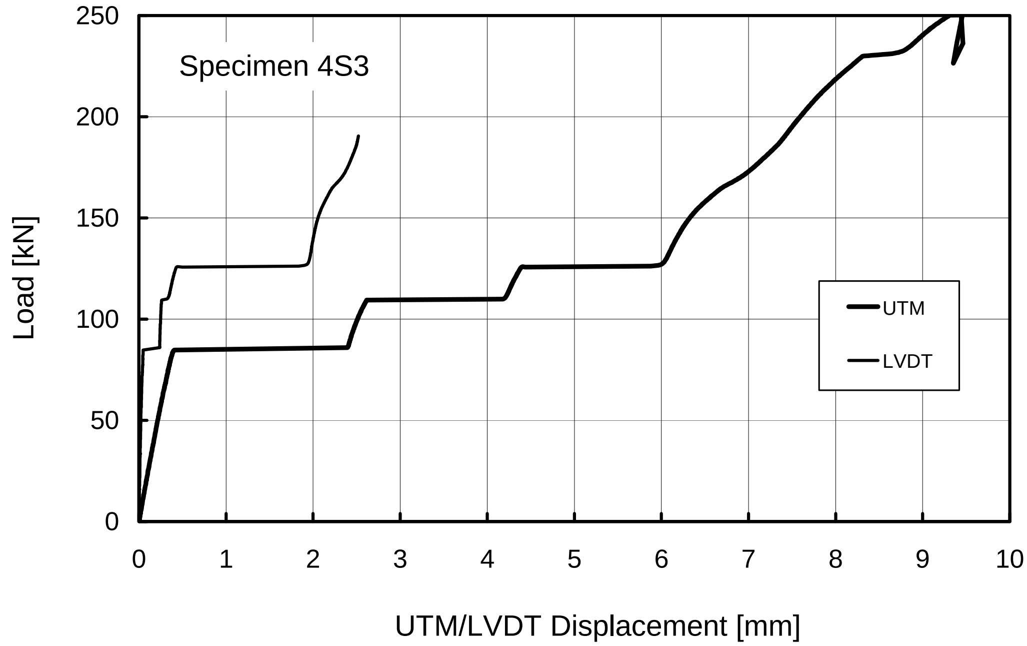

Figure 41 *– Load vs. displacement, 4S3.*

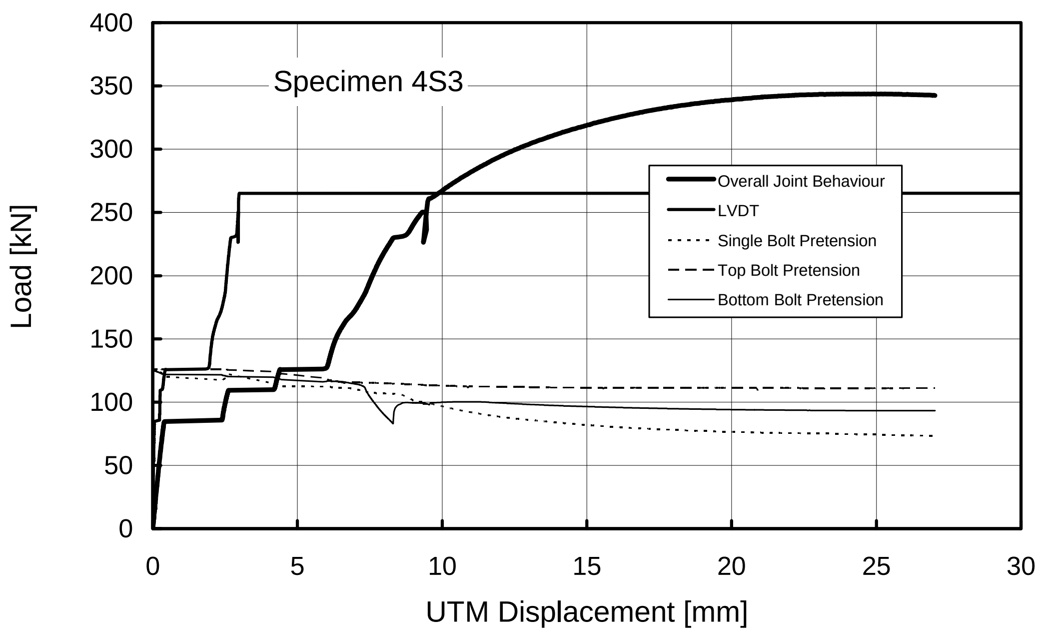

Figure 42 *– Load vs. displacement, 4S3.*

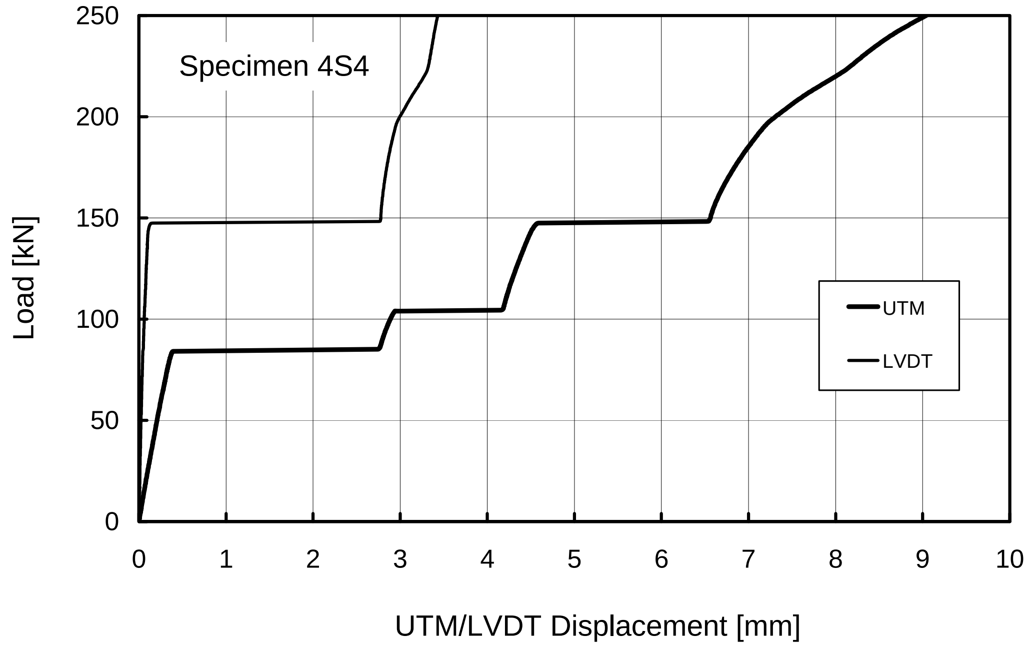

***Figure 43** – Load vs. displacement, 4S4.*

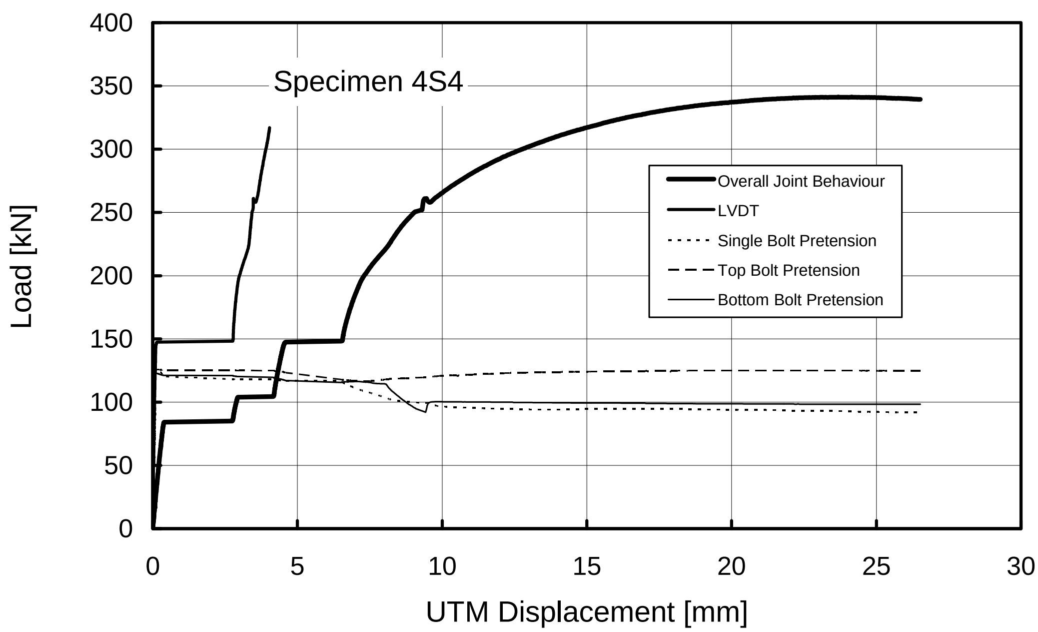

***Figure 44** – Load vs. displacement, 4S4.*

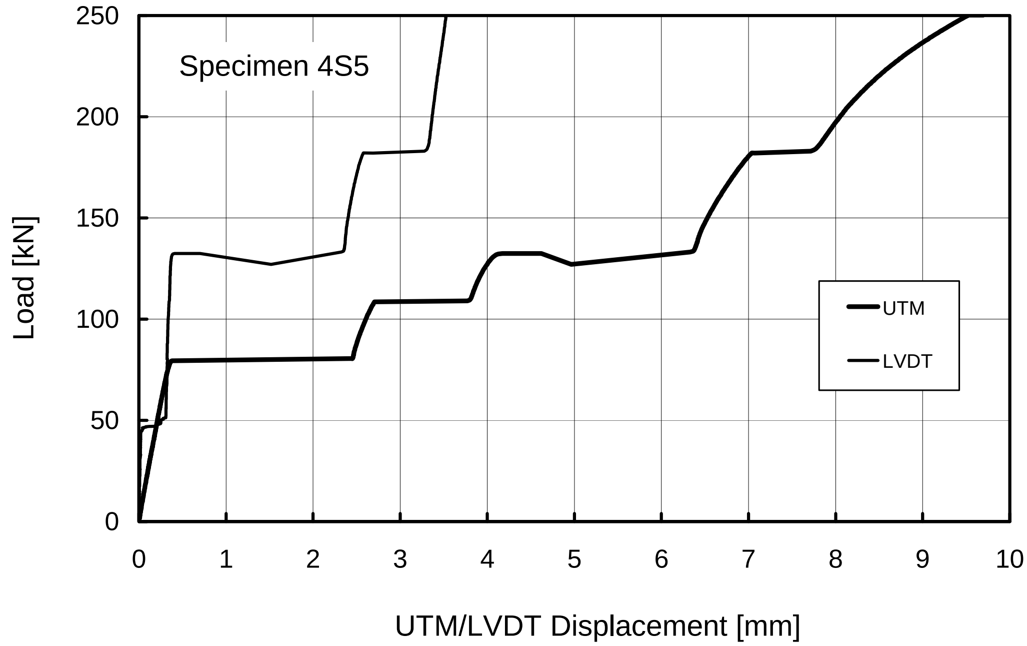

Figure 45 *– Load vs. displacement, 4S5.*

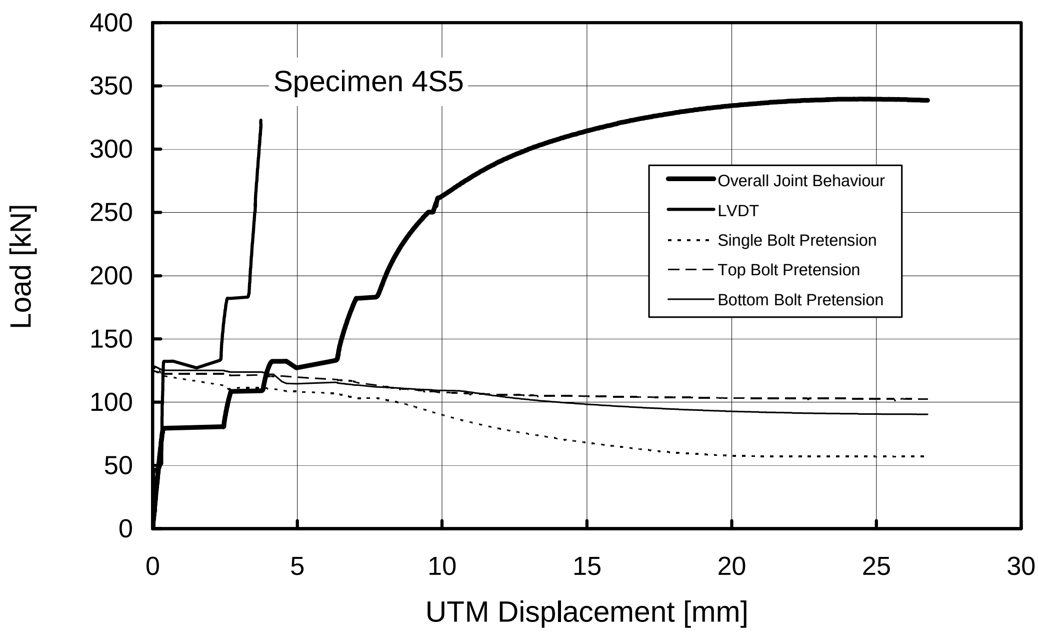

Figure 46 *– Load vs. displacement, 4S5.*

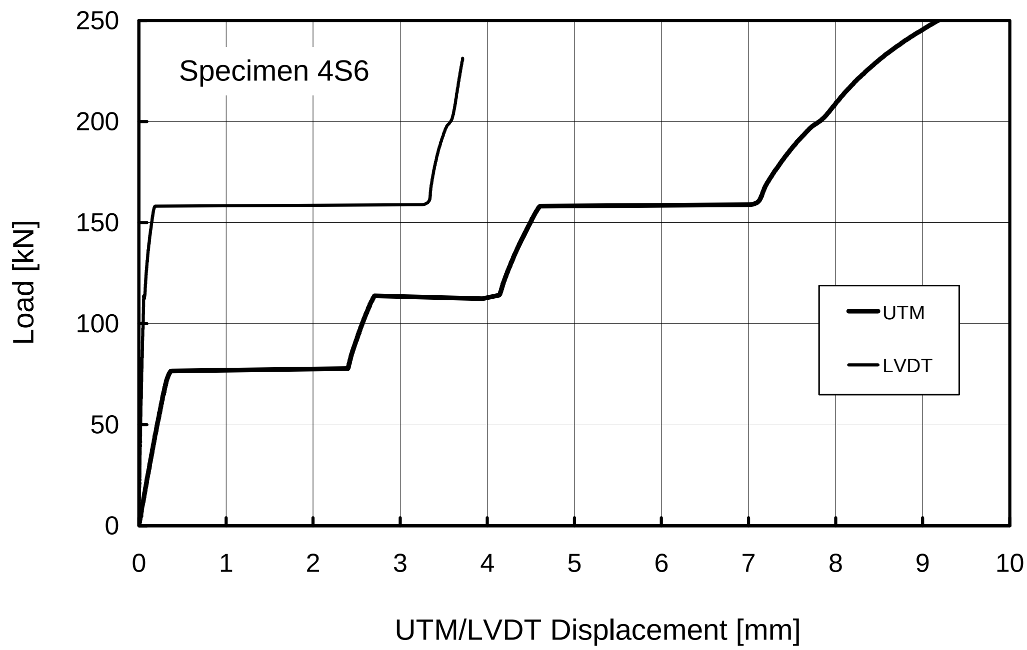

Figure 47 *– Load vs. displacement, 4S6.*

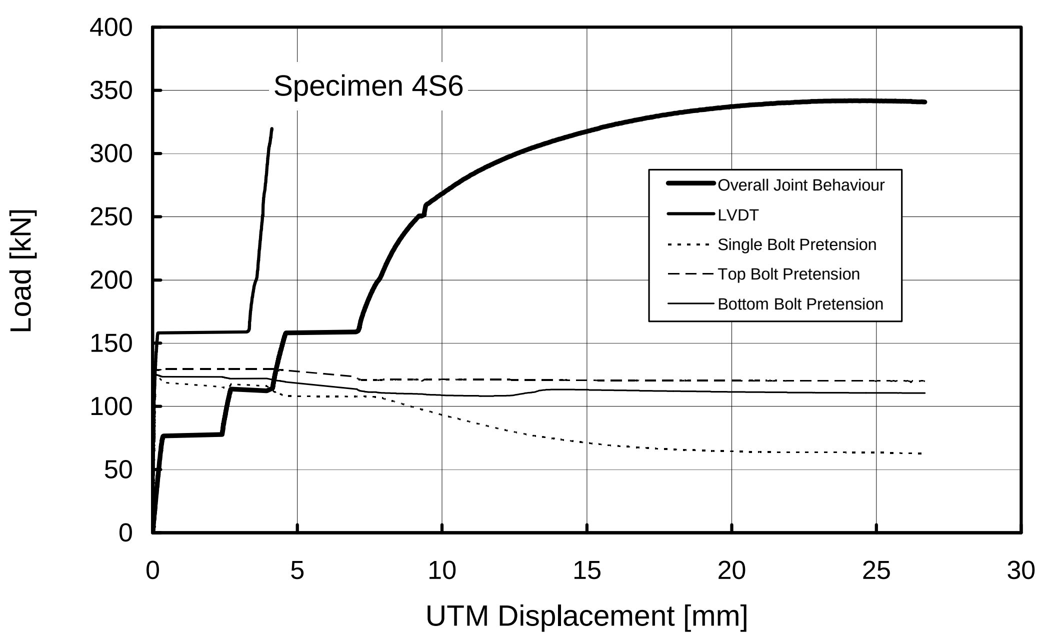

Figure 48 *– Load vs. displacement, 4S6.*

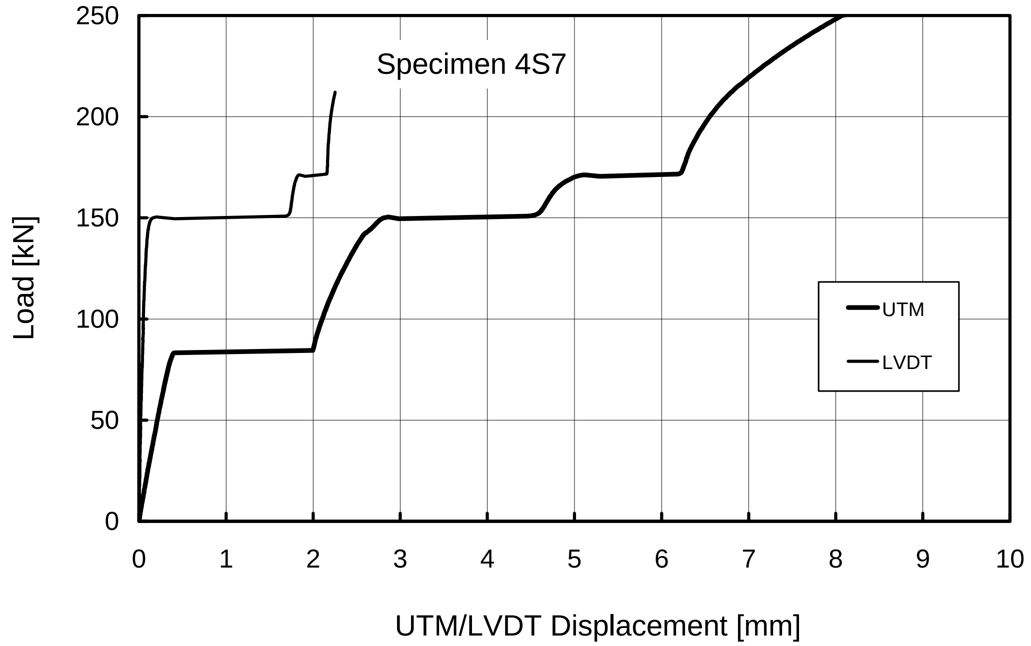

Figure 49 – *Load vs. displacement, 4S7.*

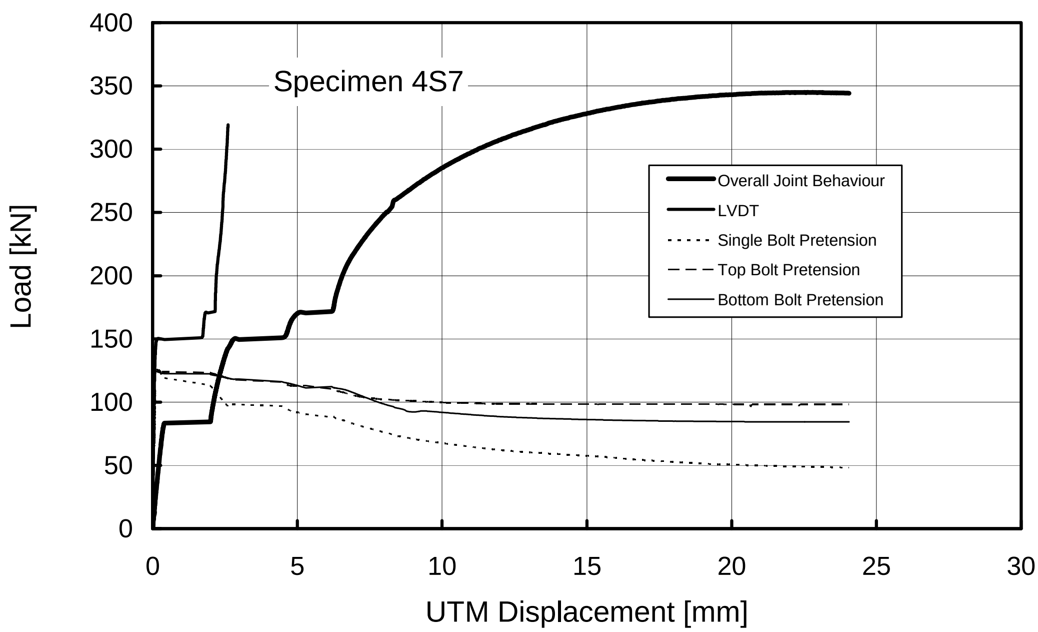

Figure 50 – *Load vs. displacement, 4S7.*

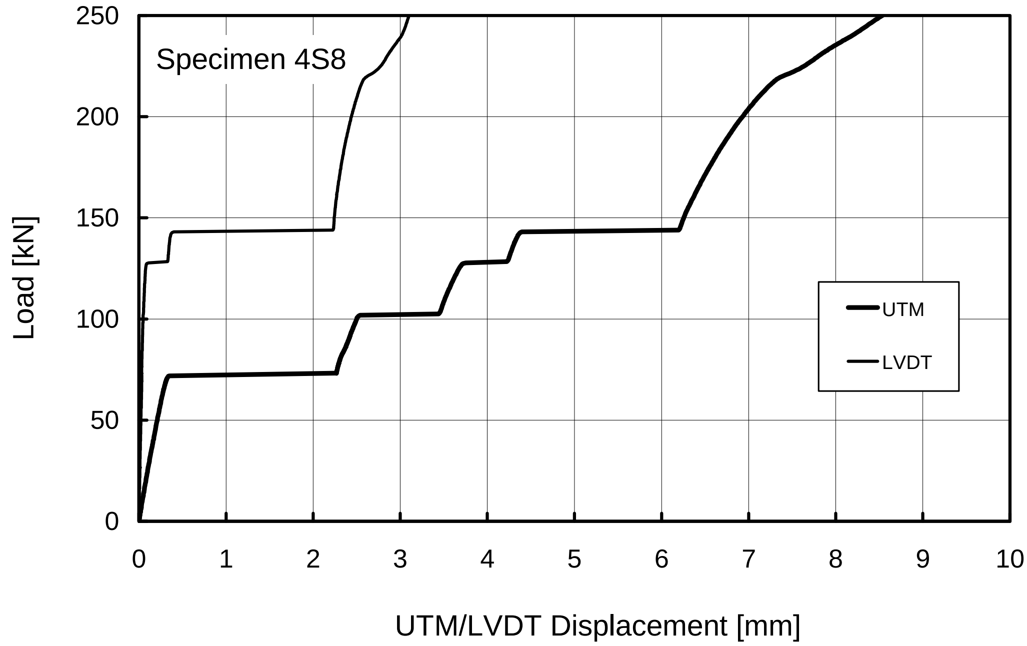

***Figure 51** – Load vs. displacement, 4S8.*

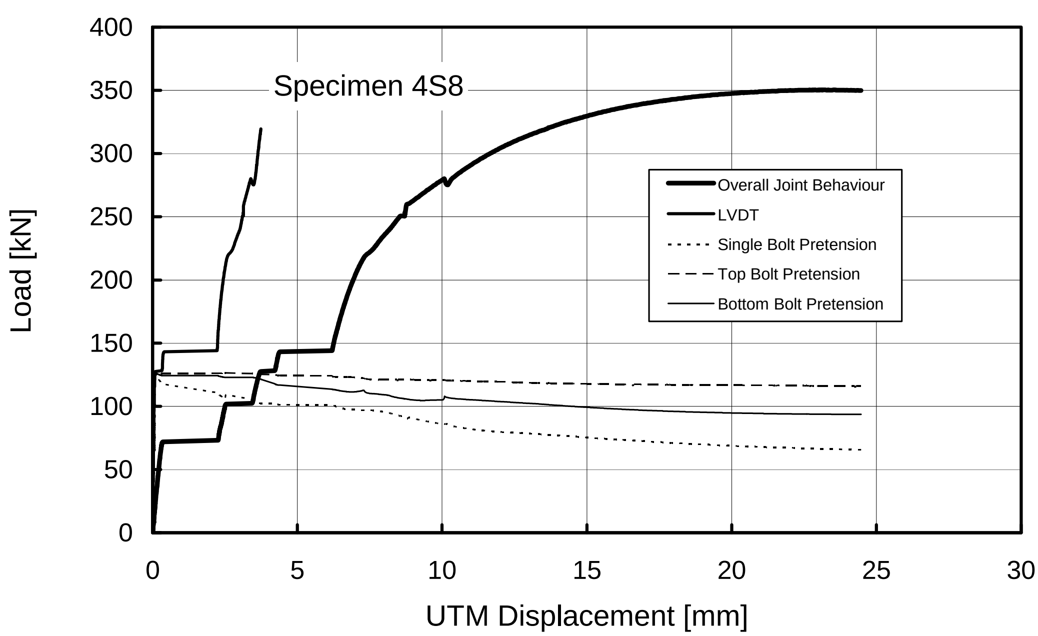

***Figure 52** – Load vs. displacement, 4S8.*

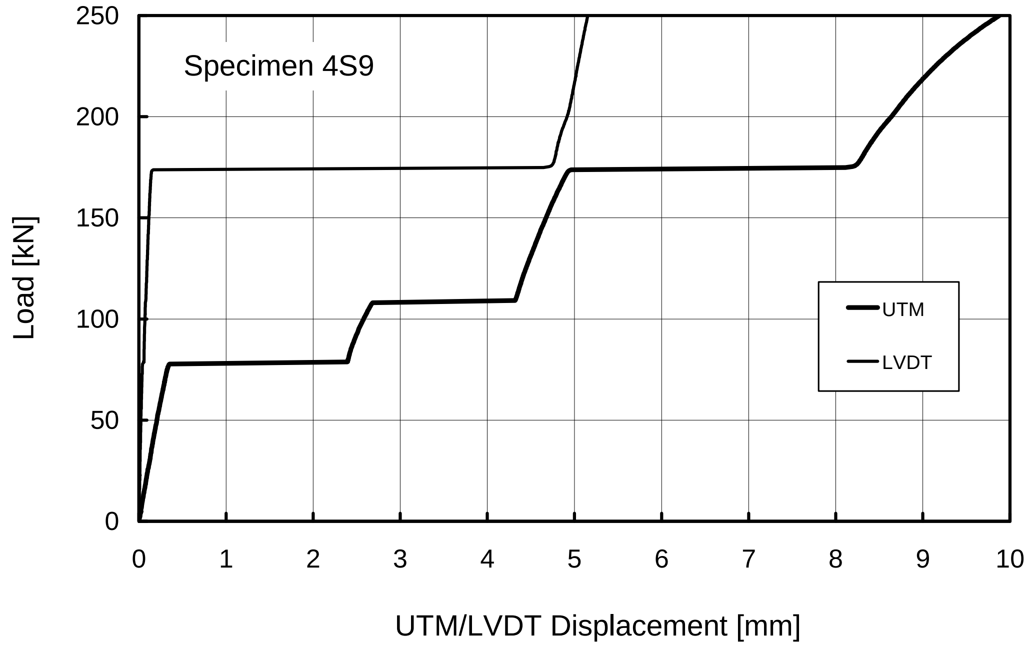

Figure 53 *– Load vs. displacement, 4S9.*

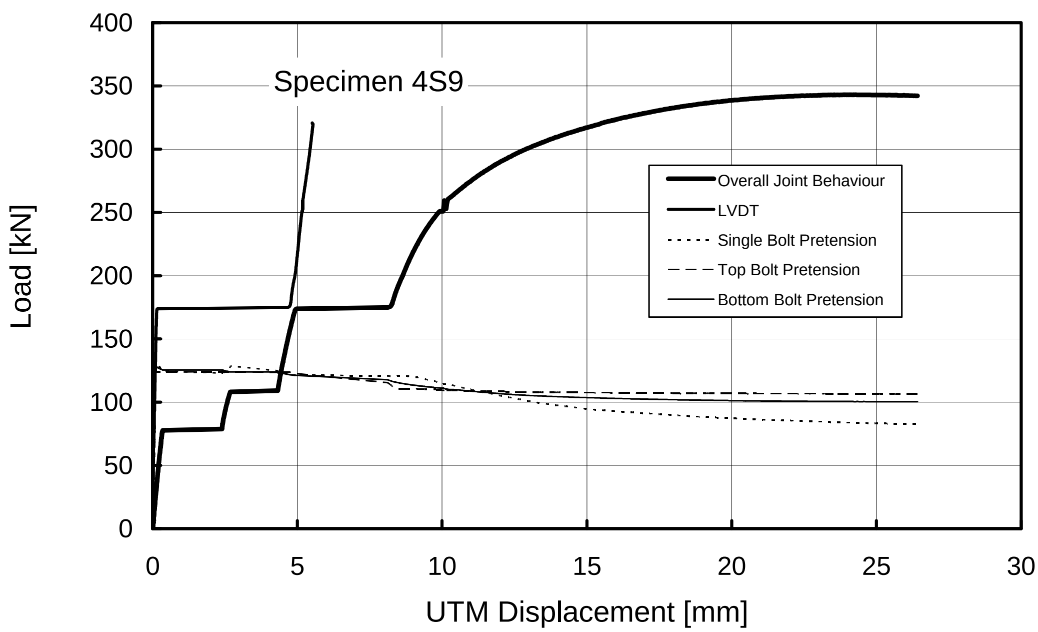

Figure 54 *– Load vs. displacement, 4S9.*

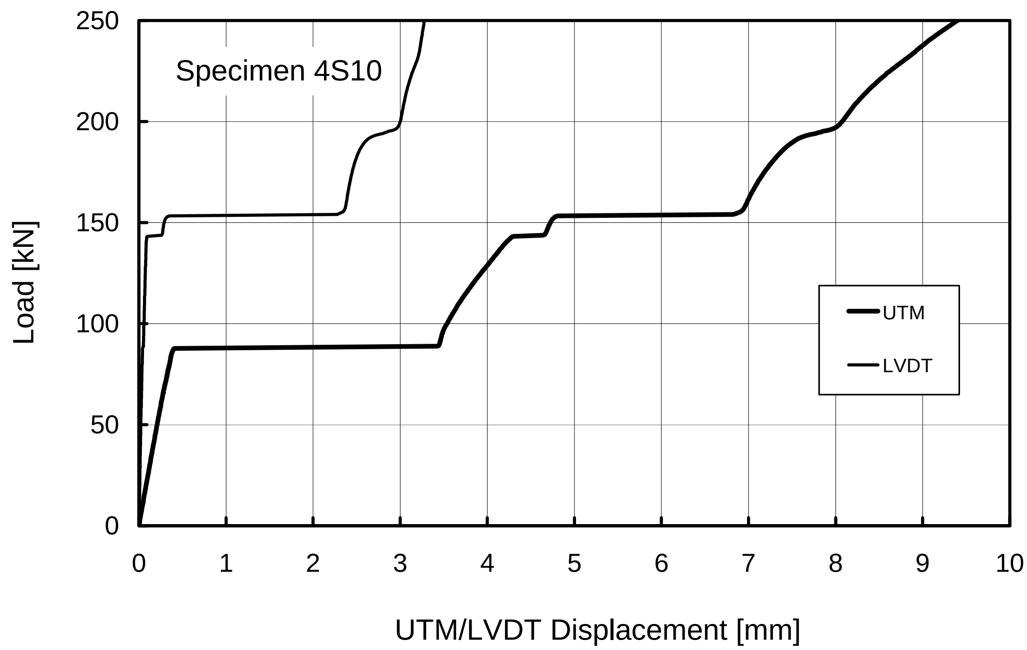

Figure 55 *– Load vs. displacement, 4S10.*

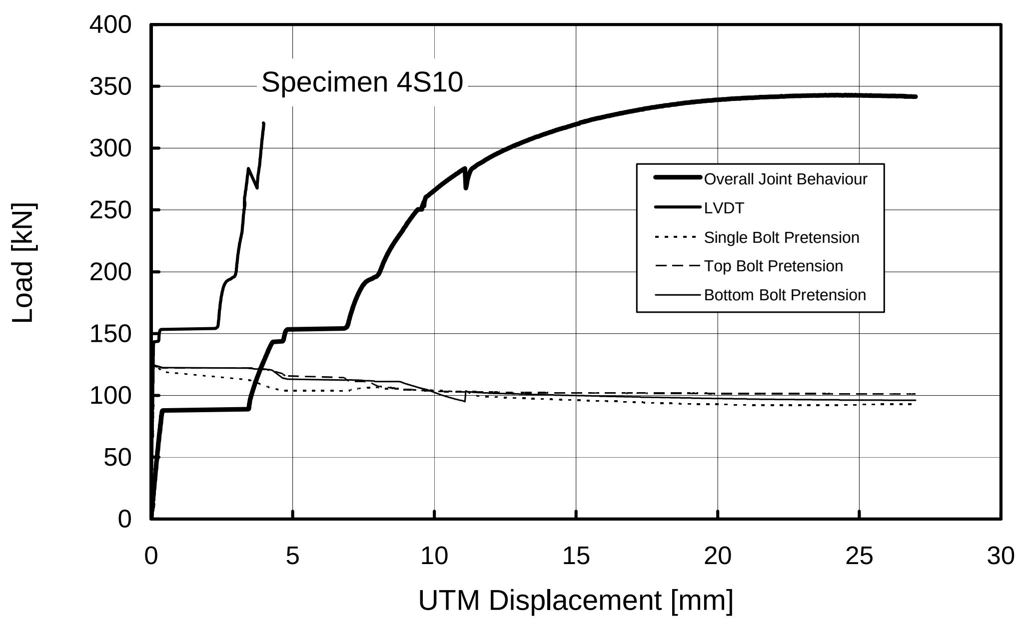

Figure 56 *– Load vs. displacement, 4S10.*

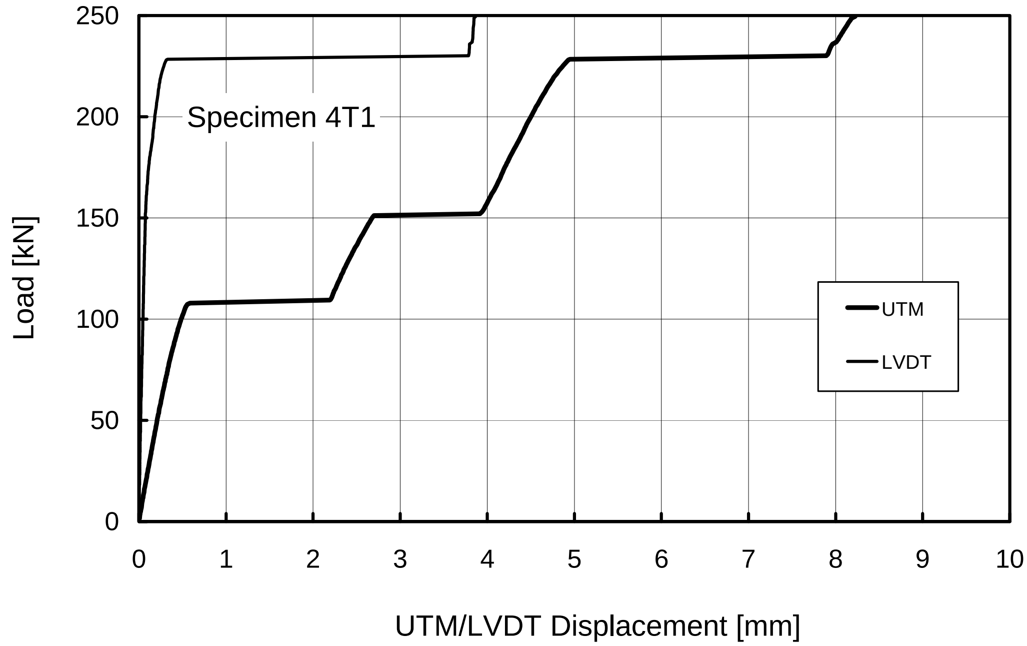

Figure 57 *– Load vs. displacement, 4T1.*

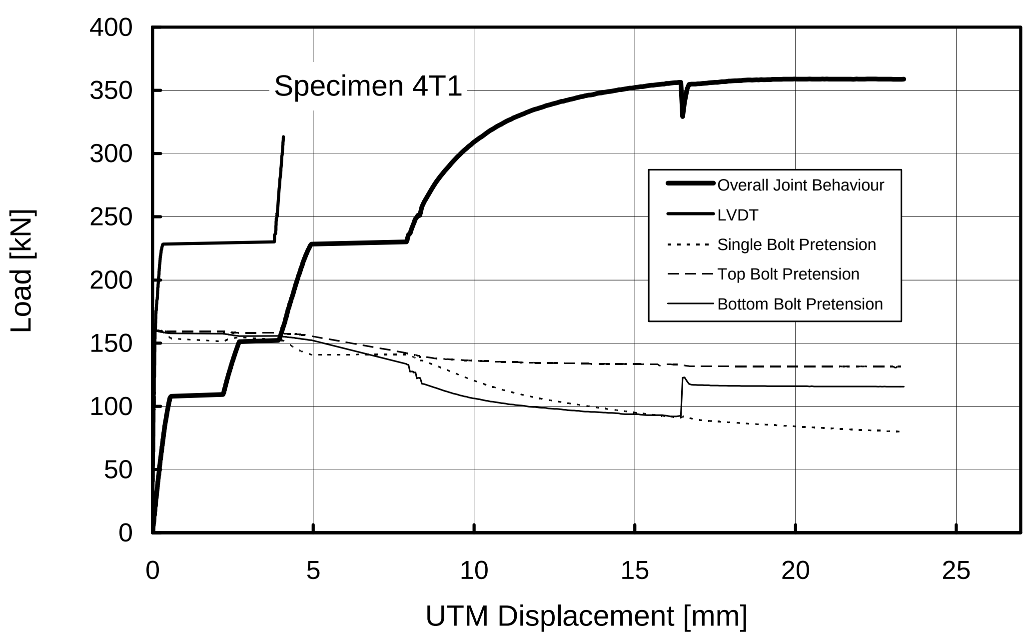

Figure 58 *– Load vs. displacement, 4T1.*

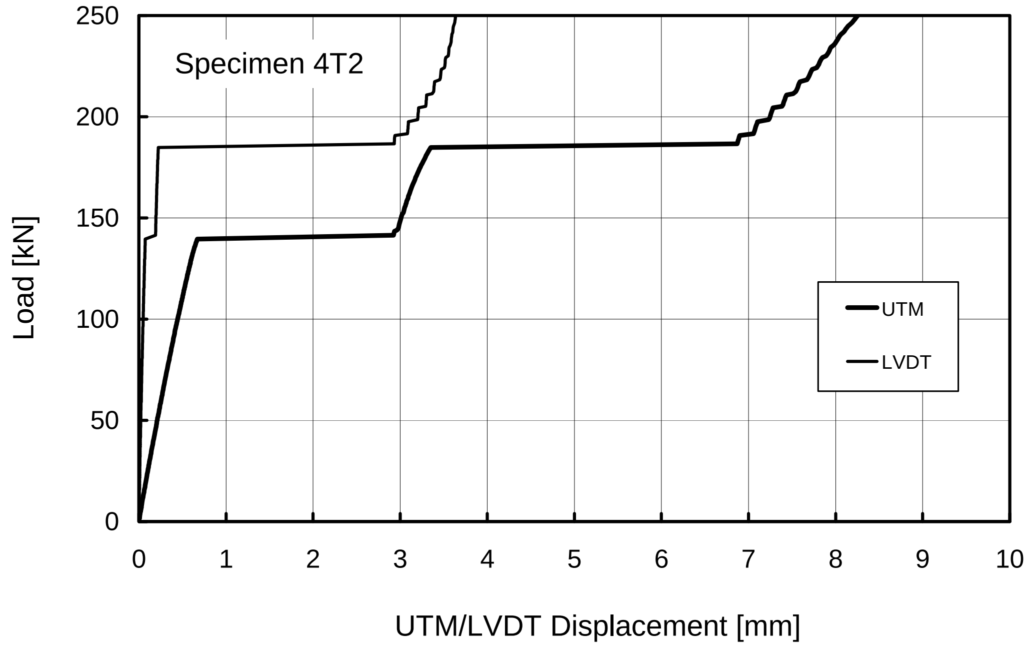

***Figure 59** – Load vs. displacement, 4T2.*

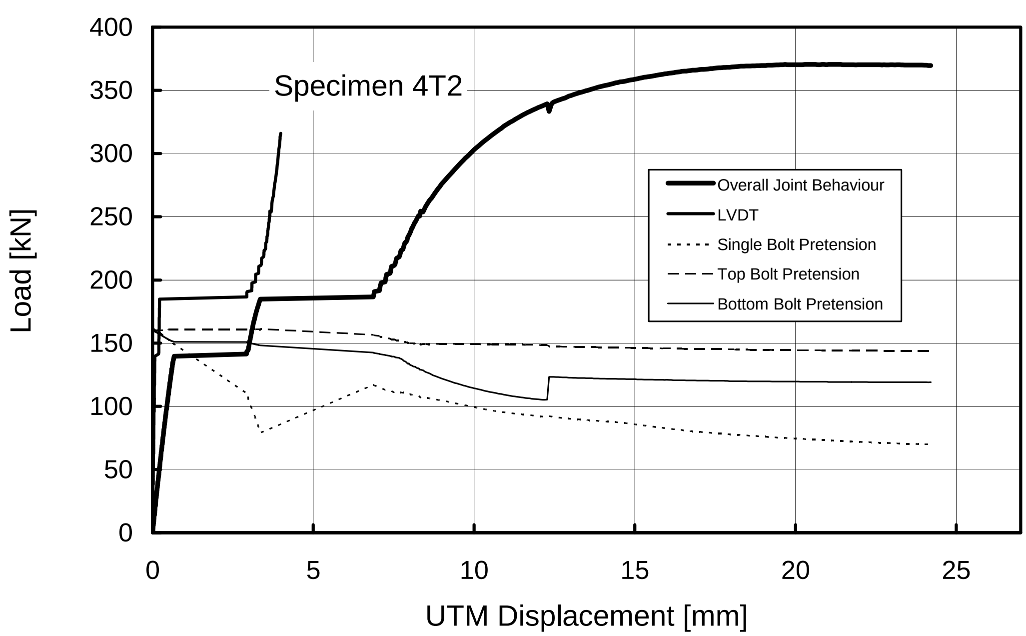

***Figure 60** – Load vs. displacement, 4T2.*

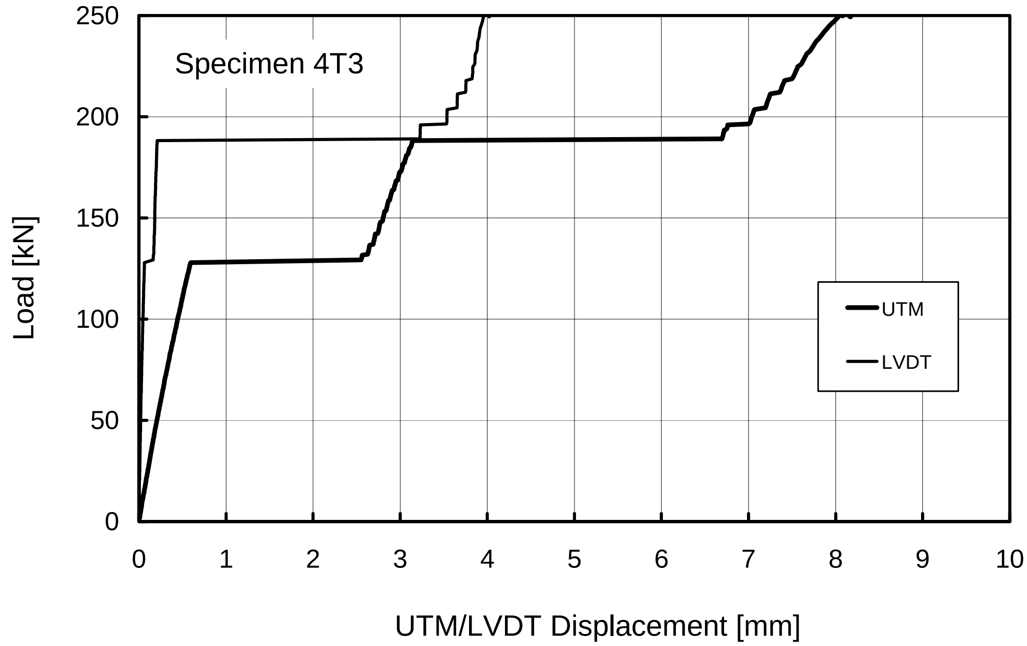

***Figure 61** – Load vs. displacement, 4T3.*

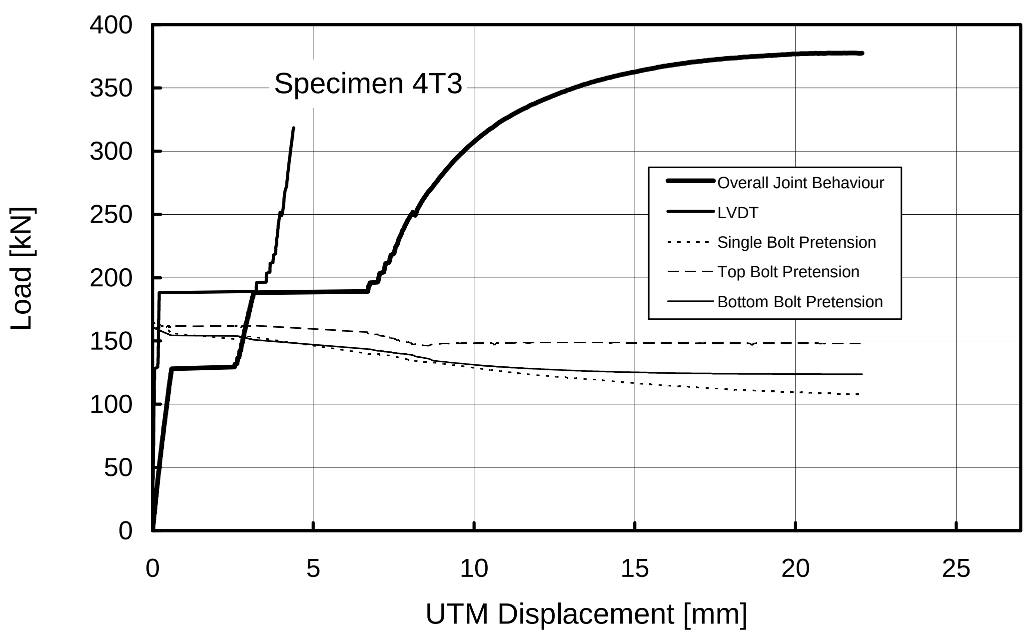

***Figure 62** – Load vs. displacement, 4T3.*

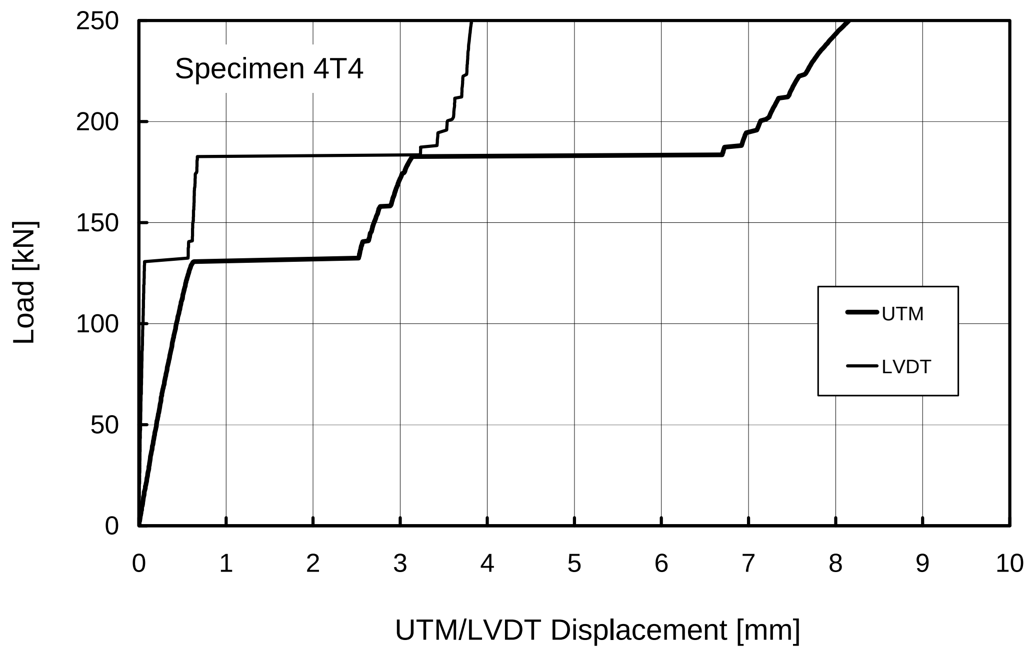

***Figure 63** – Load vs. displacement, 4T4.*

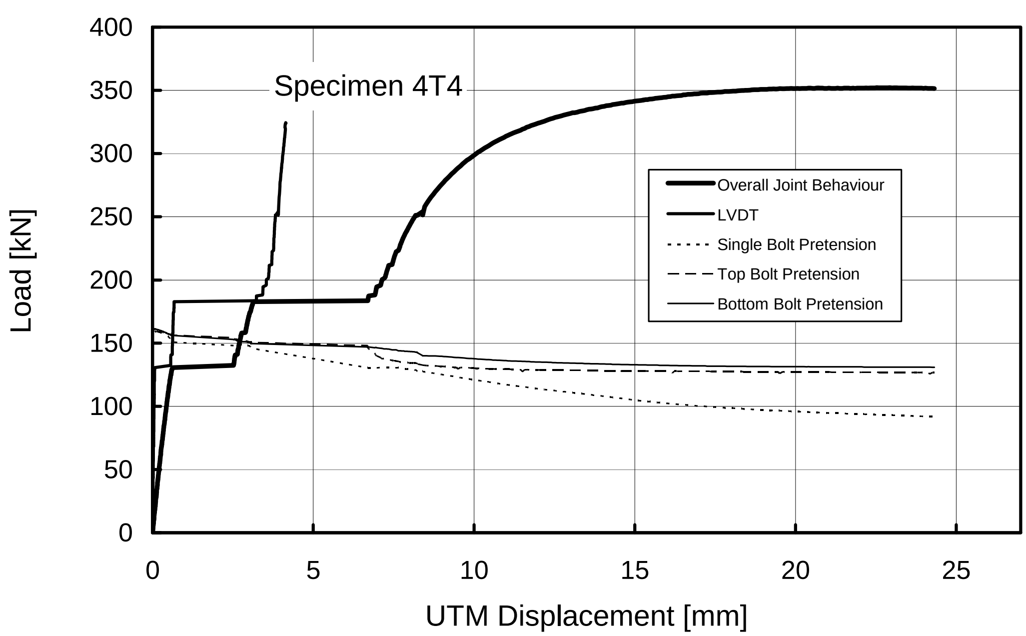

***Figure 64** – Load vs. displacement, 4T4.*

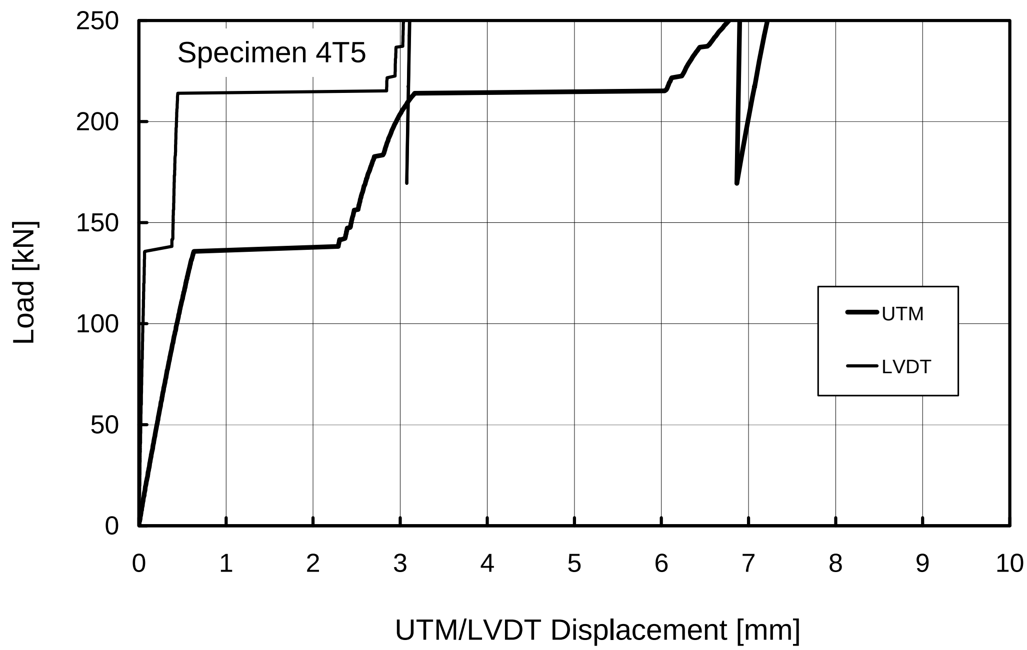

Figure 65 *– Load vs. displacement, 4T5.*

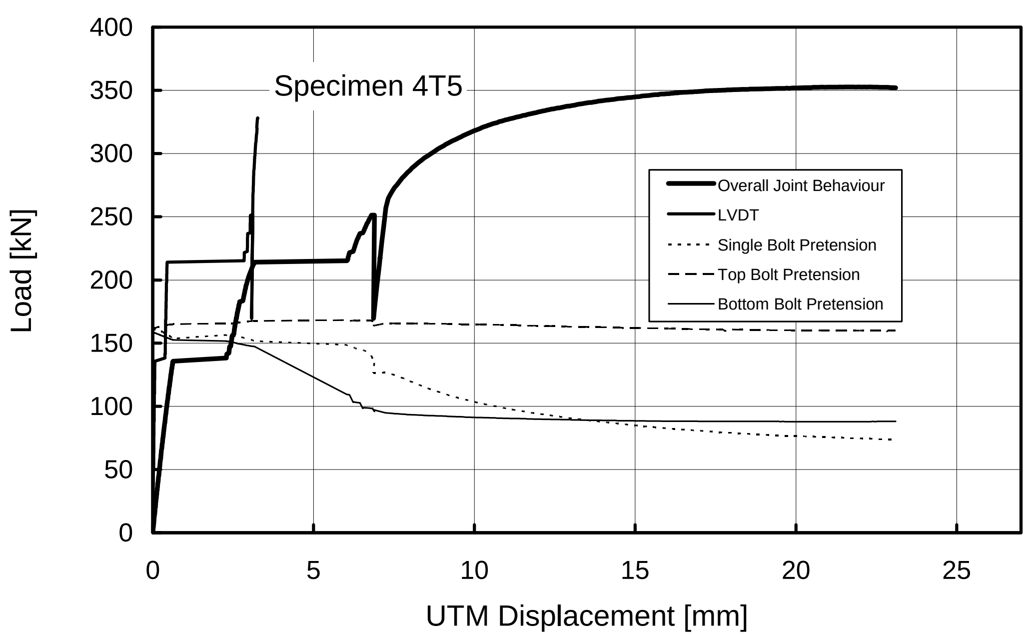

Figure 66 *– Load vs. displacement, 4T5.*

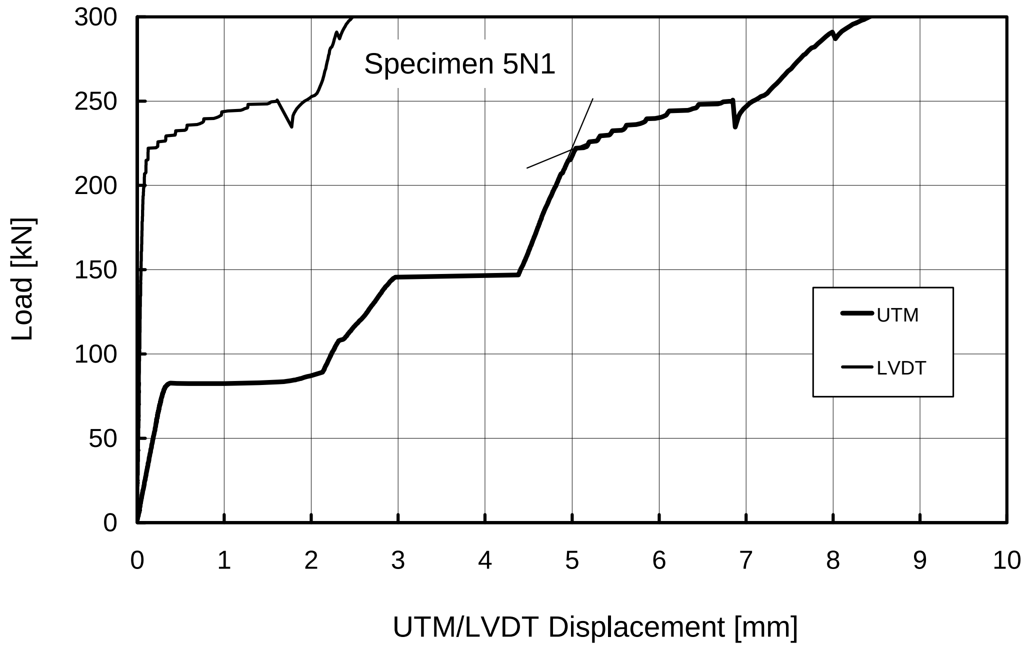

Figure 67 – *Load vs. displacement, 5N1.*

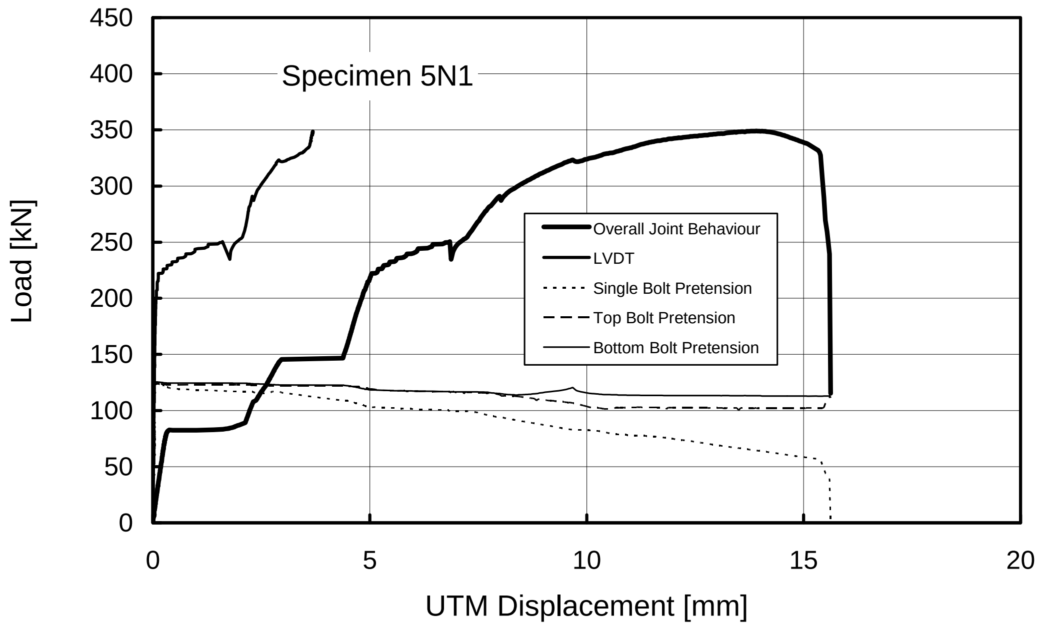

Figure 68 – *Load vs. displacement, 5N1.*

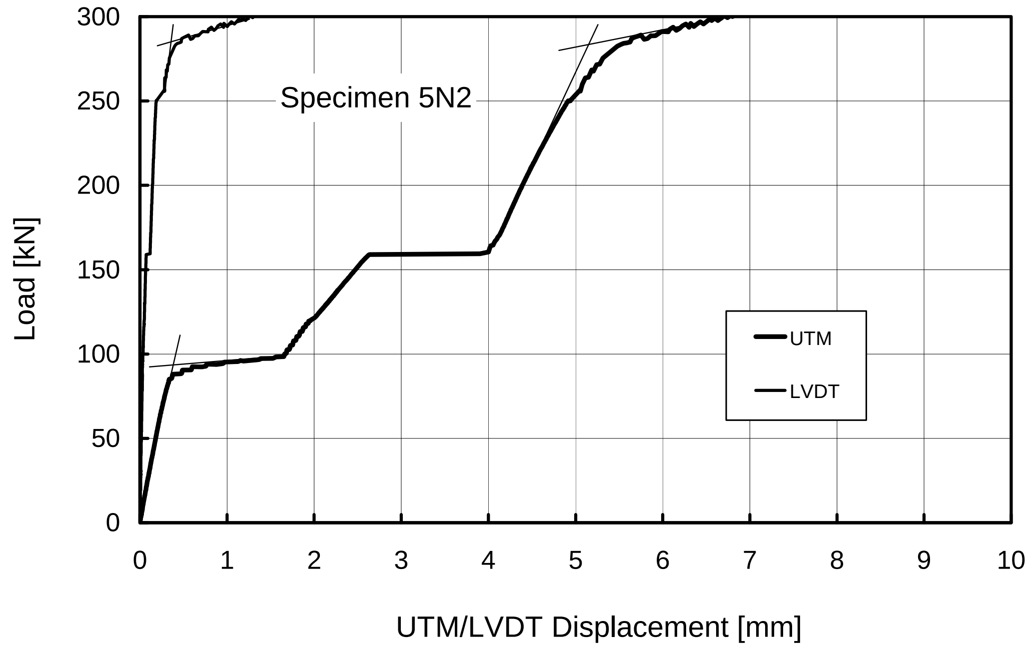

Figure 69 – *Load vs. displacement, 5N2.*

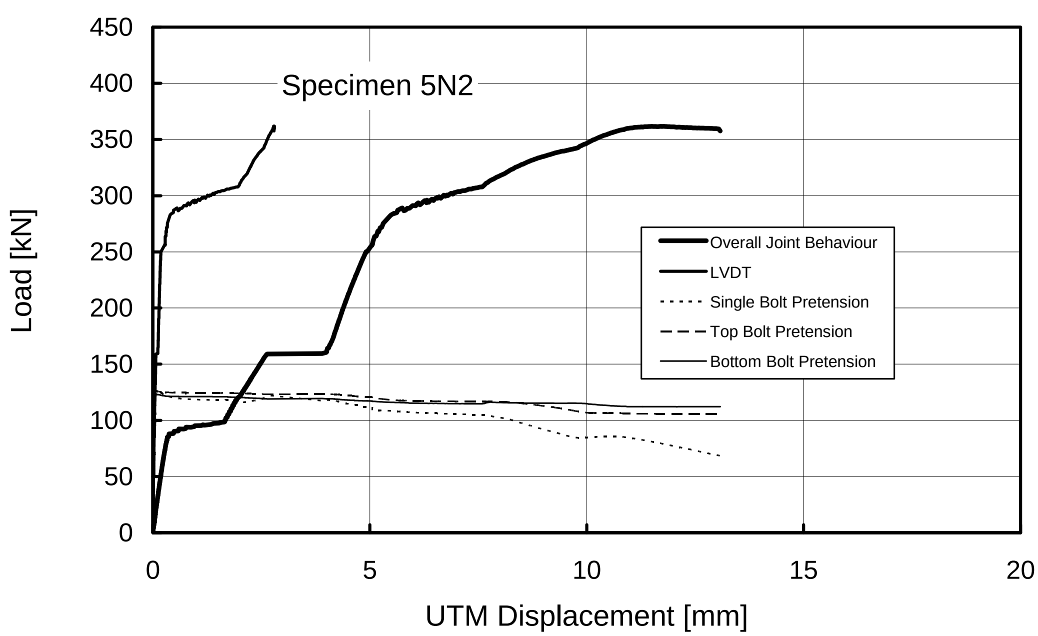

Figure 70 – *Load vs. displacement, 5N2.*

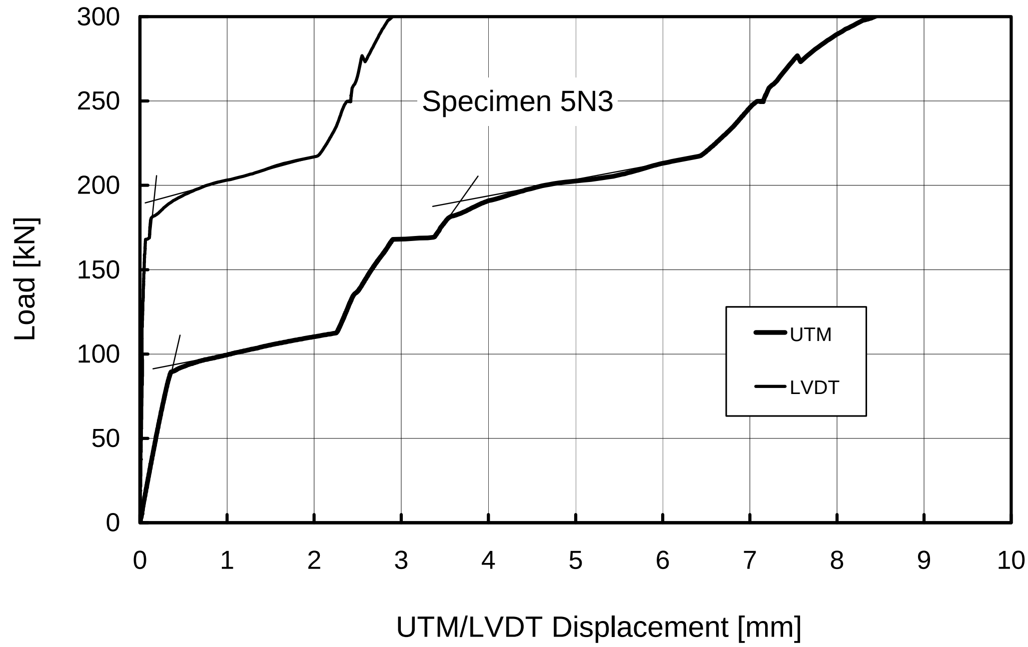

Figure 71 *– Load vs. displacement, 5N3.*

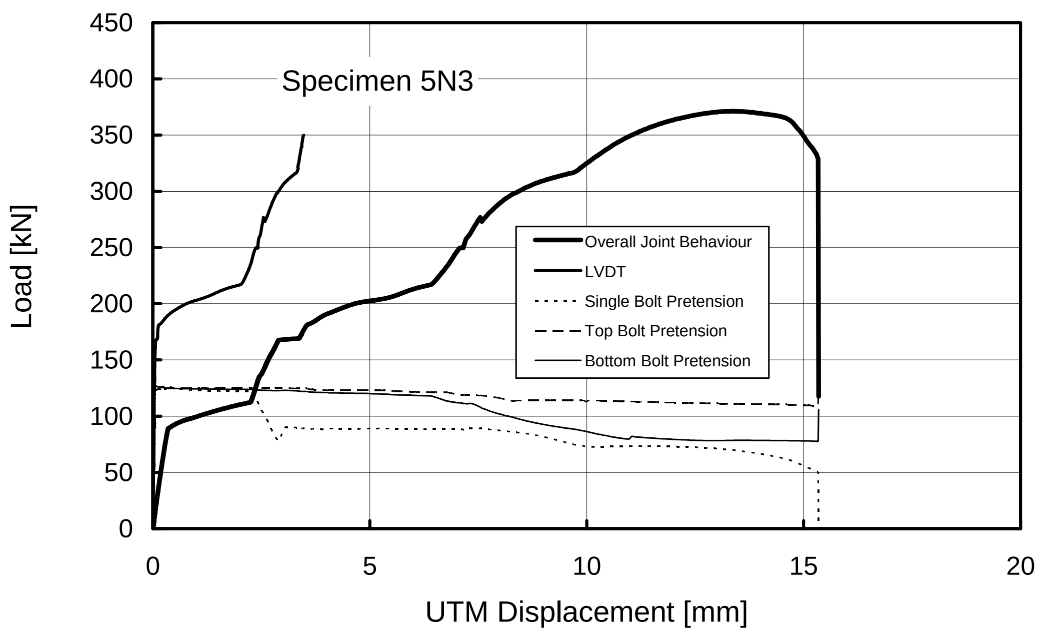

Figure 72 *– Load vs. displacement, 5N3.*

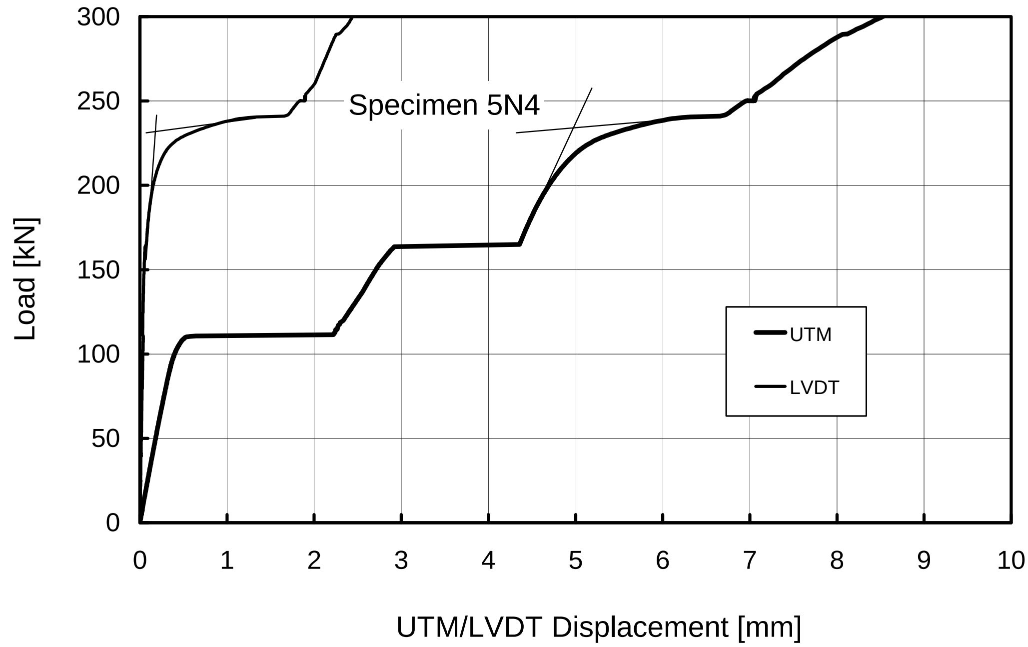

__Figure 73__ – Load vs. displacement, 5N4.

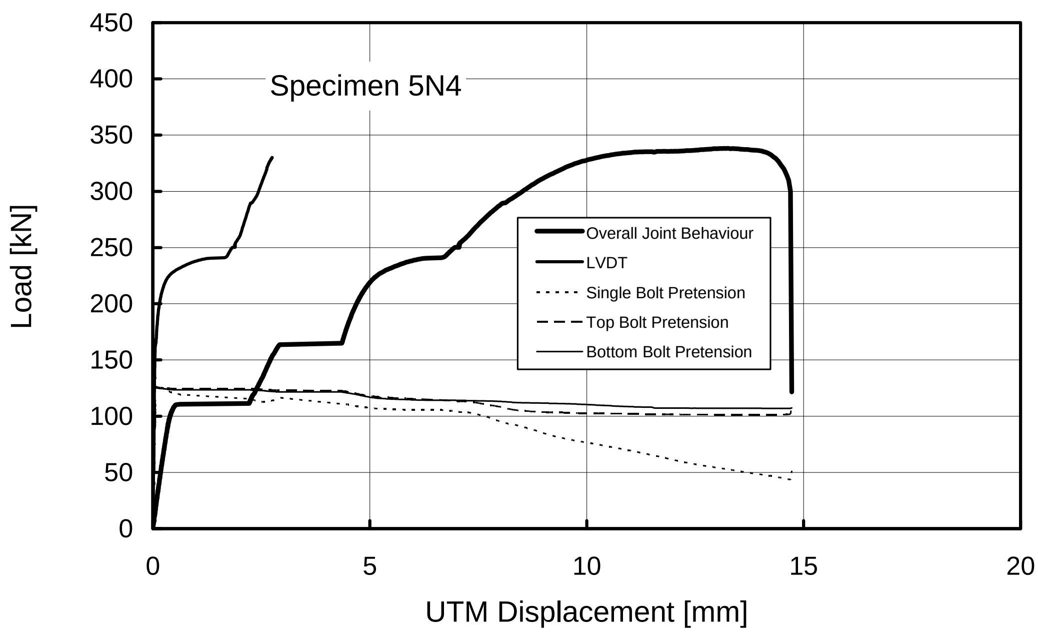

__Figure 74__ – Load vs. displacement, 5N4.

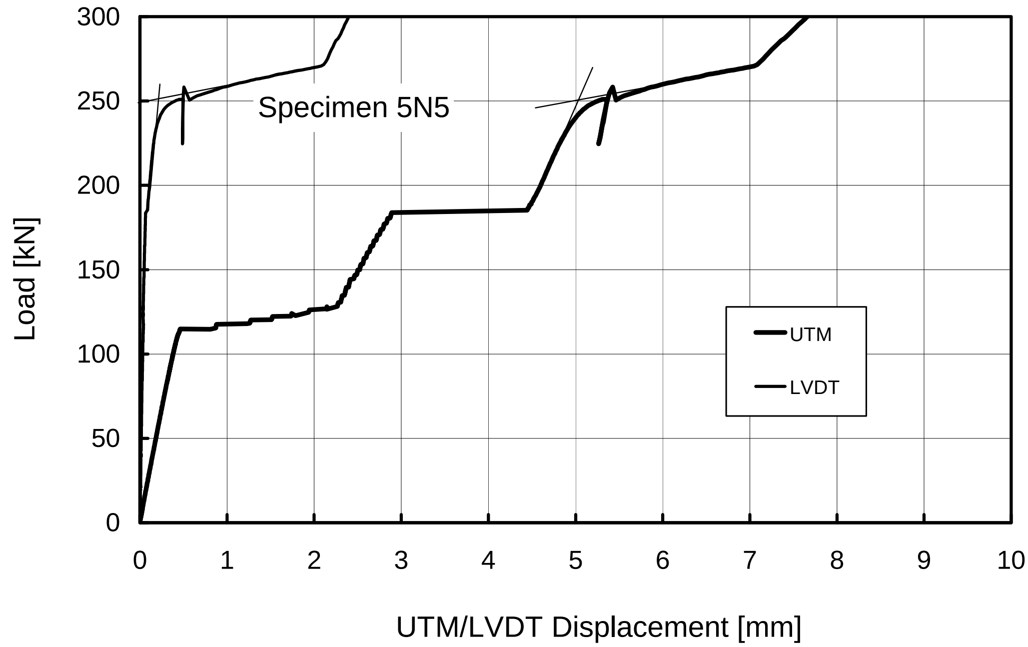

***Figure 75** – Load vs. displacement, 5N5.*

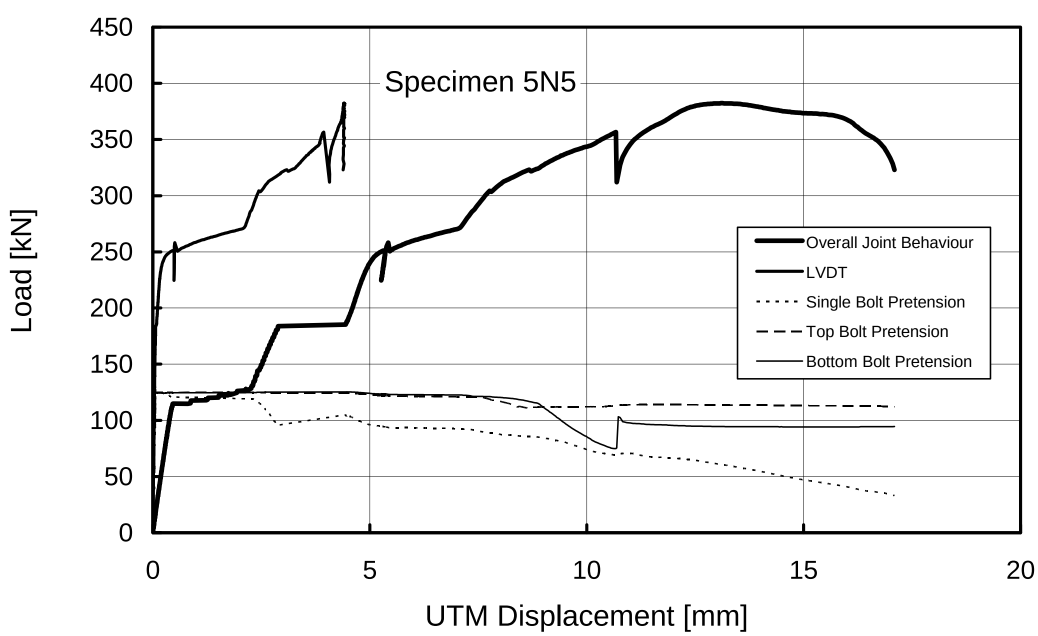

***Figure 76** – Load vs. displacement, 5N5.*

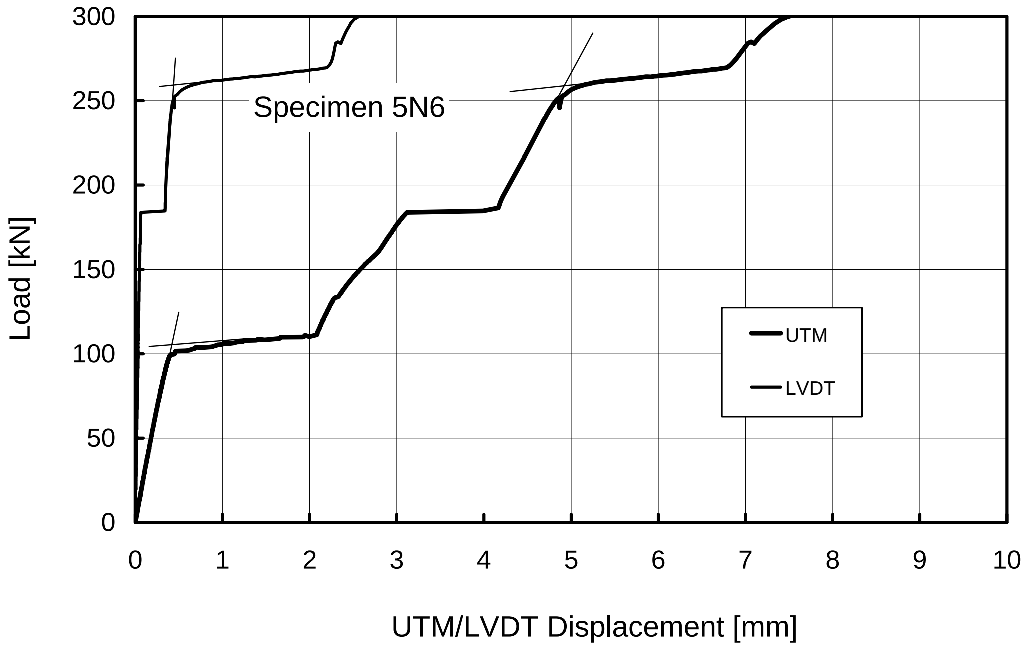

Figure 77 – Load vs. displacement, 5N6.

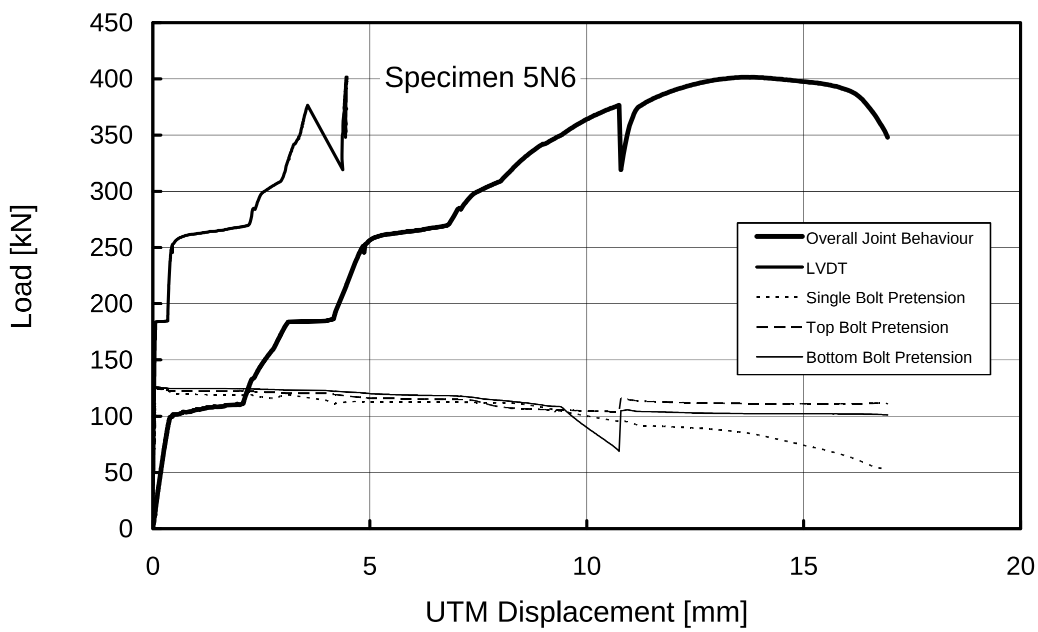

Figure 78 – Load vs. displacement, 5N6.

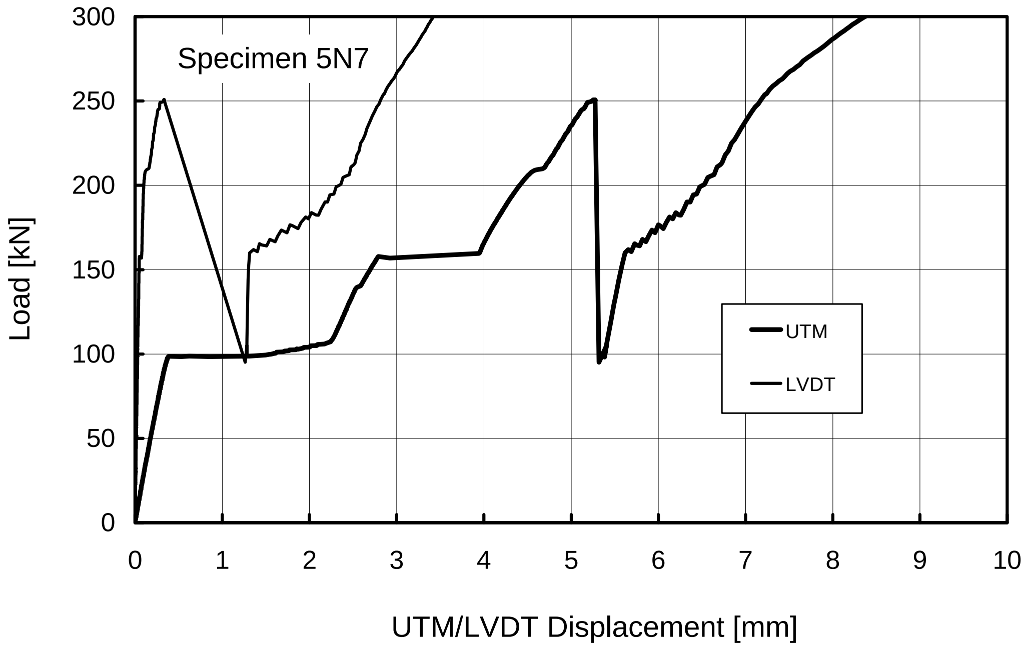

Figure 79 *– Load vs. displacement, 5N7.*

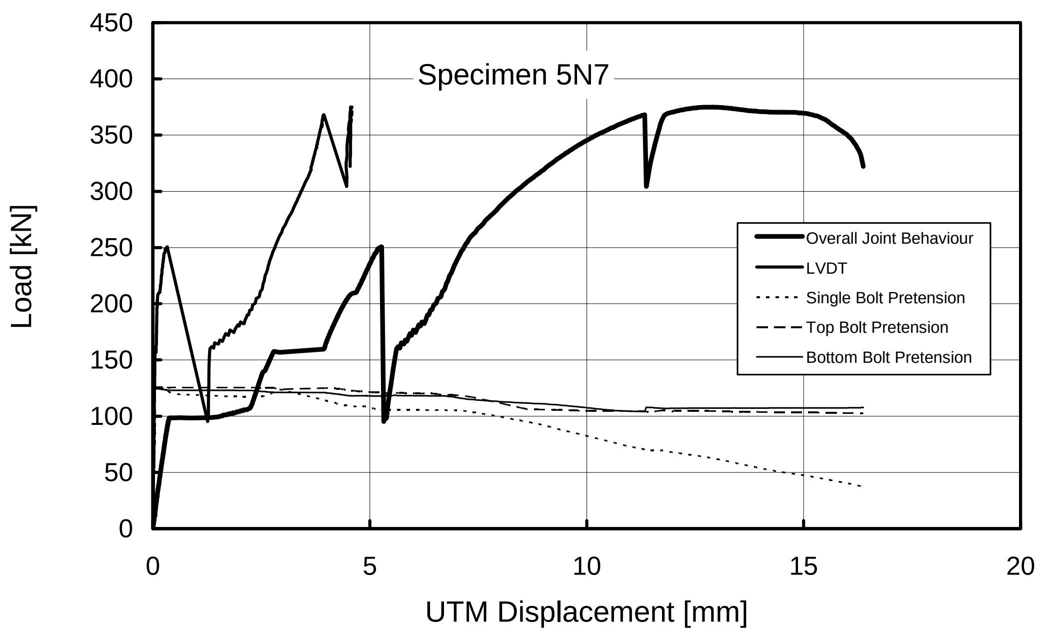

Figure 80 *– Load vs. displacement, 5N7.*

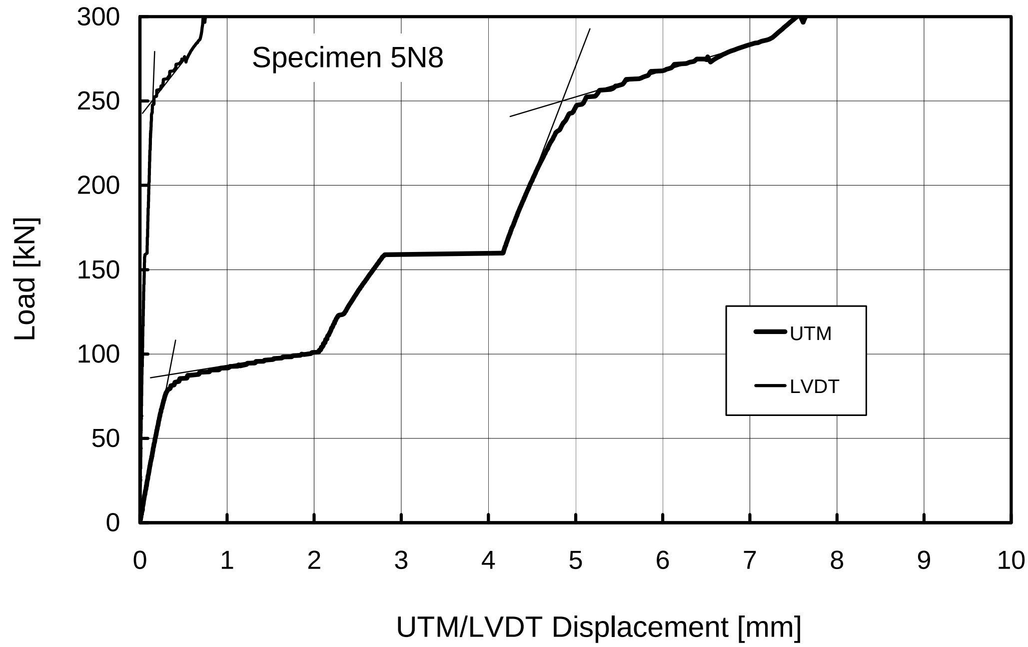

__Figure 81__ – Load vs. displacement, 5N8.

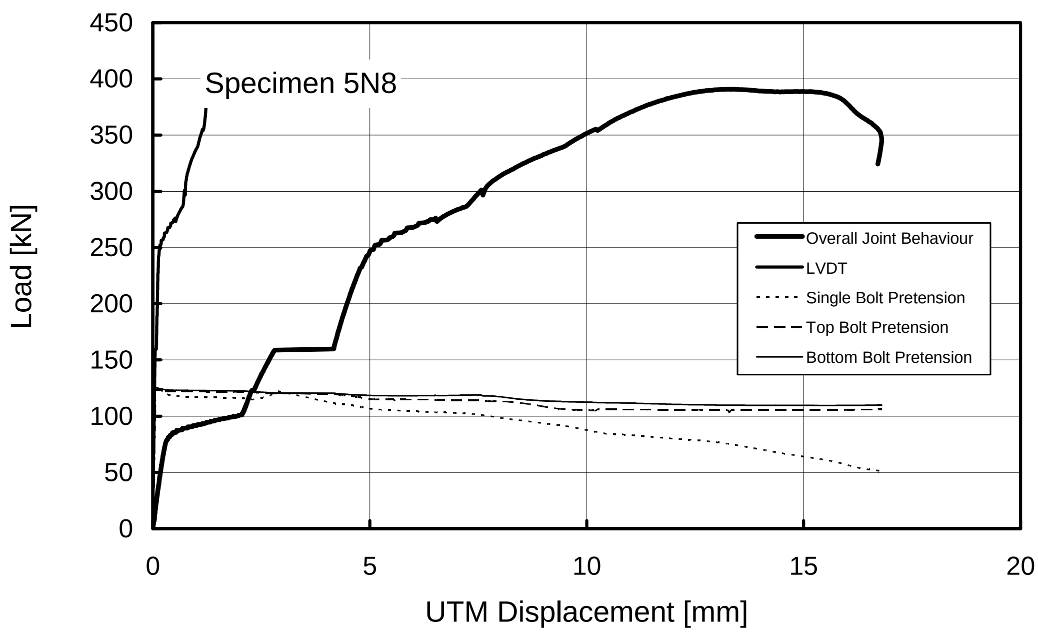

__Figure 82__ – Load vs. displacement, 5N8.

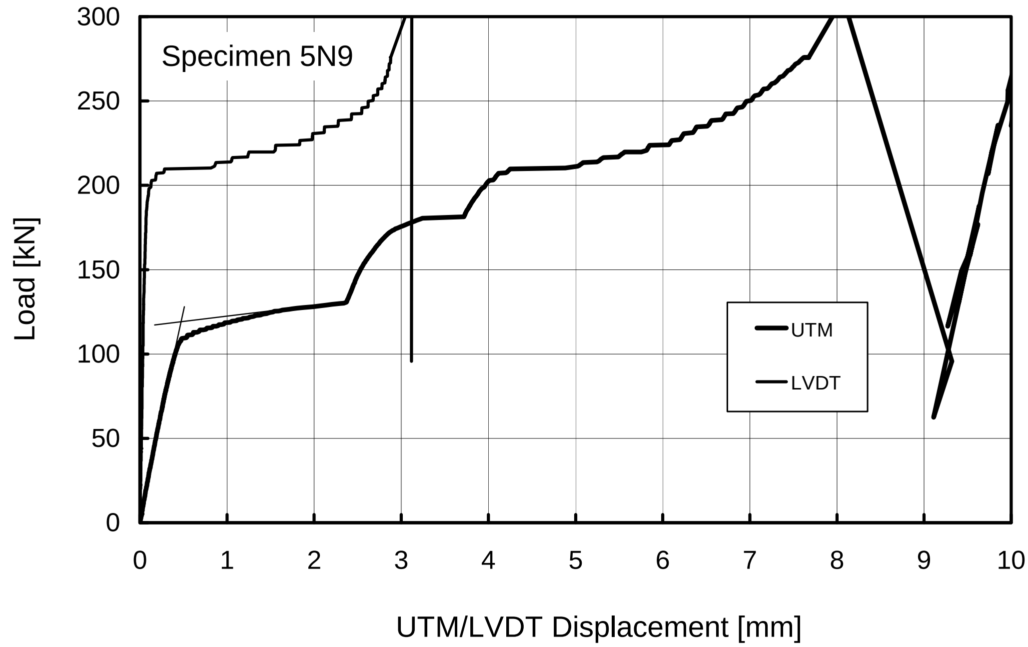

Figure 83 *– Load vs. displacement, 5N9.*

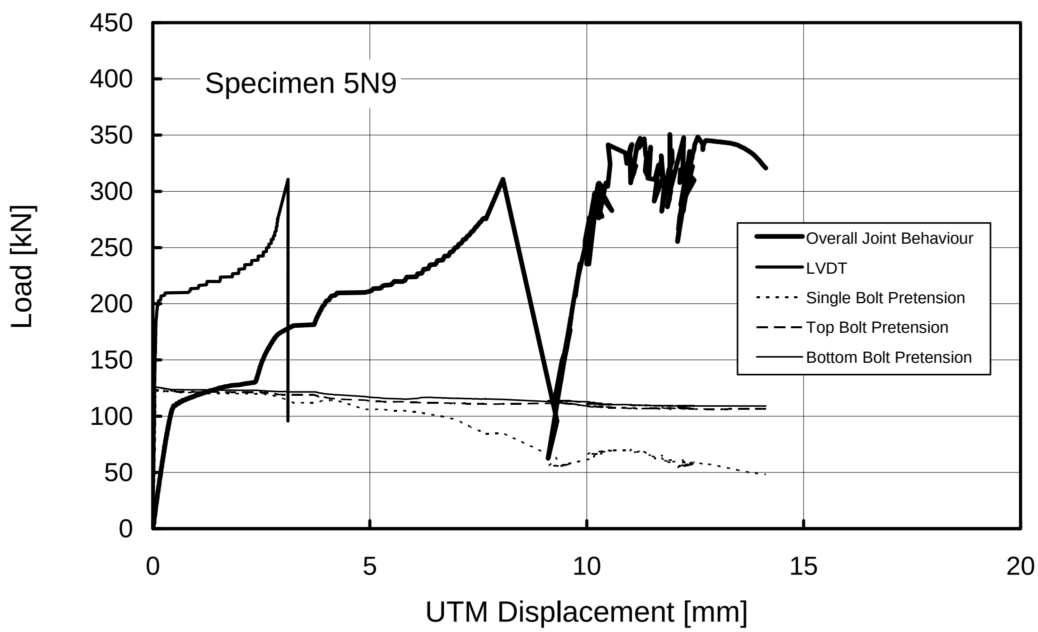

Figure 84 *– Load vs. displacement, 5N9.*

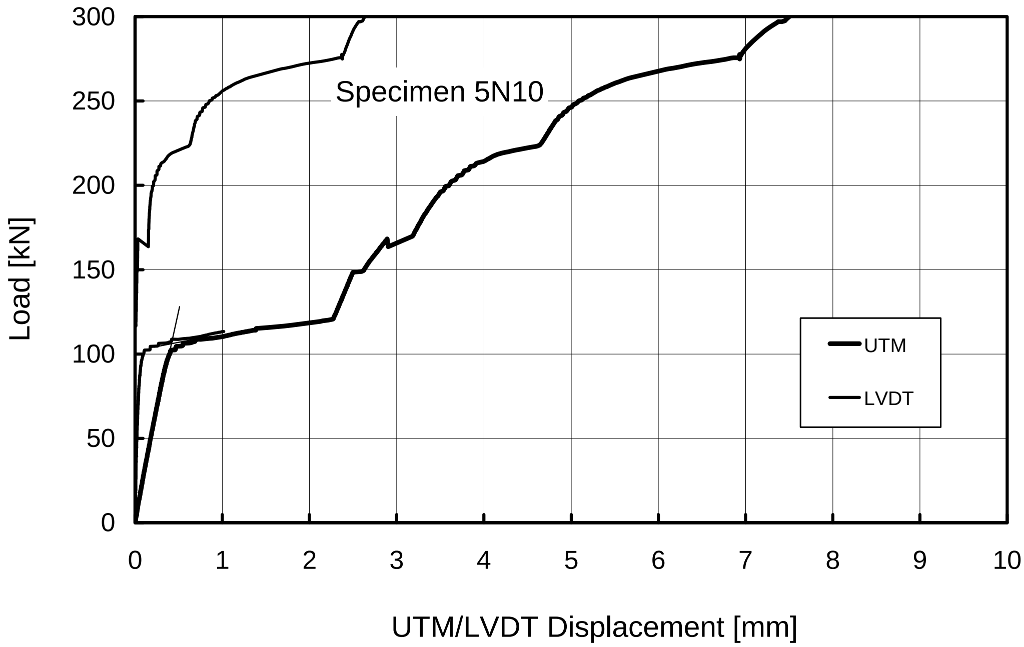

***Figure 85** – Load vs. displacement, 5N10.*

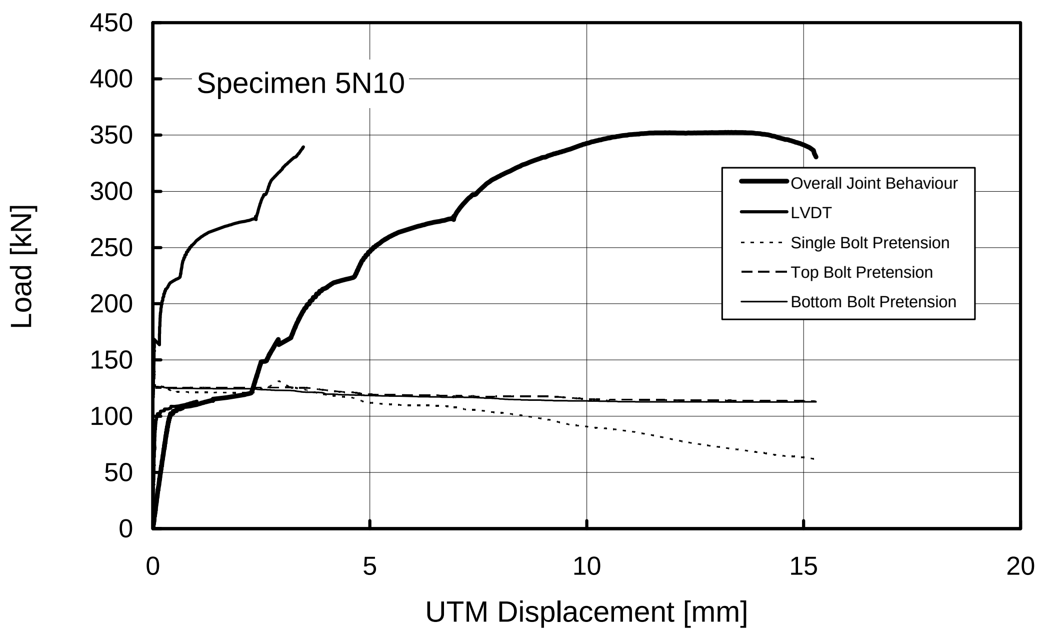

***Figure 86** – Load vs. displacement, 5N10.*

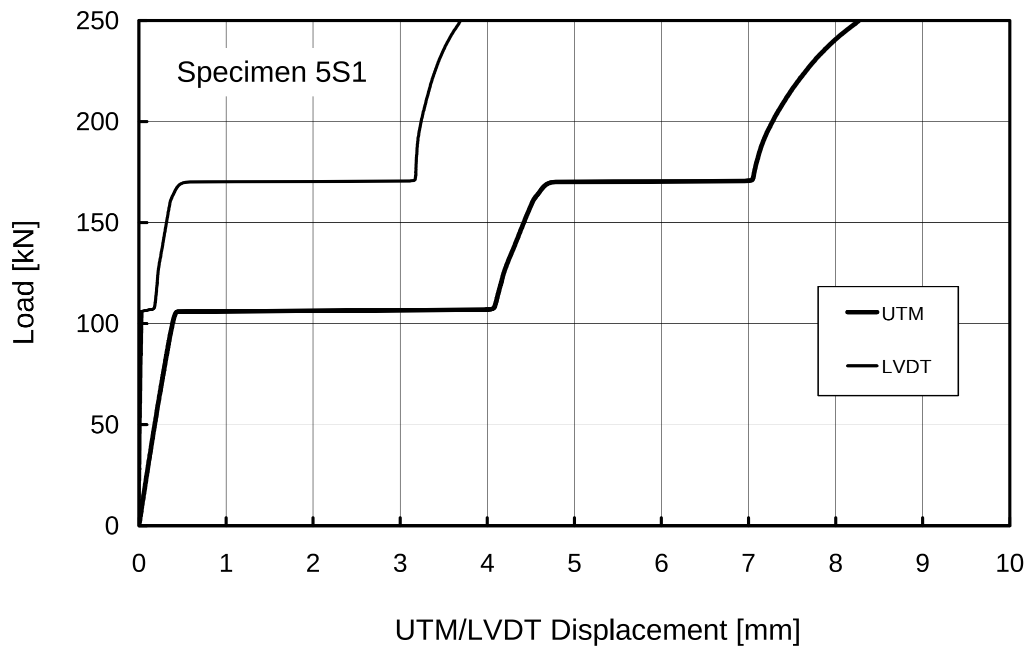

***Figure 87** – Load vs. displacement, 5S1.*

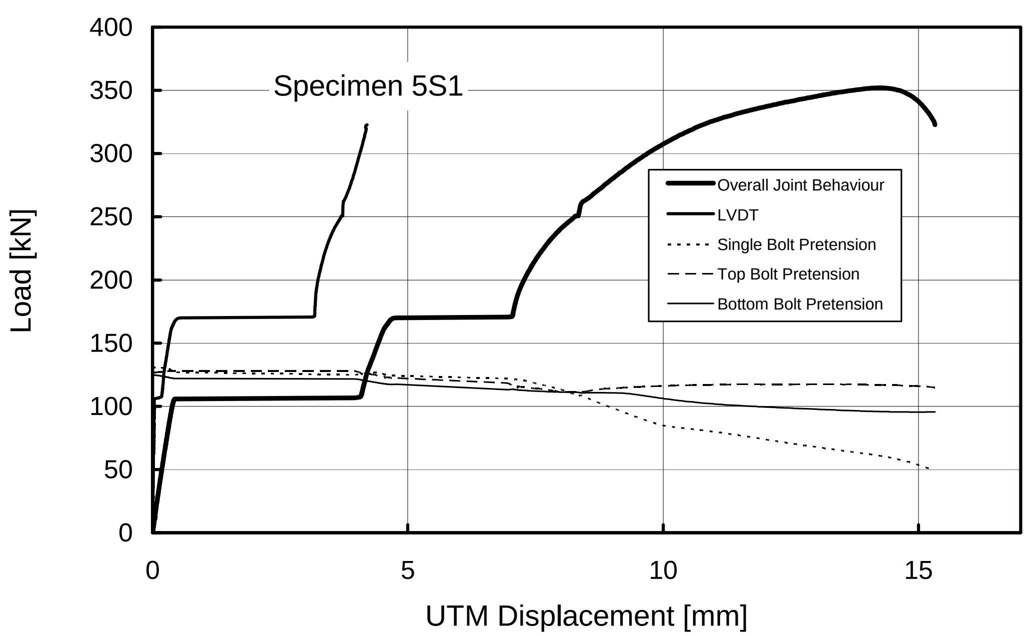

***Figure 88** – Load vs. displacement, 5S1.*

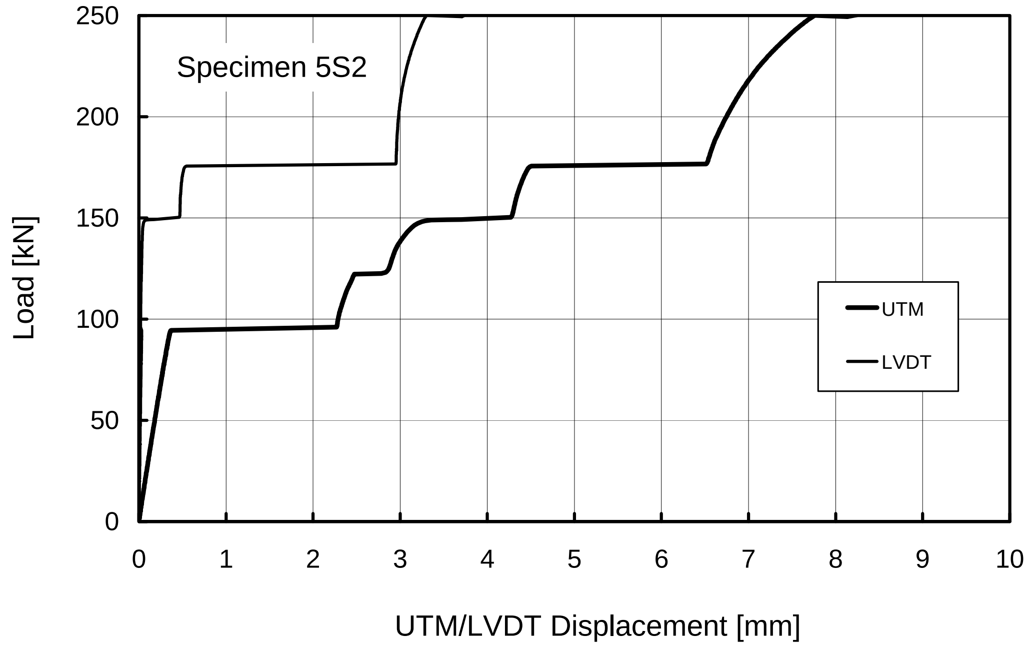

Figure 89 *– Load vs. displacement, 5S2.*

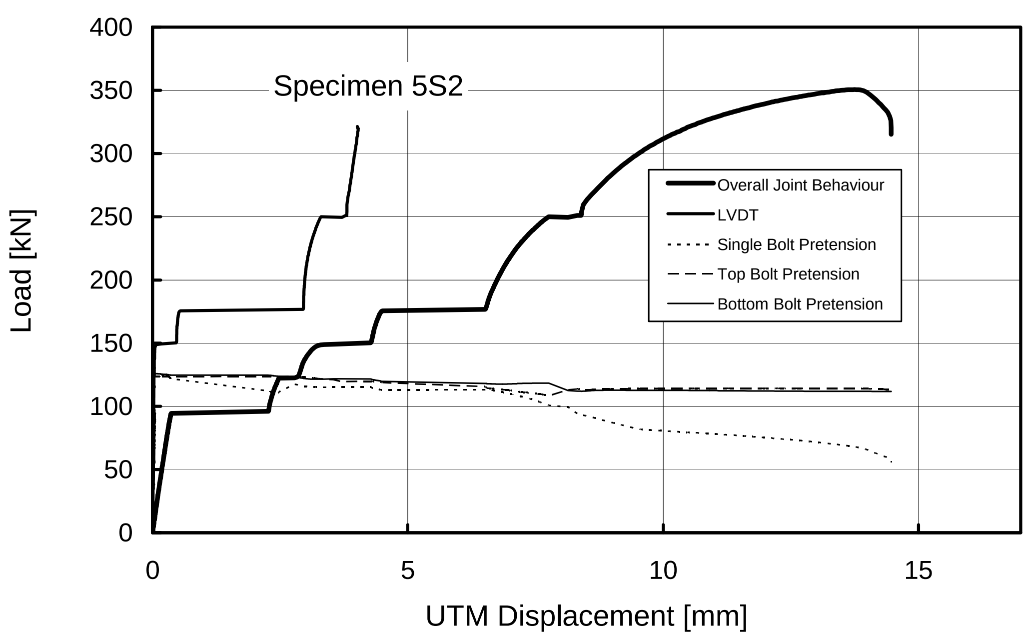

Figure 90 *– Load vs. displacement, 5S2.*

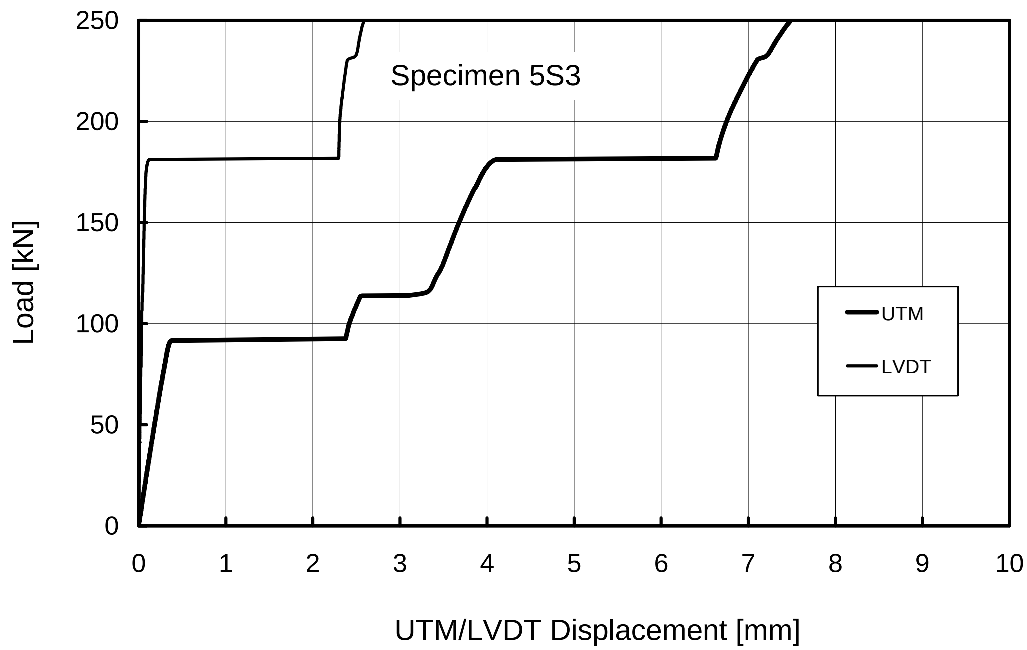

__Figure 91__ – Load vs. displacement, 5S3.

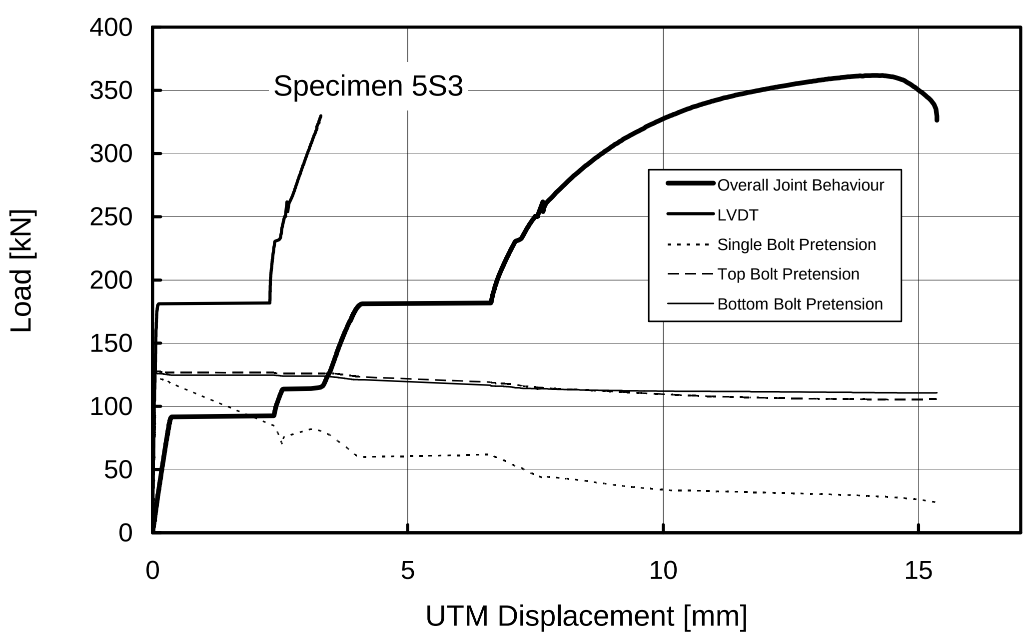

__Figure 92__ – Load vs. displacement, 5S3.

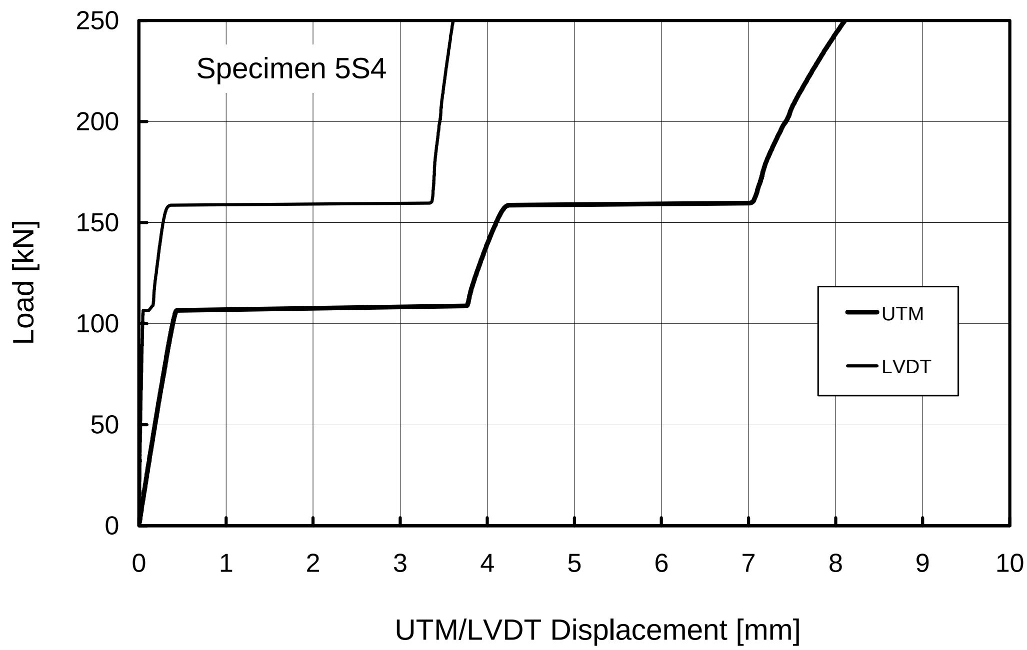

Figure 93 *– Load vs. displacement, 5S4.*

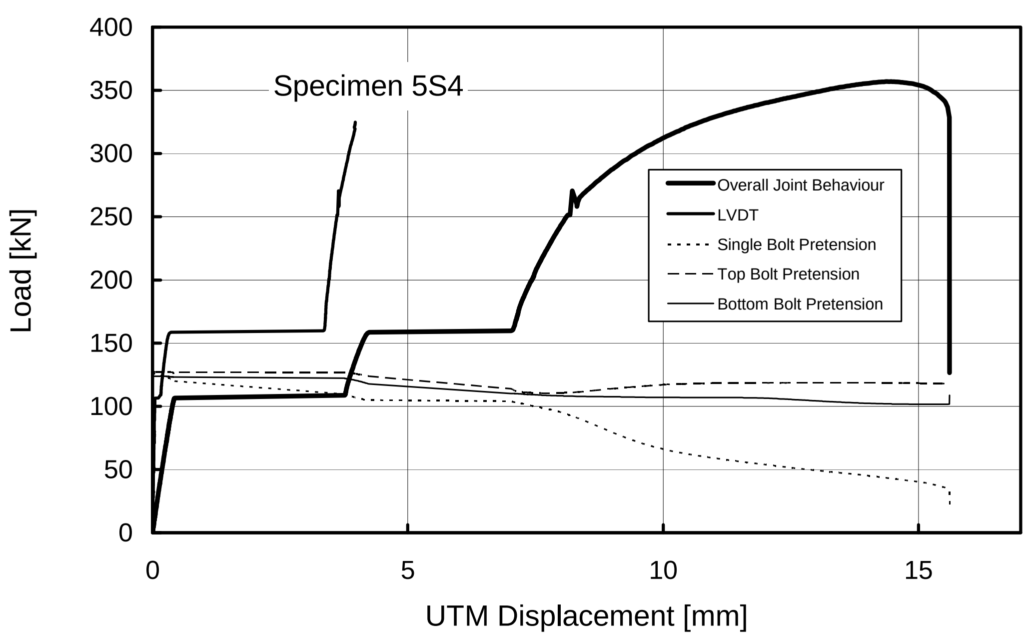

Figure 94 *– Load vs. displacement, 5S4.*

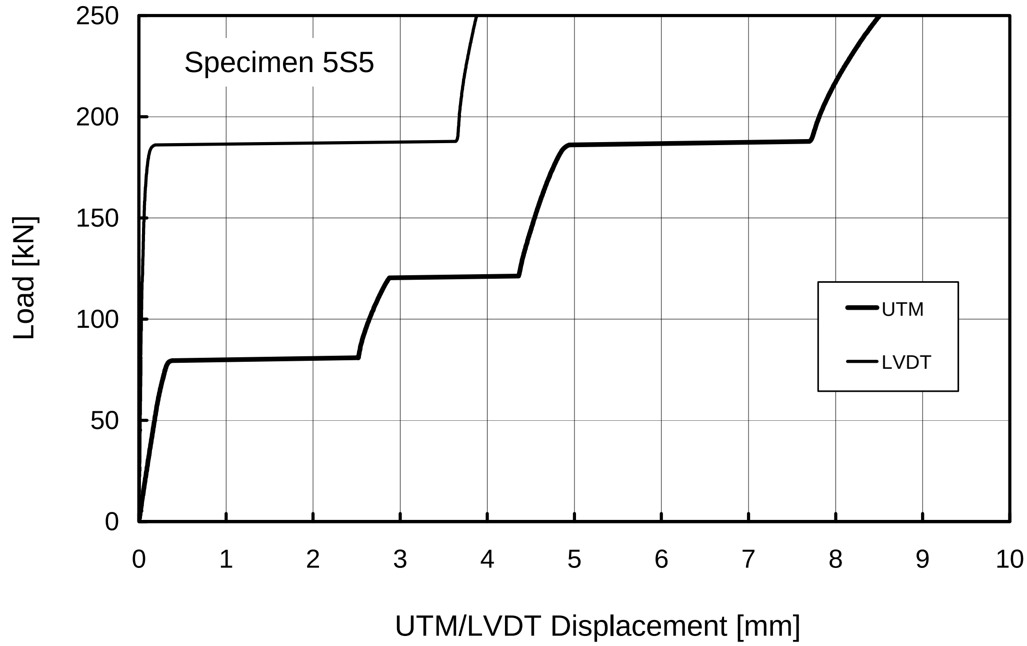

Figure 95 *– Load vs. displacement, 5S5.*

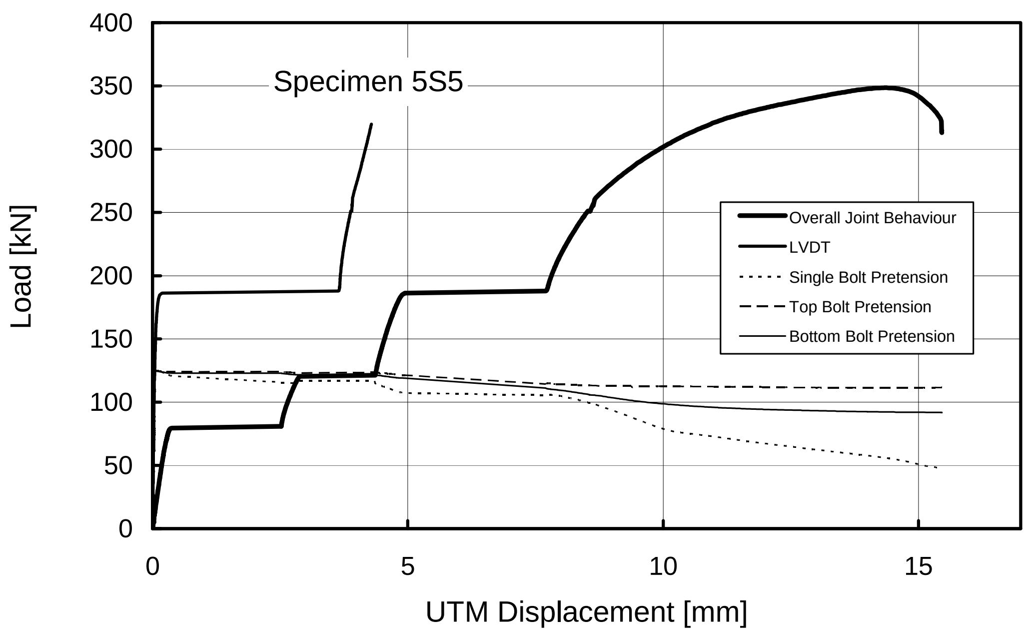

Figure 96 *– Load vs. displacement, 5S5.*

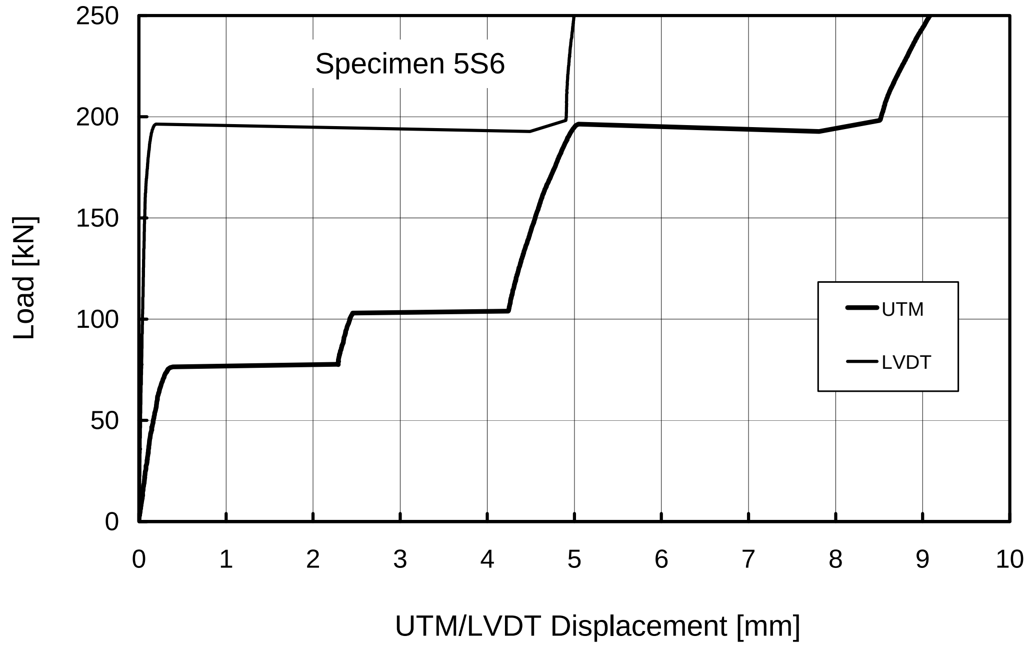

***Figure 97** – Load vs. displacement, 5S6.*

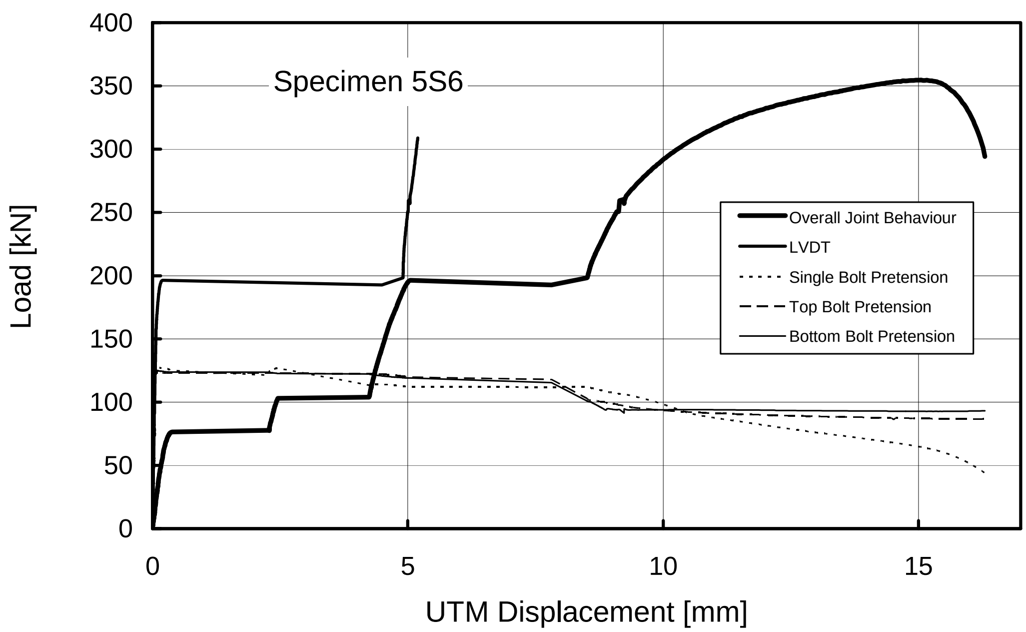

***Figure 98** – Load vs. displacement, 5S6.*

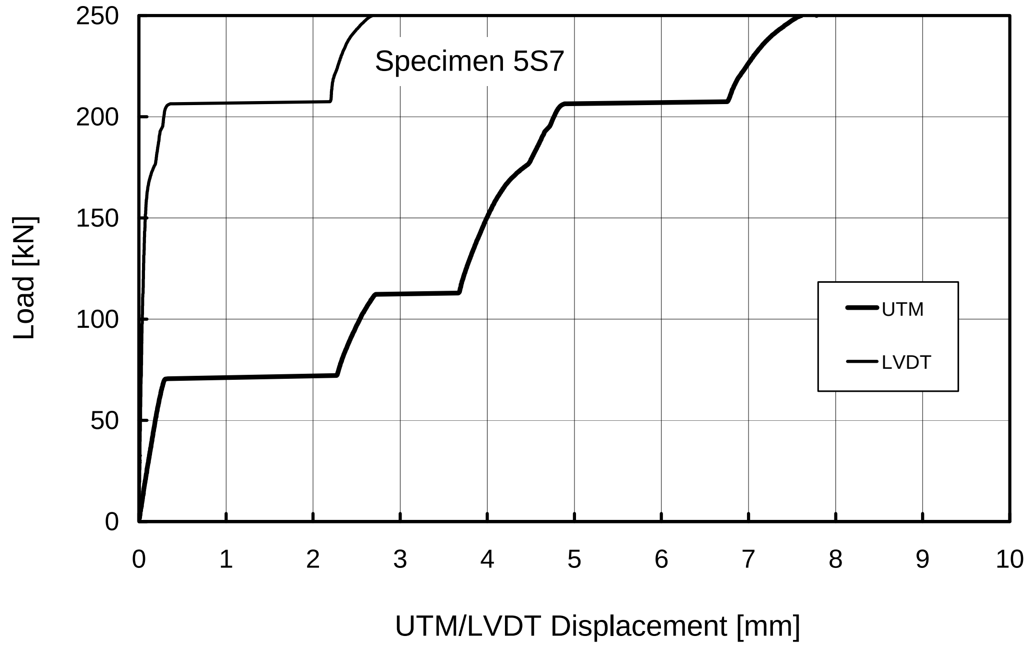

***Figure 99** – Load vs. displacement, 5S7.*

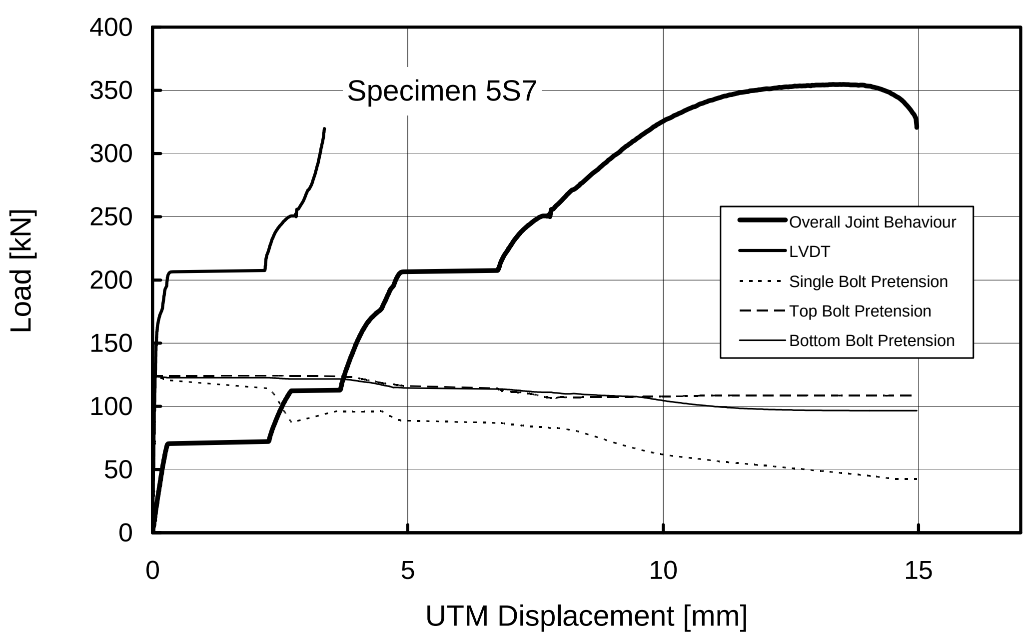

***Figure 100** – Load vs. displacement, 5S7.*

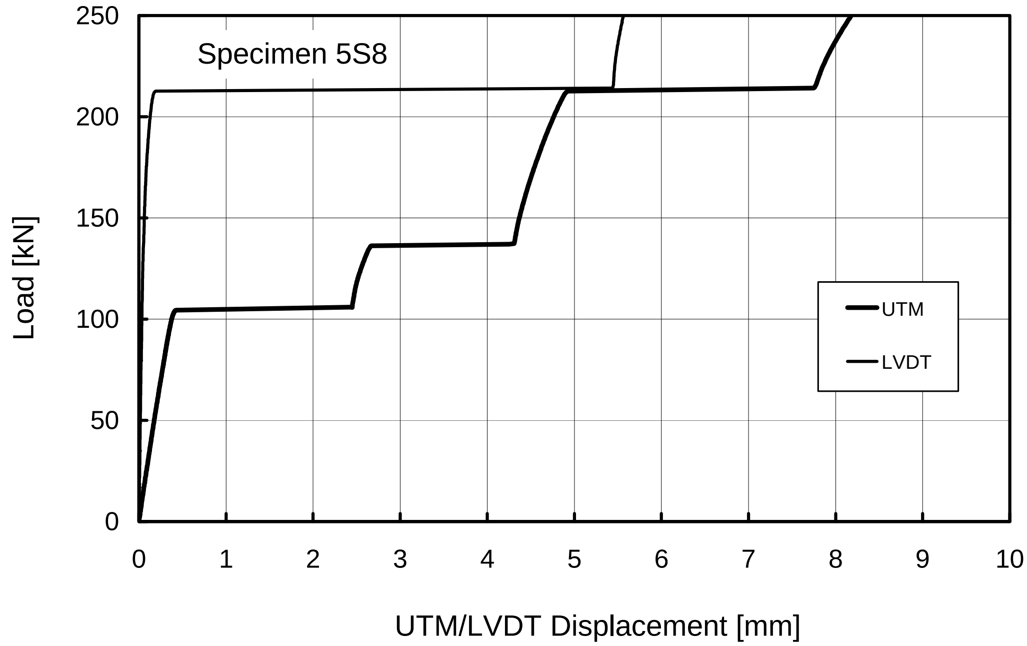

Figure 101 *– Load vs. displacement, 5S8.*

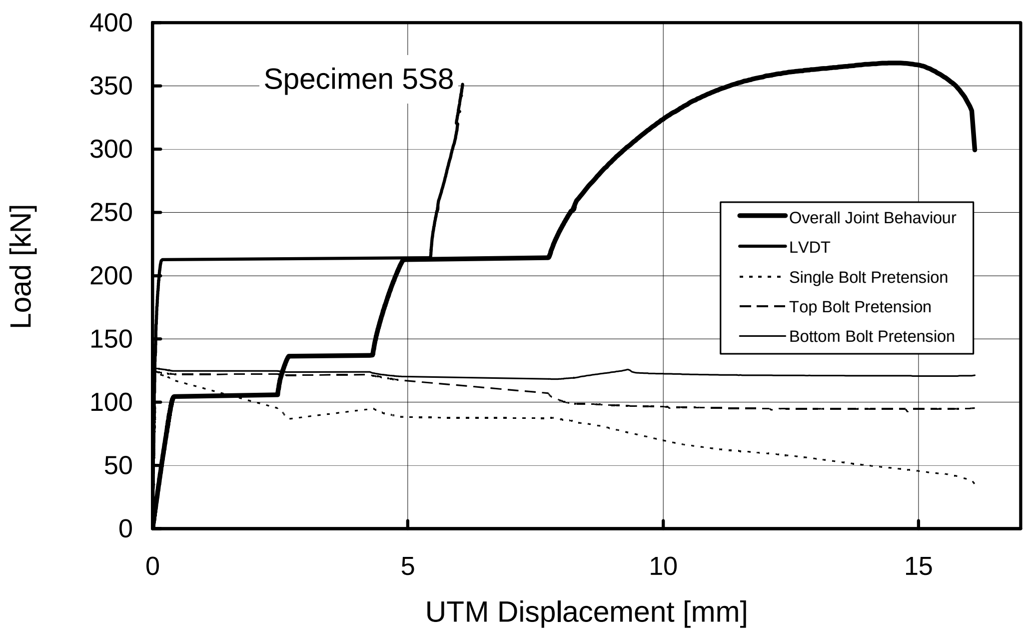

Figure 102 *– Load vs. displacement, 5S8.*

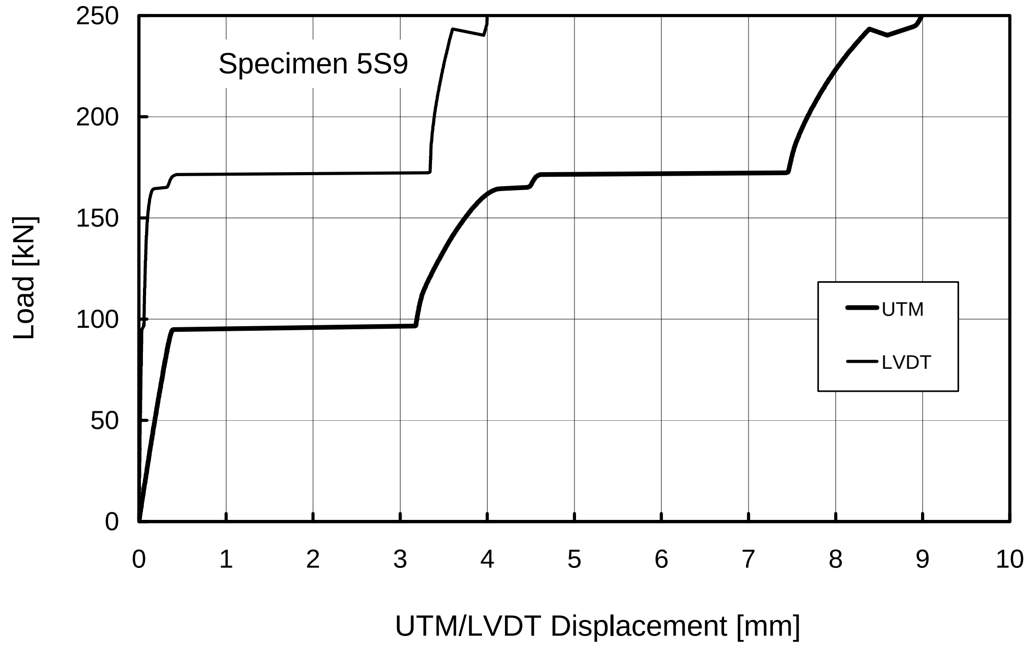

Figure 103 *– Load vs. displacement, 5S9.*

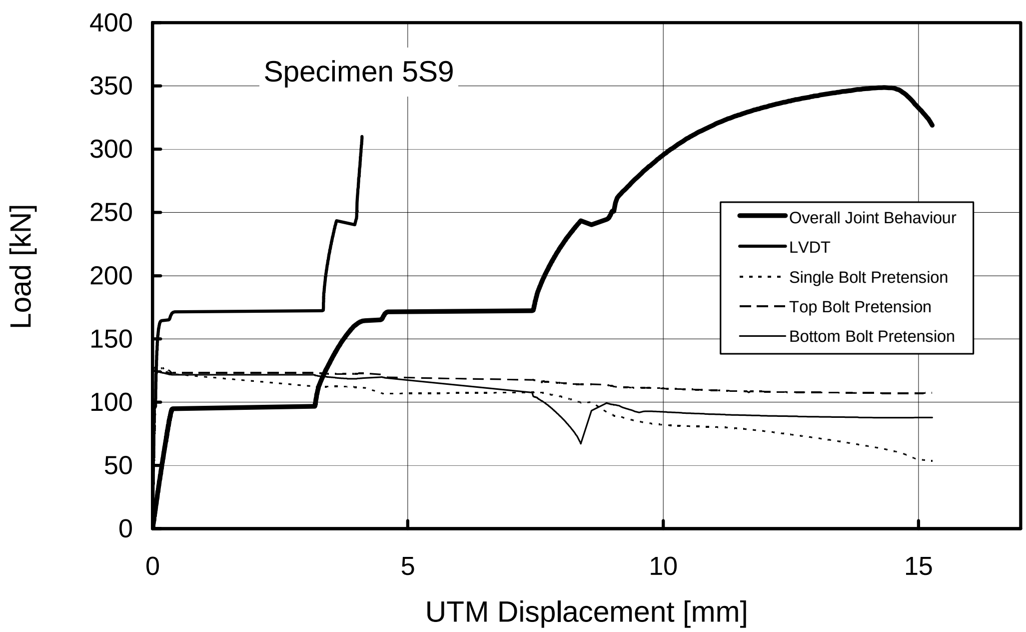

Figure 104 *– Load vs. displacement, 5S9.*

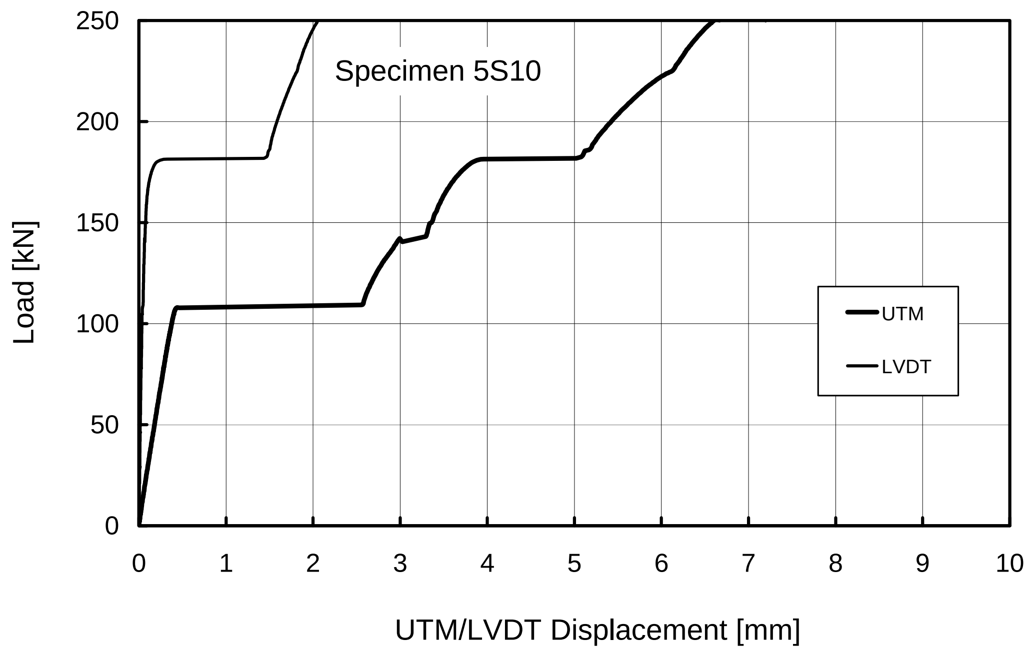

Figure 105 *– Load vs. displacement, 5S10.*

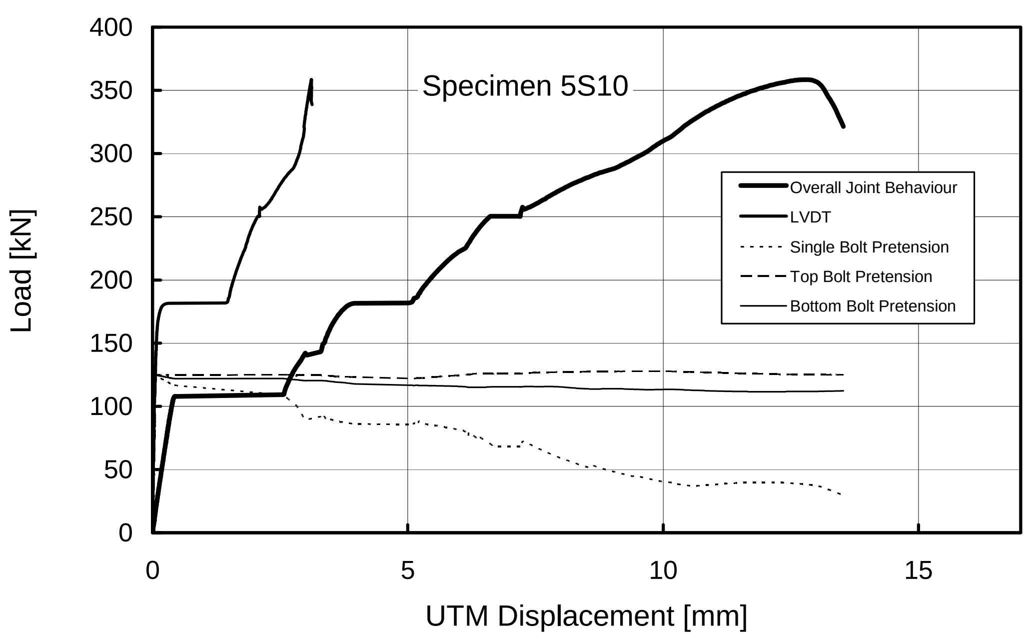

Figure 106 *– Load vs. displacement, 5S10.*

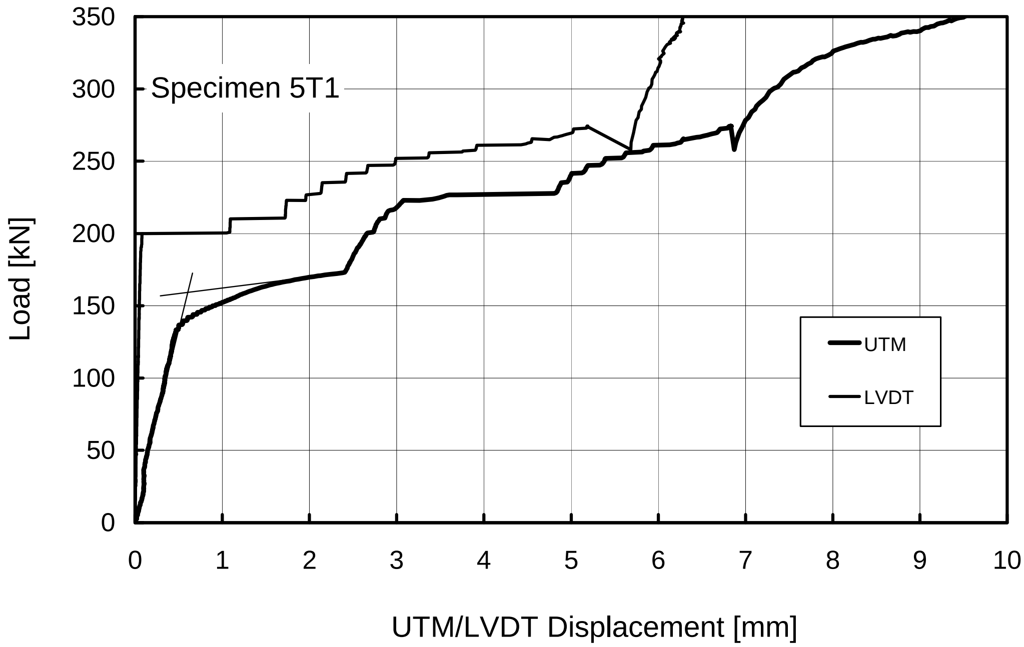

Figure 107 *– Load vs. displacement, 5T1.*

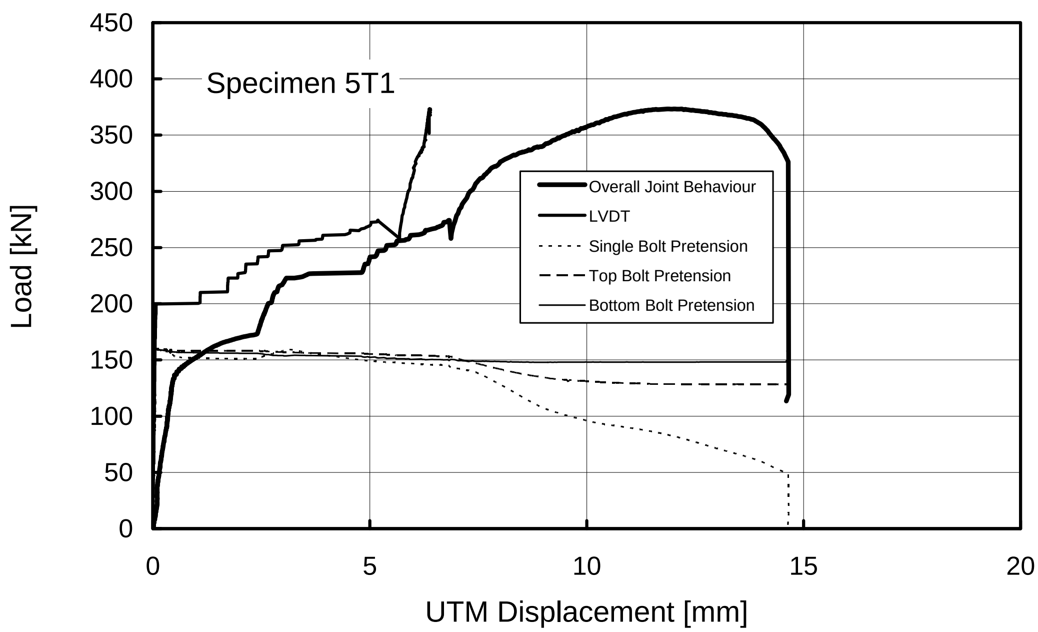

Figure 108 *– Load vs. displacement, 5T1.*

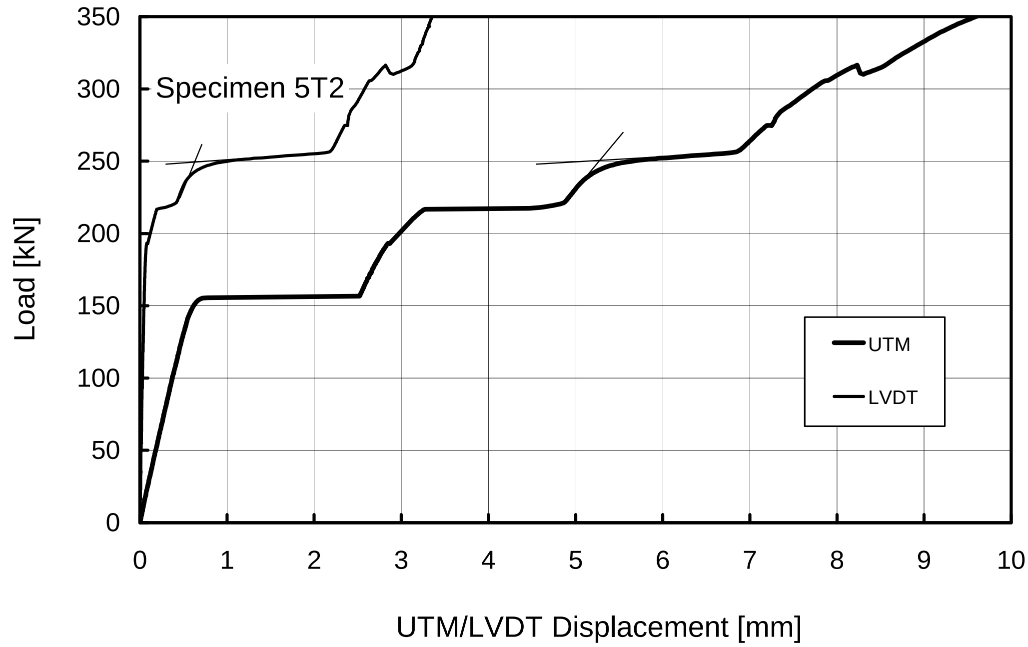

Figure 109 – *Load vs. displacement, 5T2.*

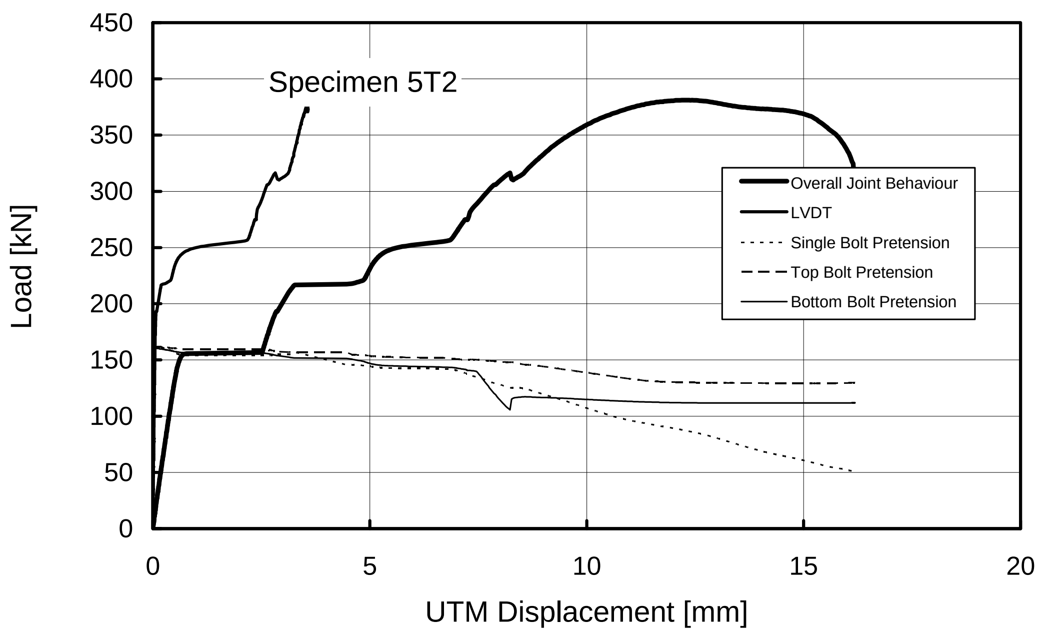

Figure 110 – *Load vs. displacement, 5T2.*

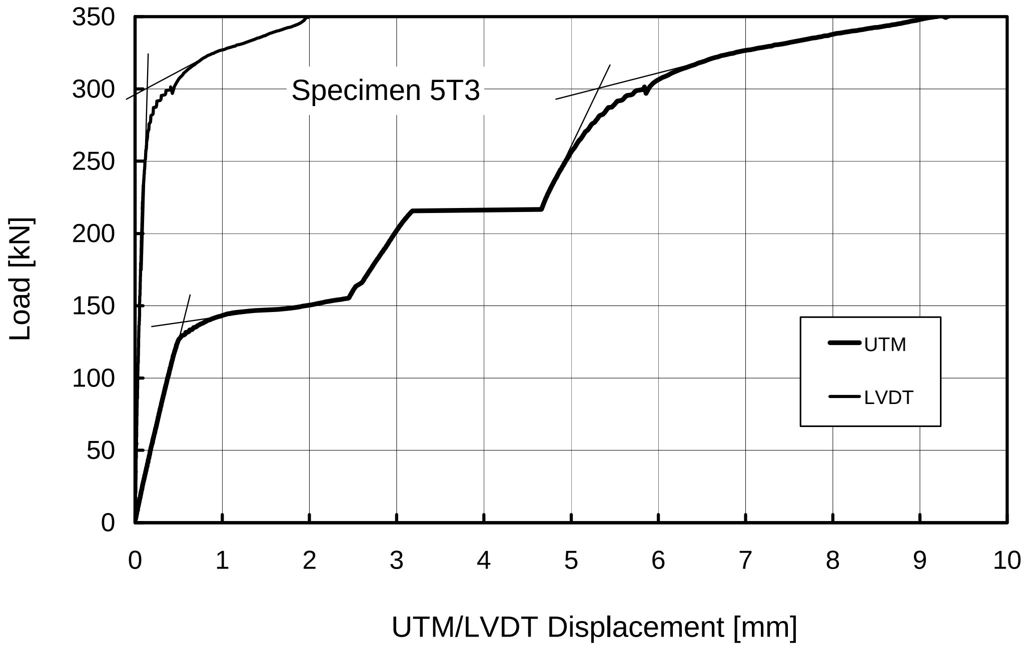

Figure 111 *– Load vs. displacement, 5T3.*

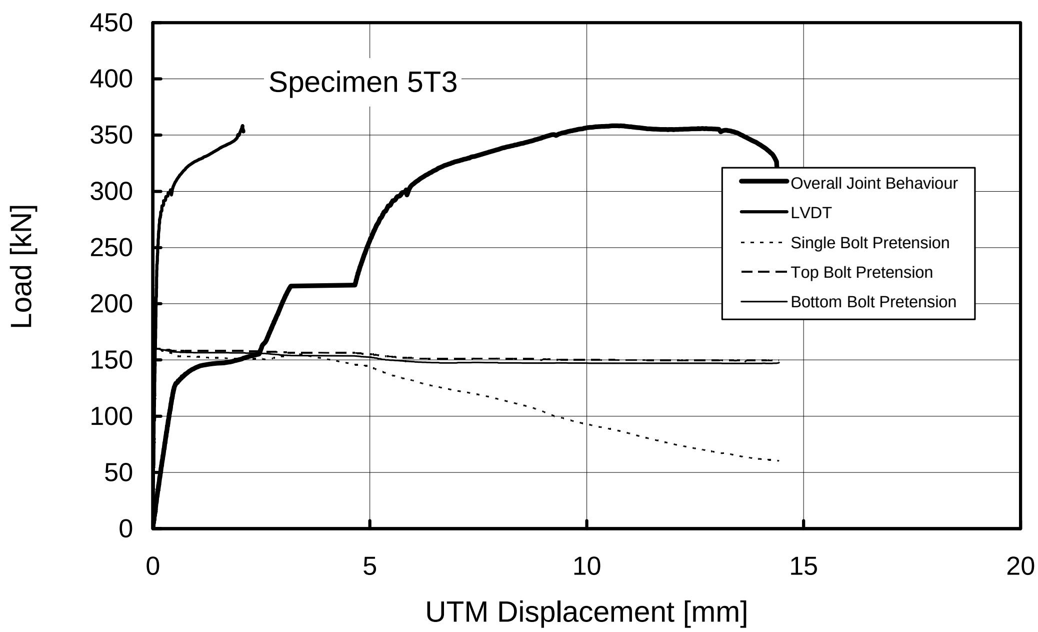

Figure 112 *– Load vs. displacement, 5T3.*

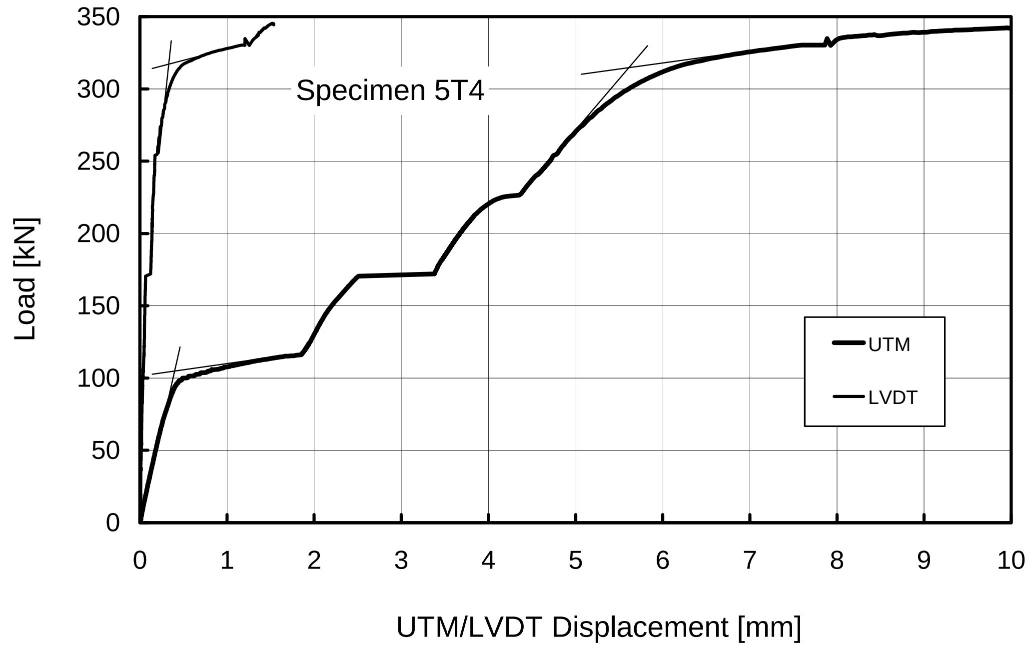

***Figure 113** – Load vs. displacement, 5T4.*

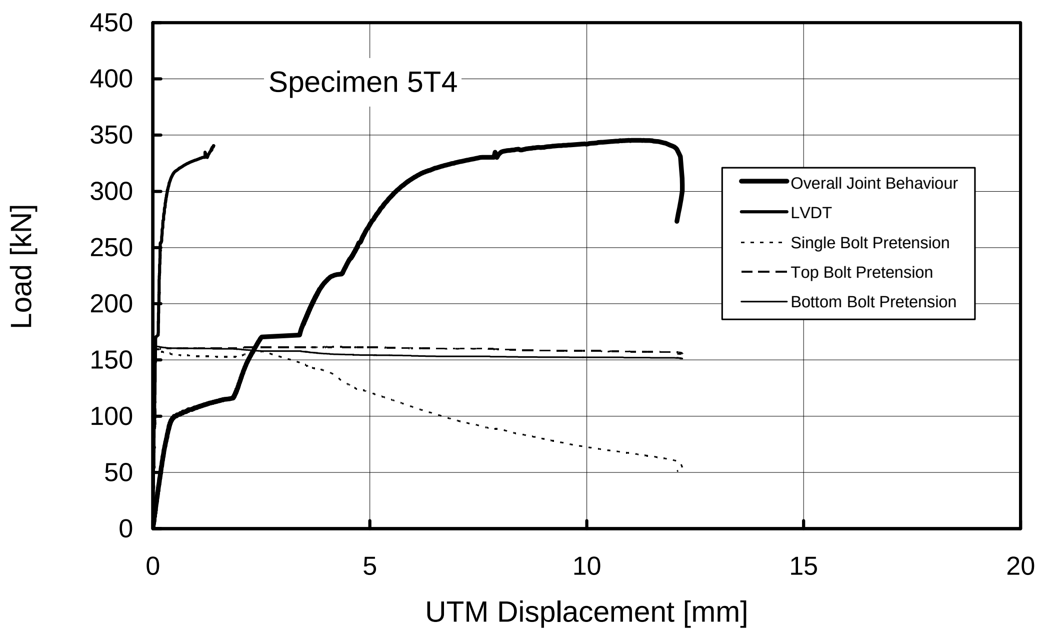

***Figure 114** – Load vs. displacement, 5T4.*

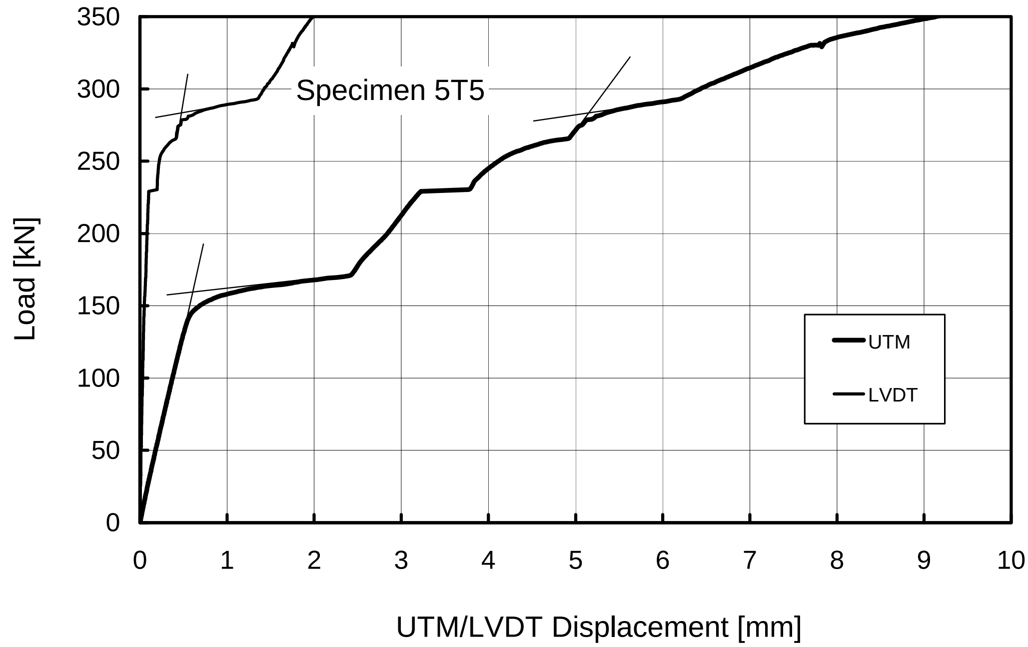

Figure 115 *– Load vs. displacement, 5T5.*

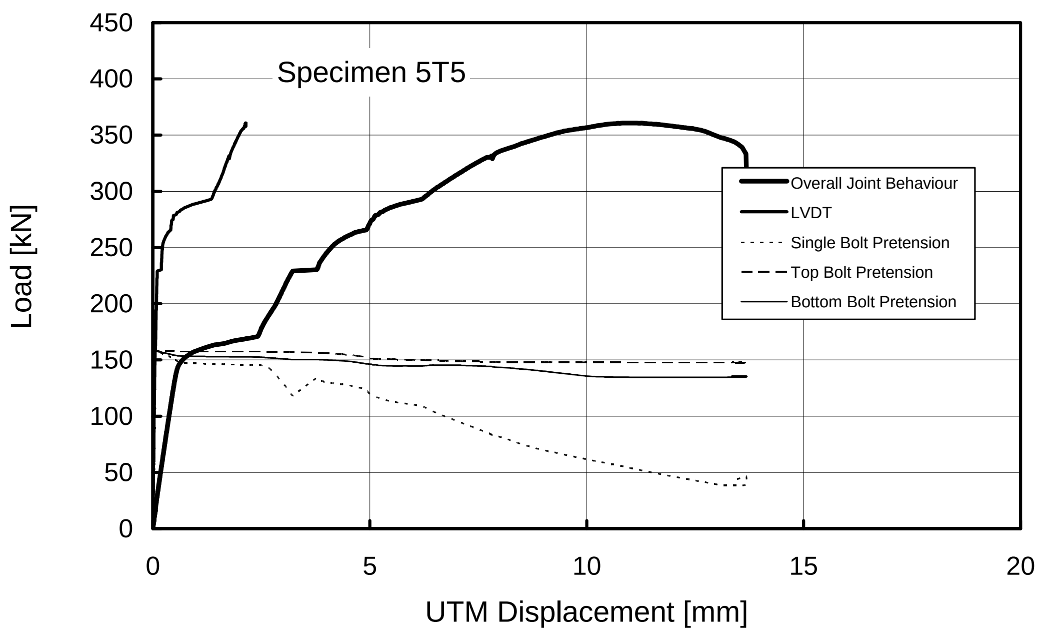

Figure 116 *– Load vs. displacement, 5T5.*

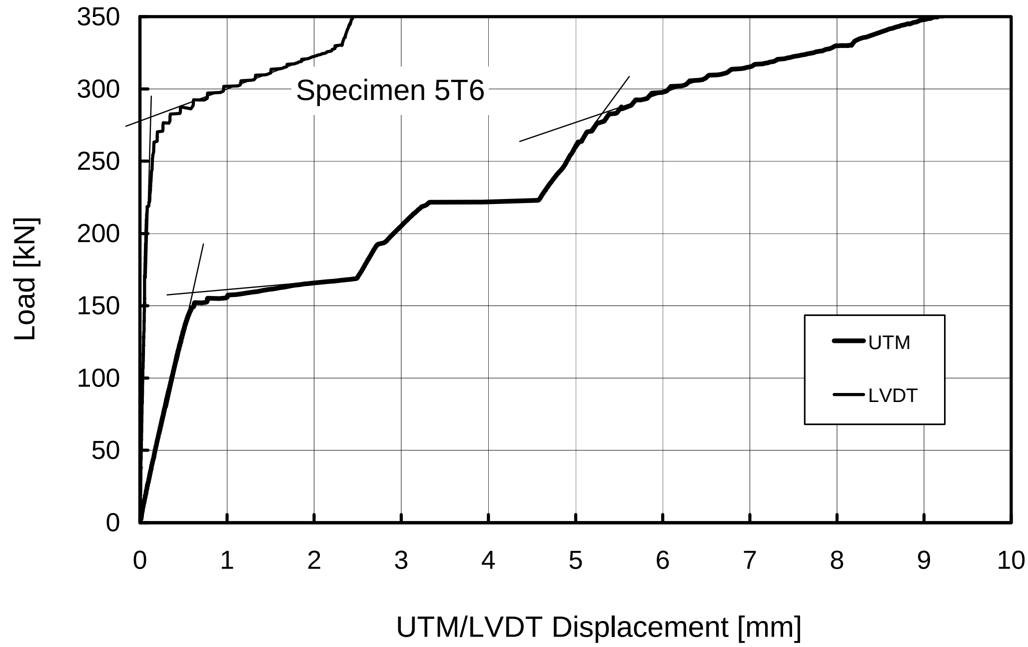

***Figure 117** – Load vs. displacement, 5T6.*

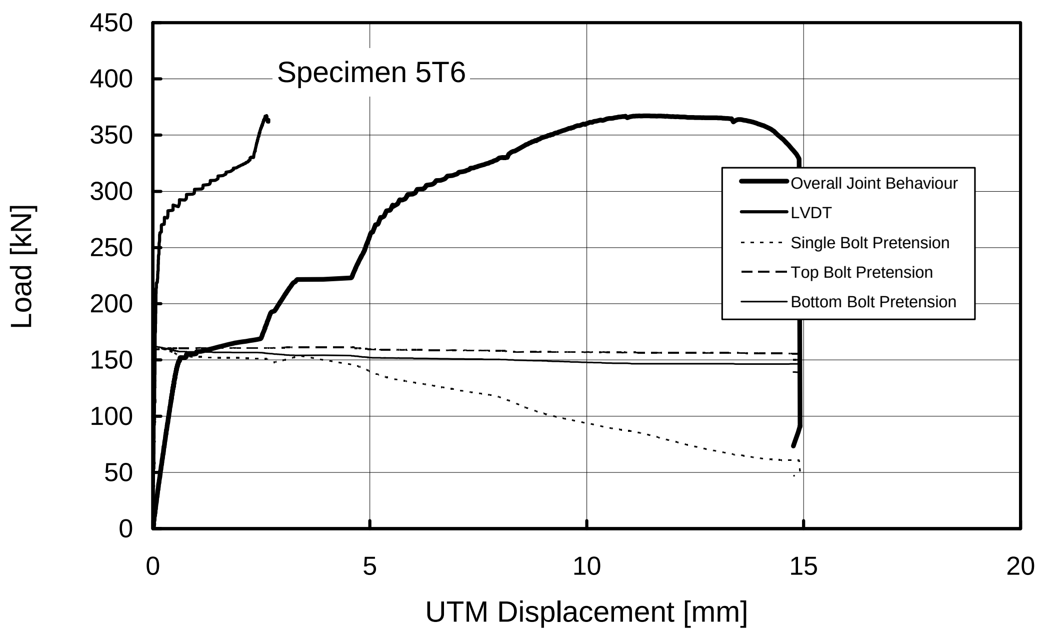

***Figure 118** – Load vs. displacement, 5T6.*

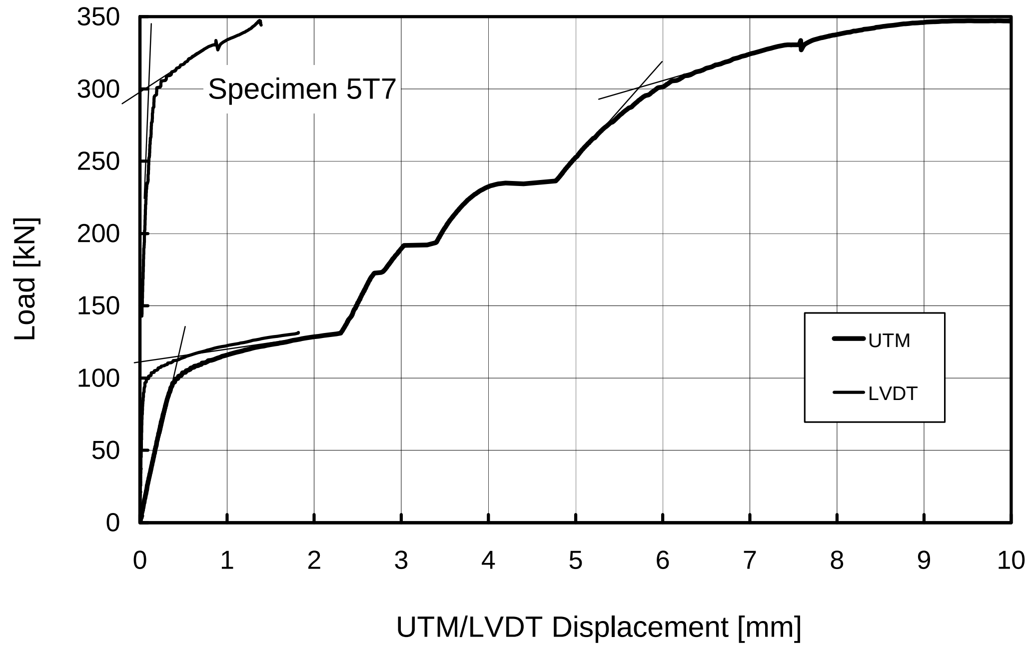

Figure 119 *– Load vs. displacement, 5T7.*

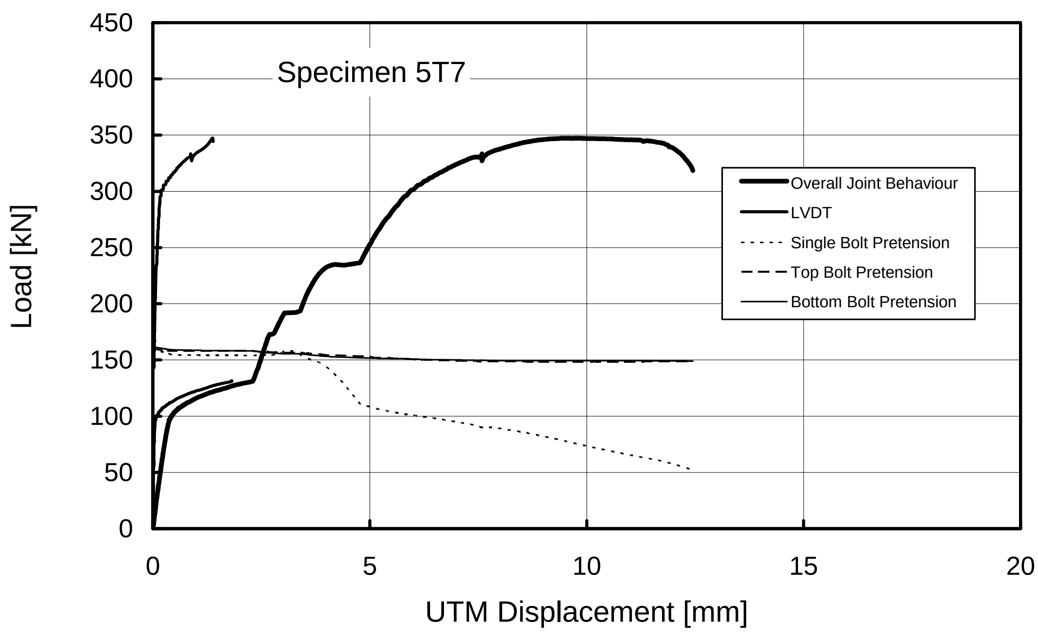

Figure 120 *– Load vs. displacement, 5T7.*

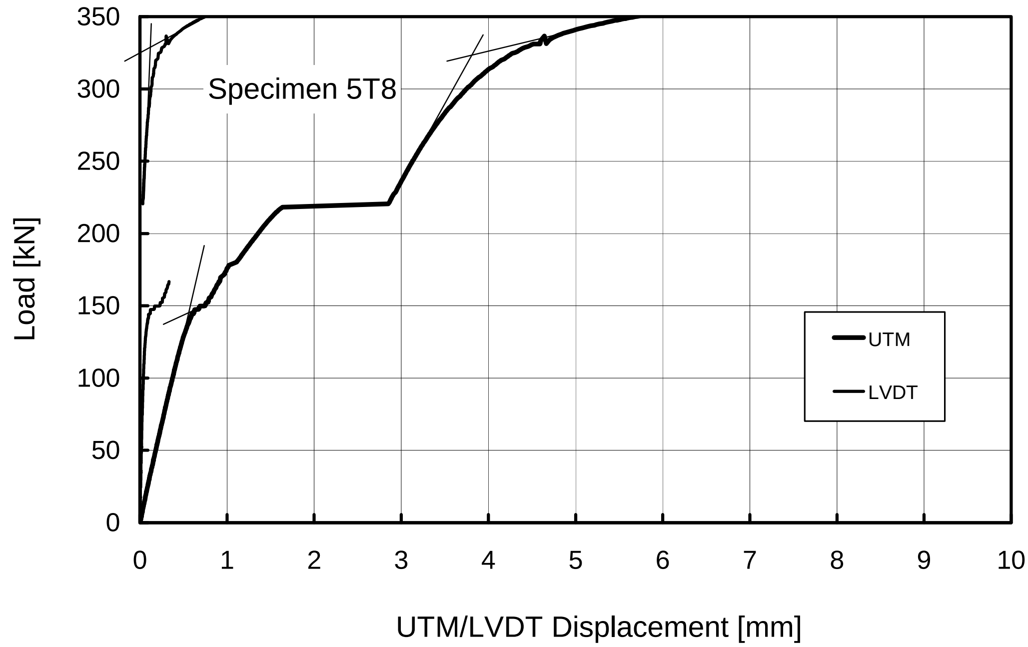

Figure 121 *– Load vs. displacement, 5T8.*

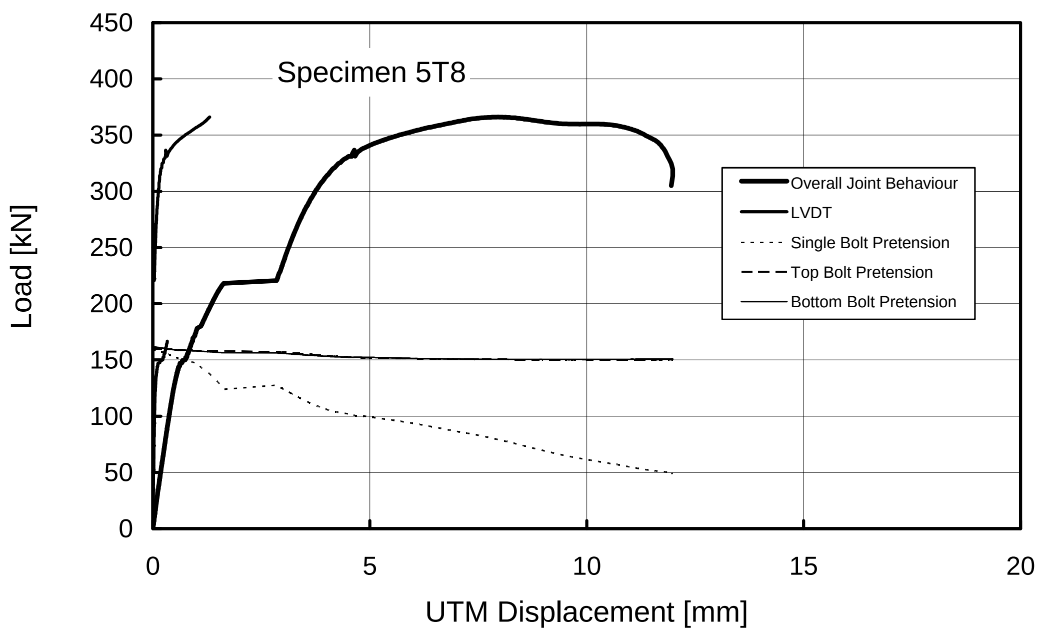

Figure 122 *– Load vs. displacement, 5T8.*

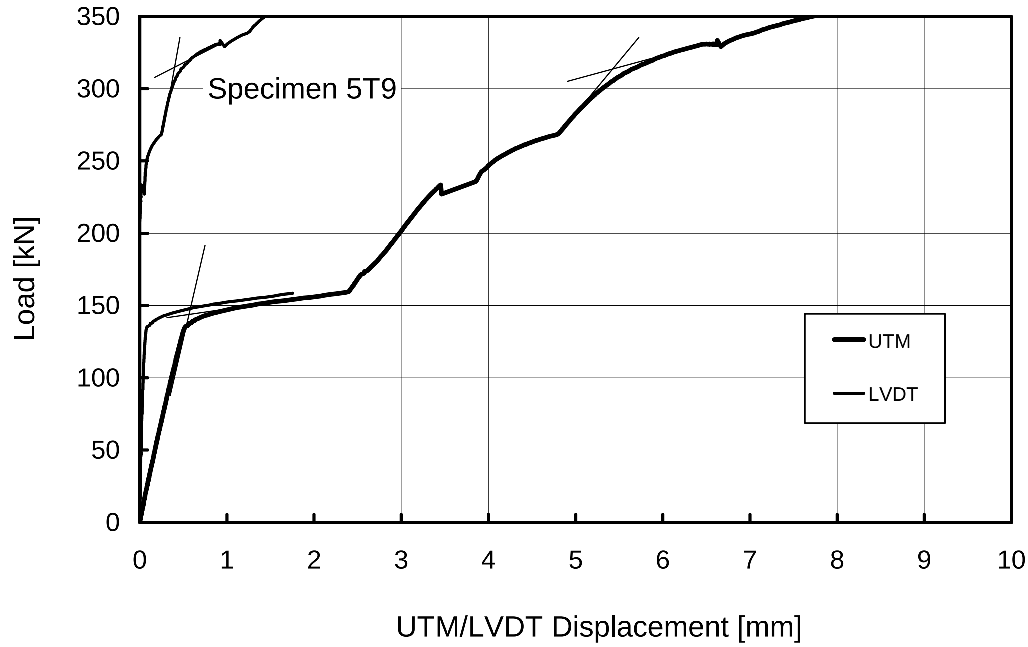

***Figure 123** – Load vs. displacement, 5T9.*

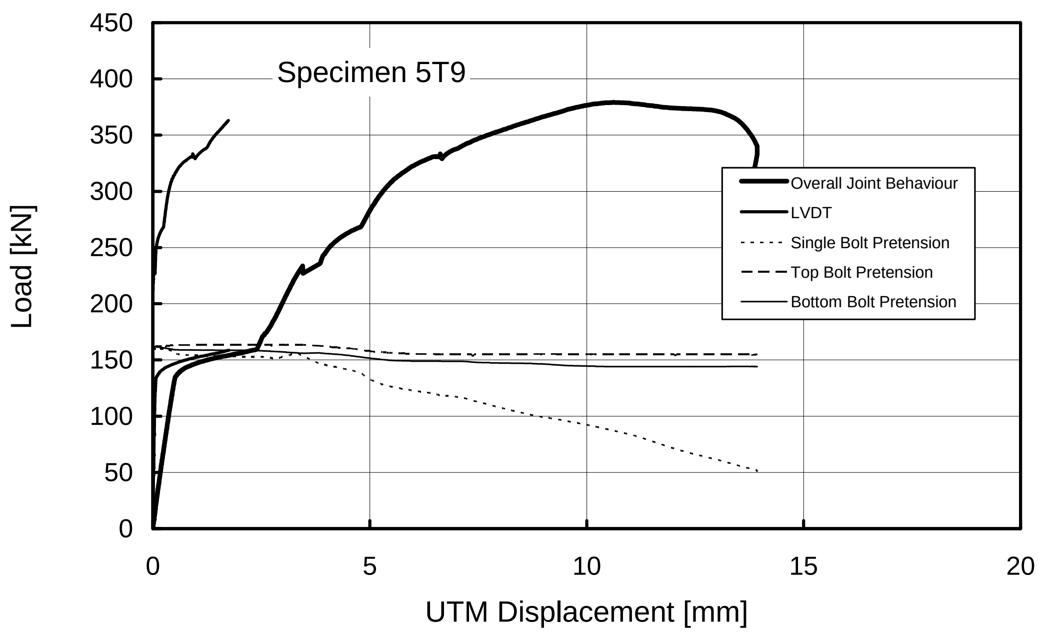

***Figure 124** – Load vs. displacement, 5T9.*

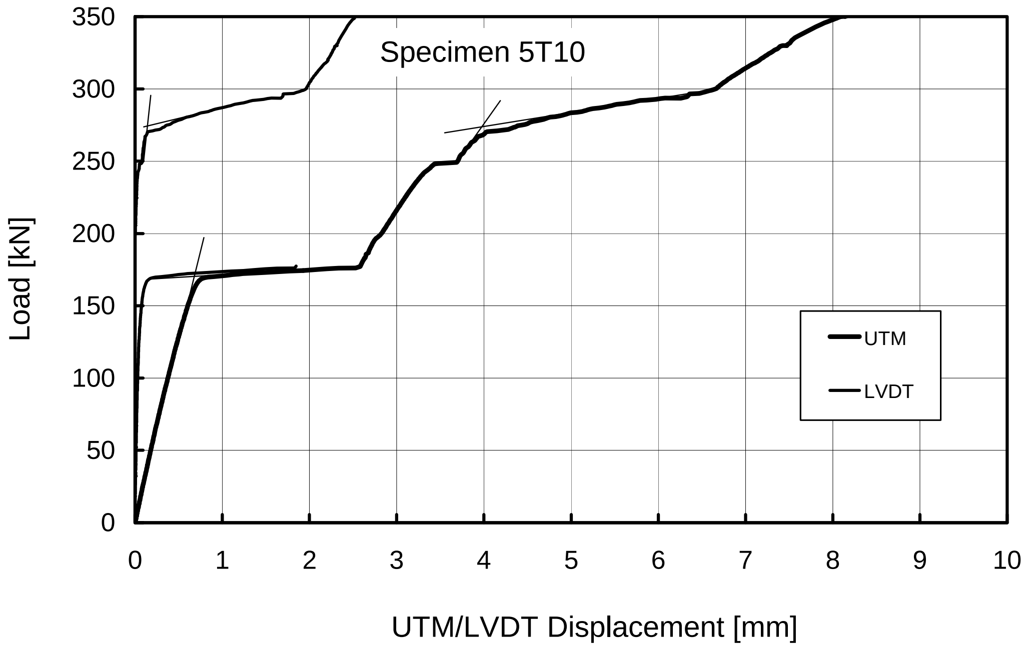

***Figure 125** – Load vs. displacement, 5T10.*

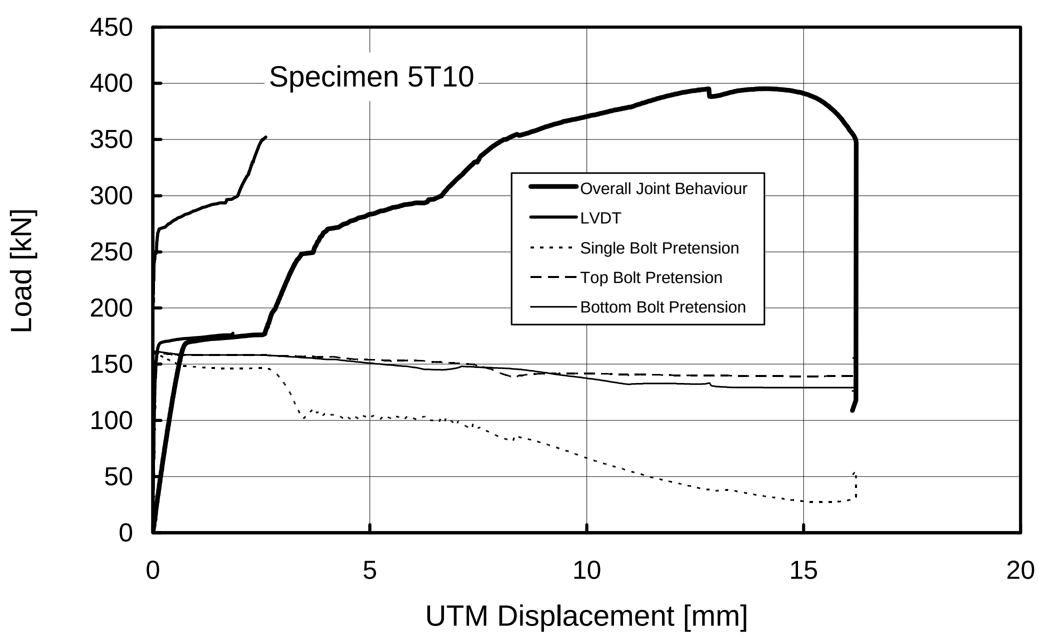

***Figure 126** – Load vs. displacement, 5T10.*

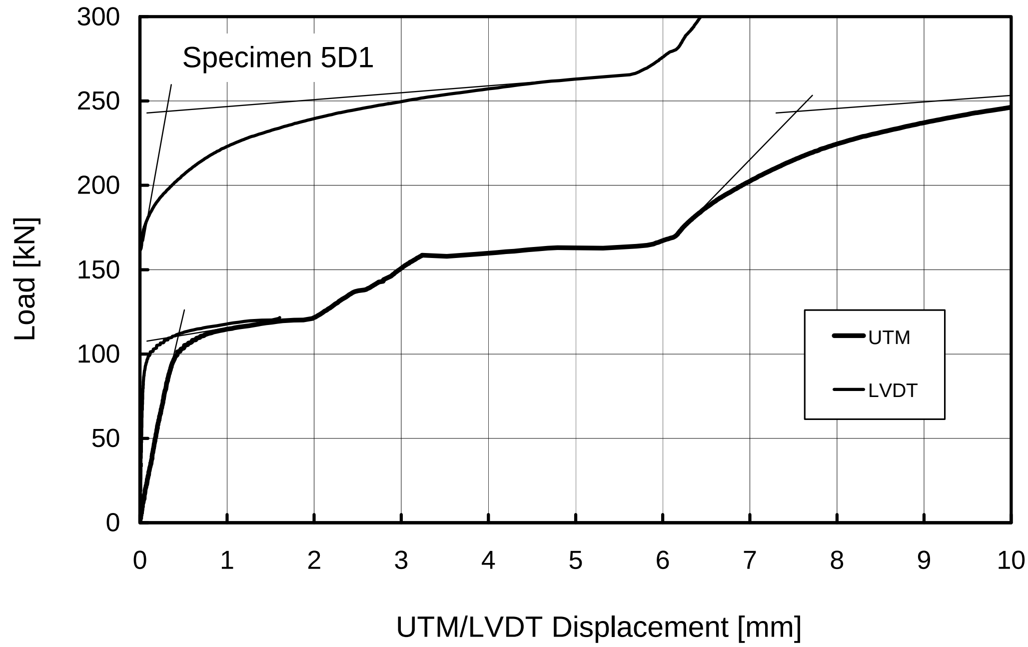

***Figure 127** – Load vs. displacement, 5D1.*

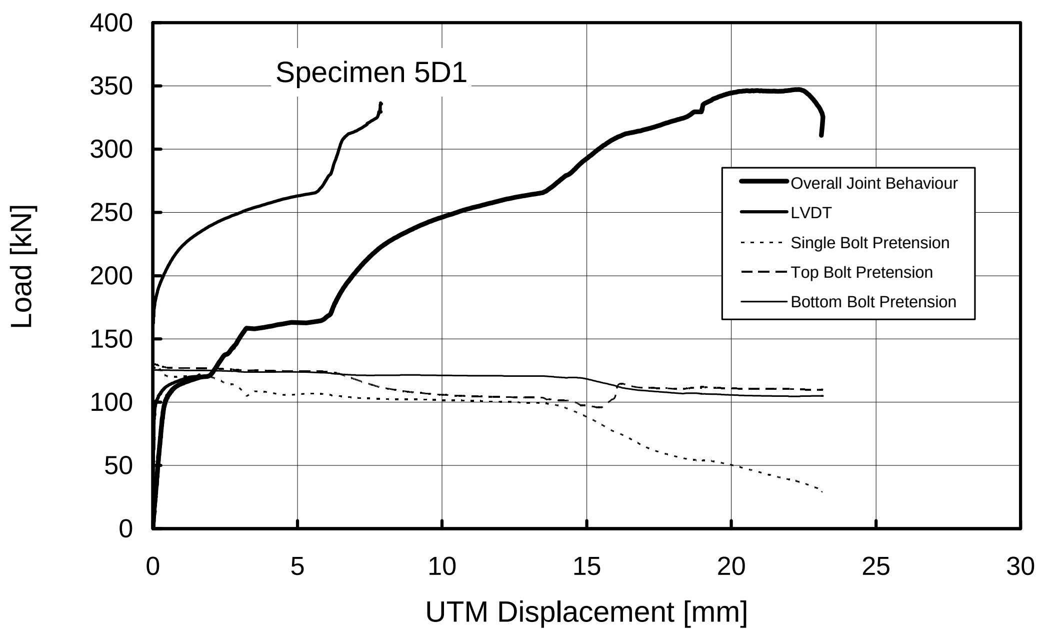

***Figure 128** – Load vs. displacement, 5D1.*

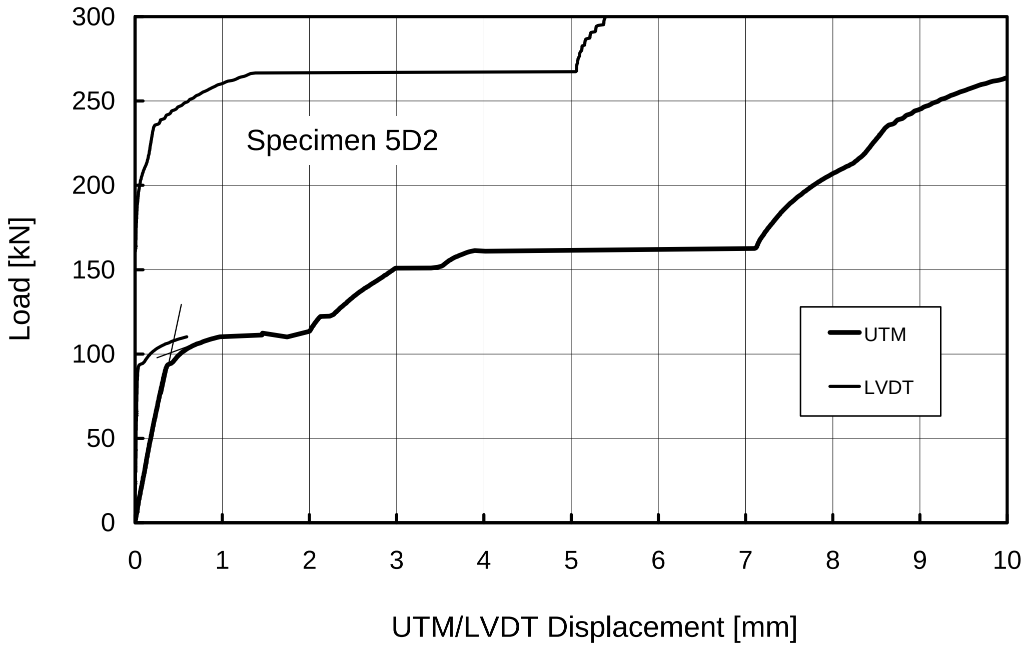

Figure 129 *– Load vs. displacement, 5D2.*

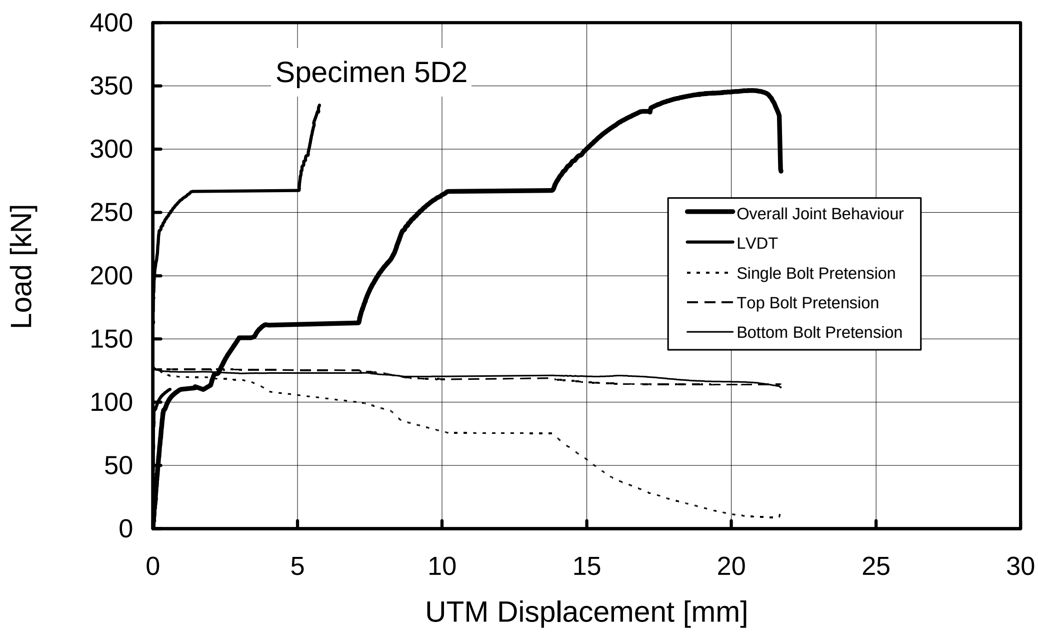

Figure 130 *– Load vs. displacement, 5D2.*

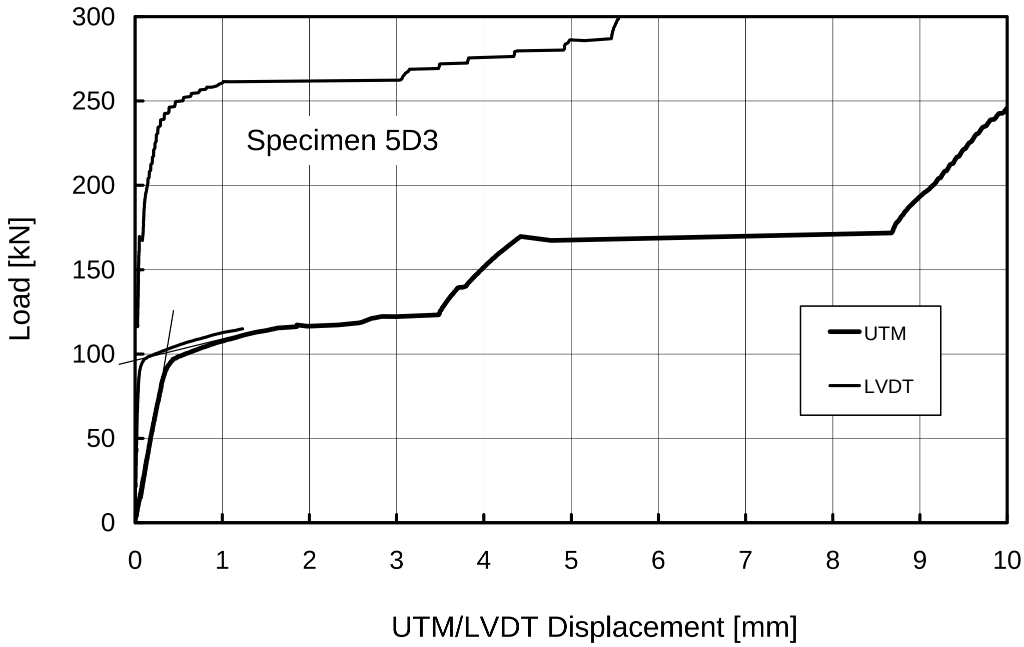

***Figure 131** – Load vs. displacement, 5D3.*

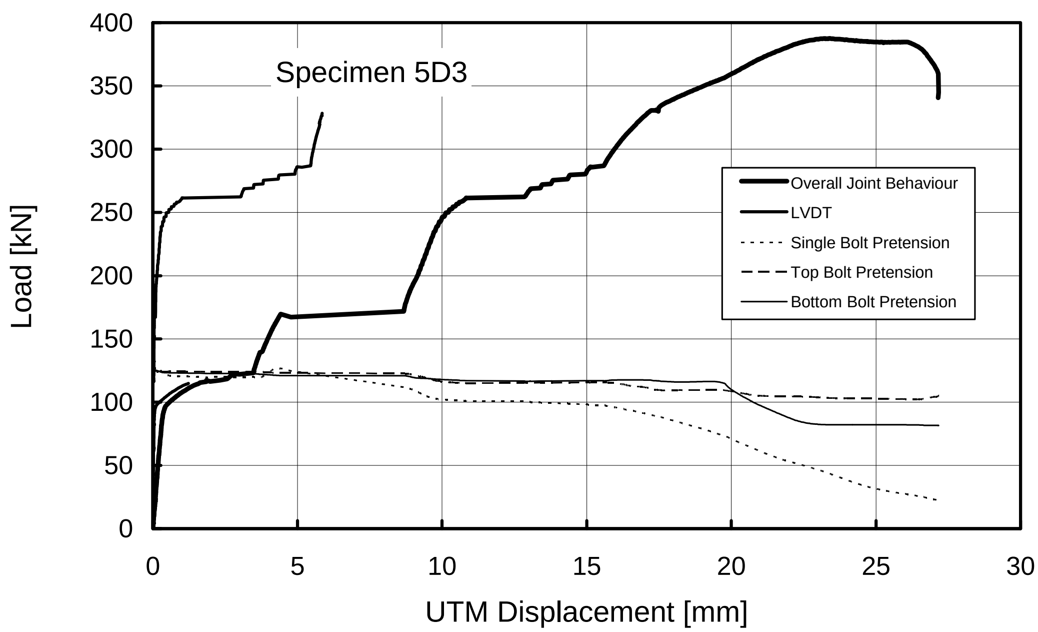

***Figure 132** – Load vs. displacement, 5D3.*

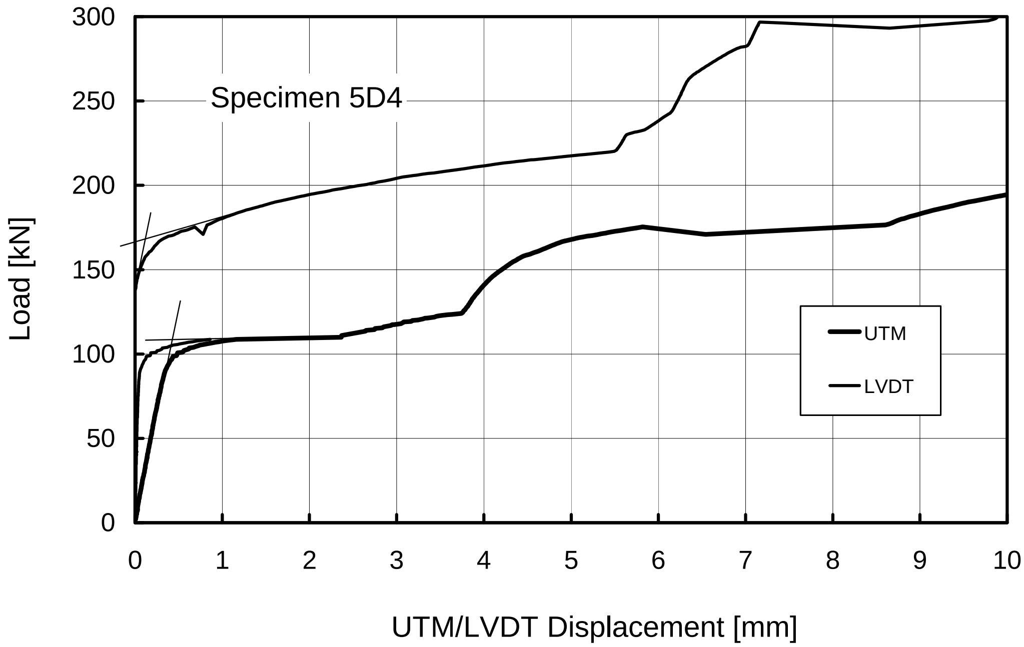

Figure 133 *– Load vs. displacement, 5D4.*

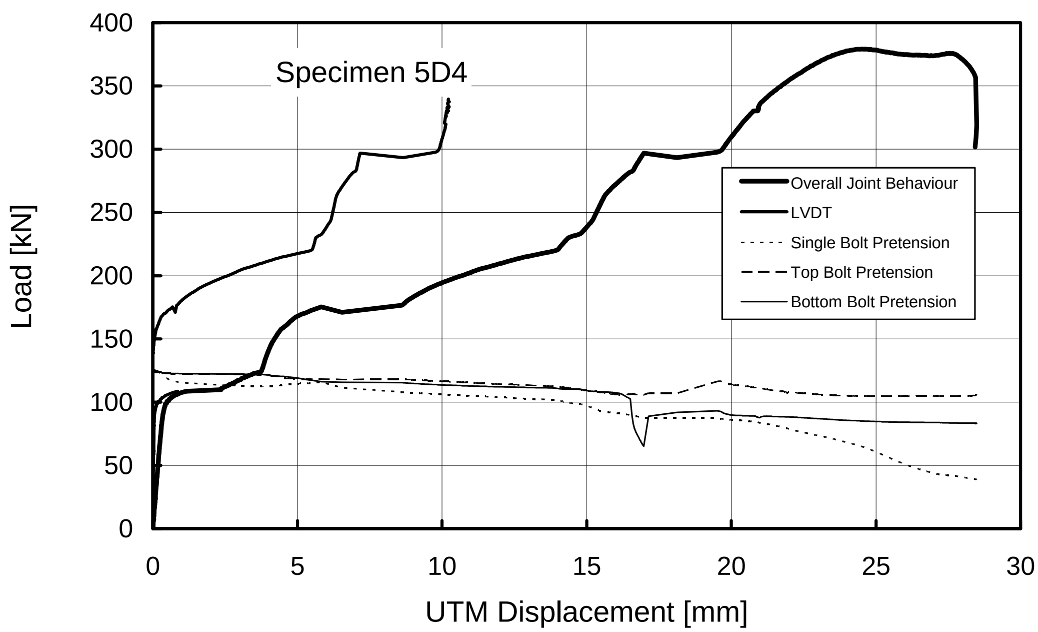

Figure 134 *– Load vs. displacement, 5D4.*

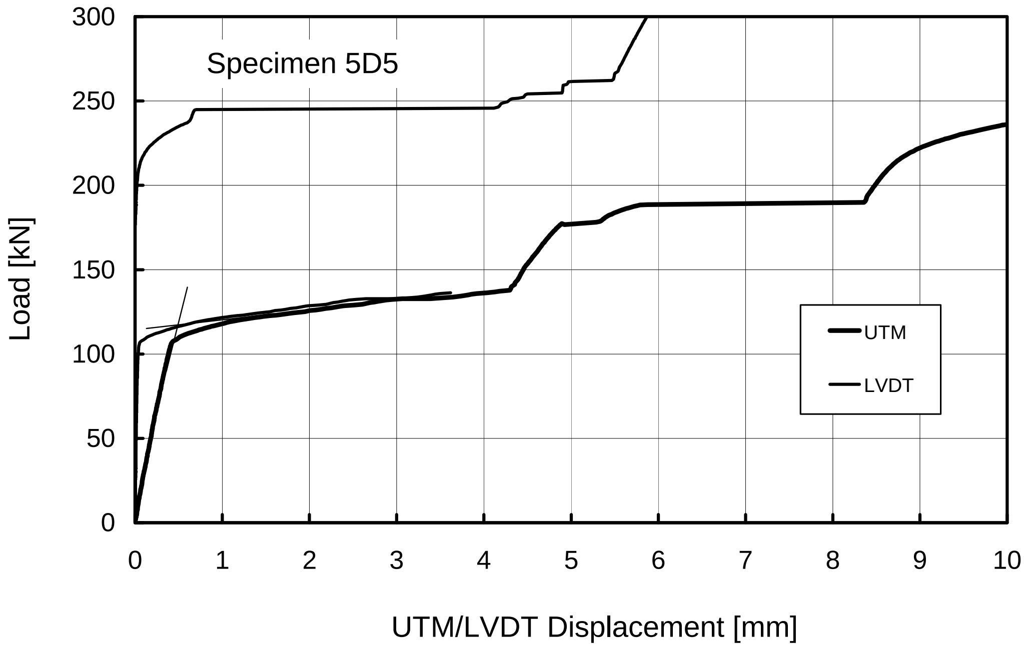

Figure 135 *– Load vs. displacement, 5D5.*

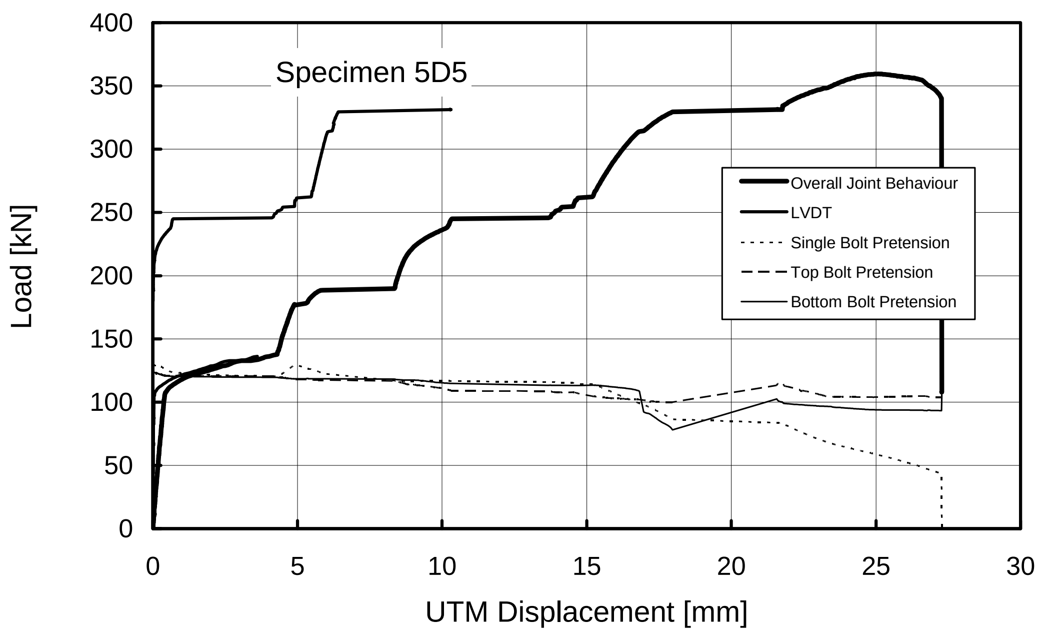

Figure 136 *– Load vs. displacement, 5D5.*

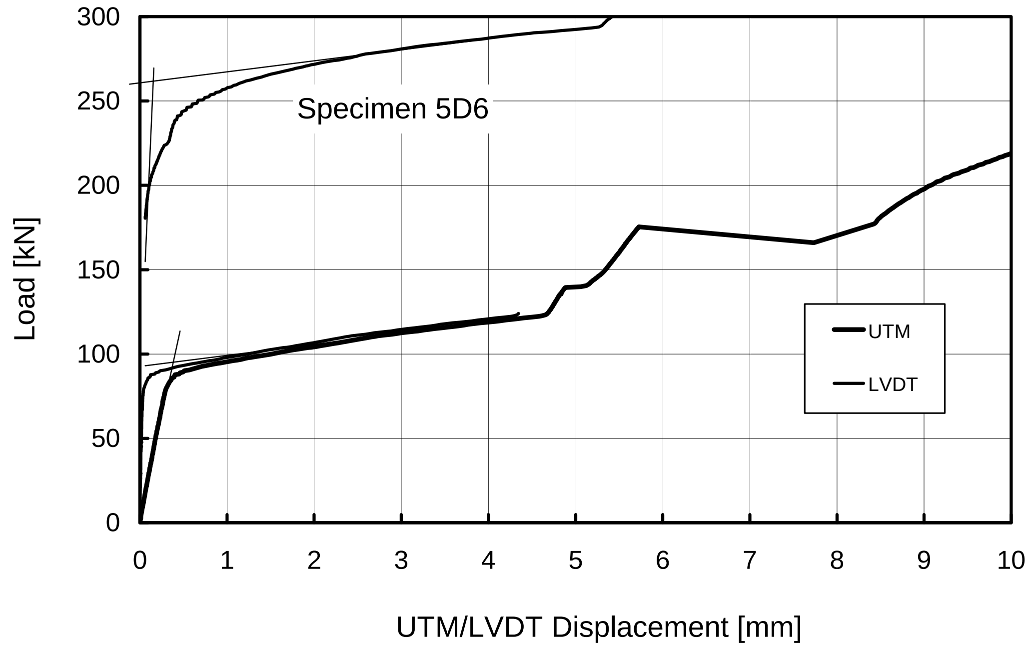

Figure 137 *– Load vs. displacement, 5D6.*

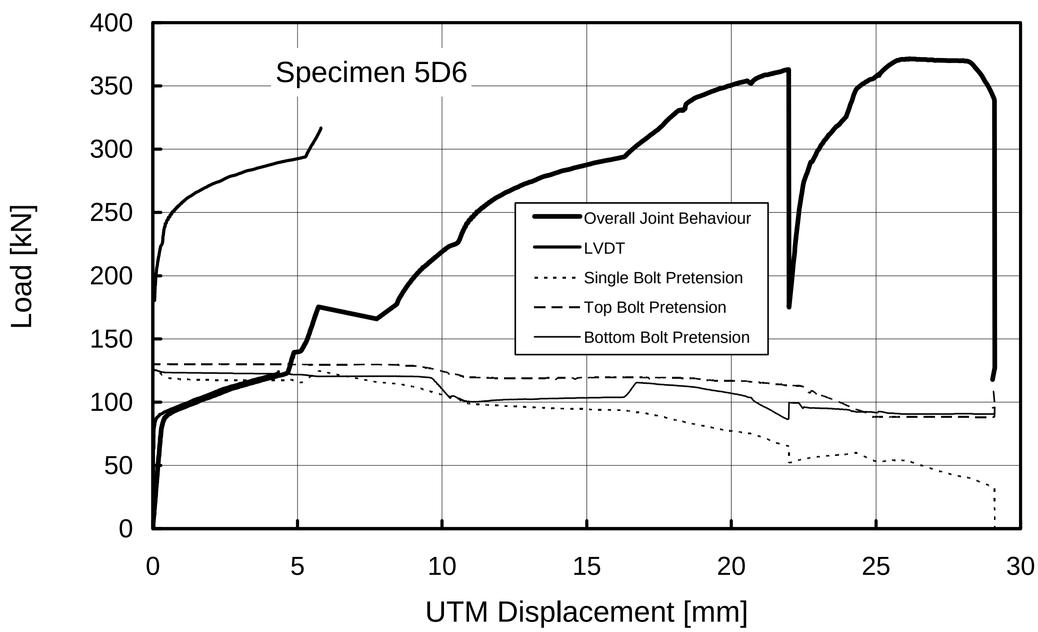

Figure 138 *– Load vs. displacement, 5D6.*

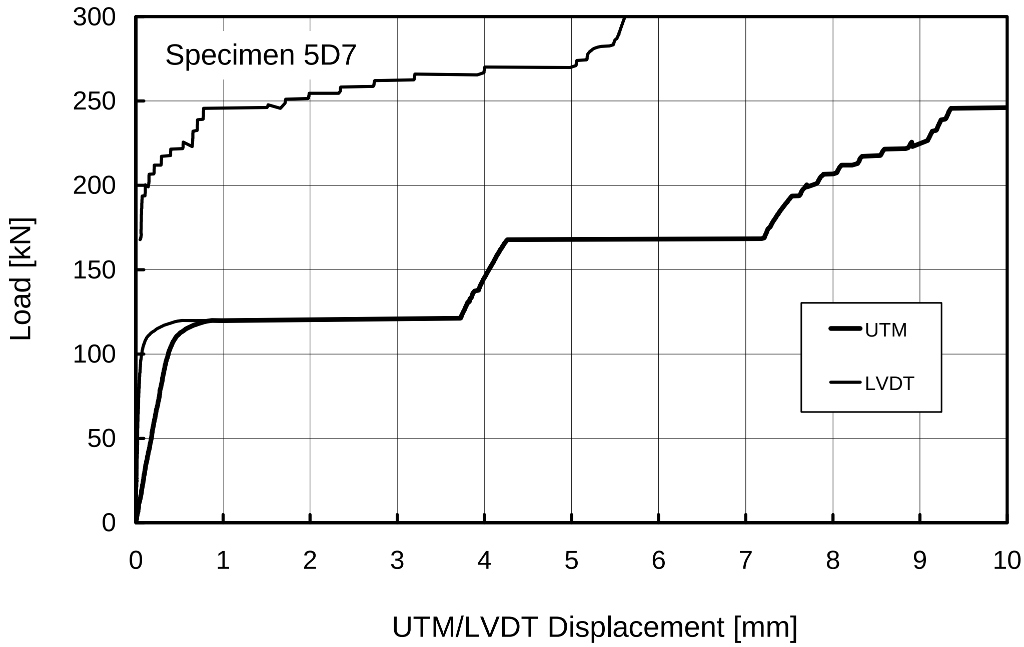

__Figure 139__ – Load vs. displacement, 5D7.

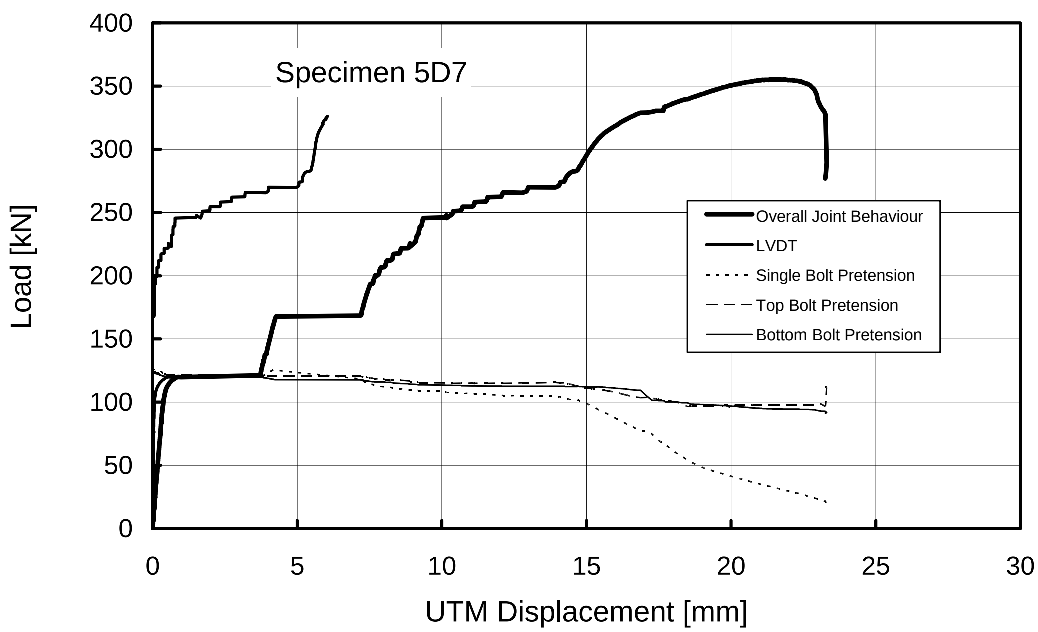

__Figure 140__ – Load vs. displacement, 5D7.

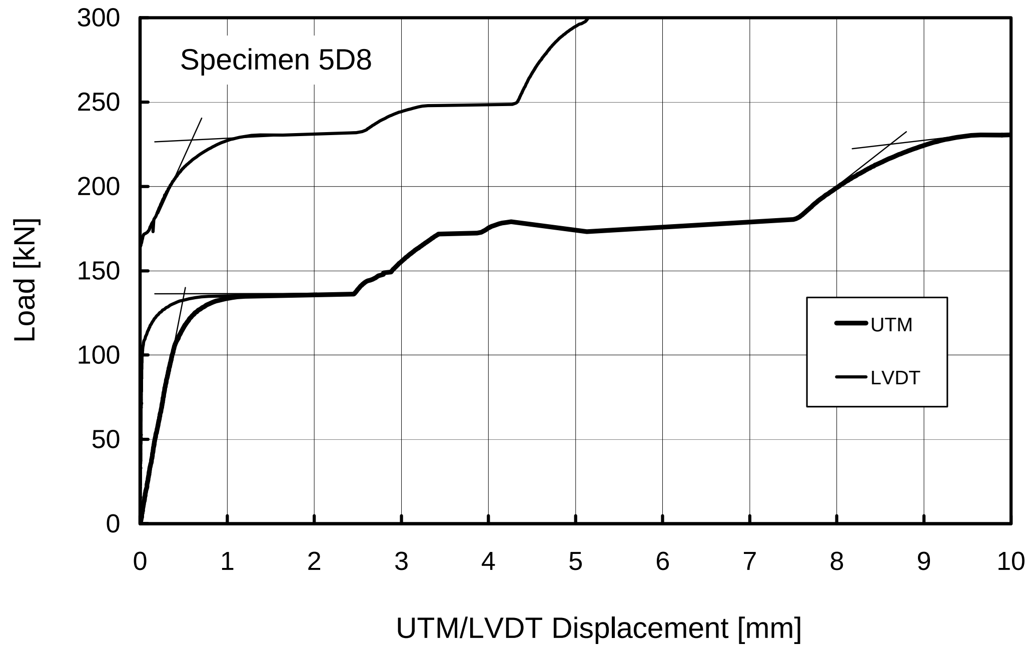

***Figure 141** – Load vs. displacement, 5D8.*

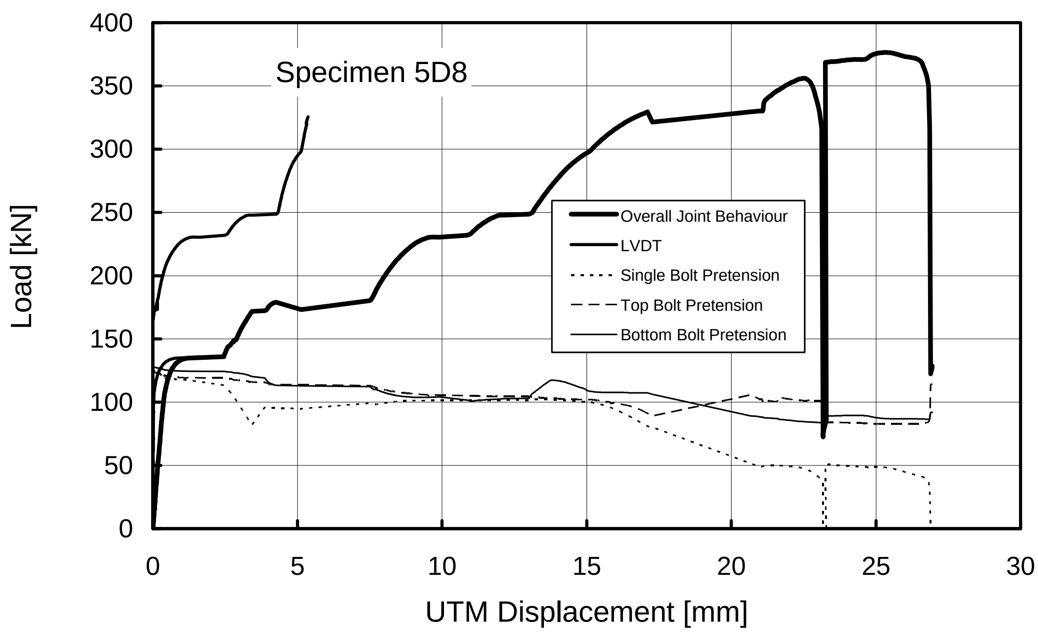

***Figure 142** – Load vs. displacement, 5D8.*

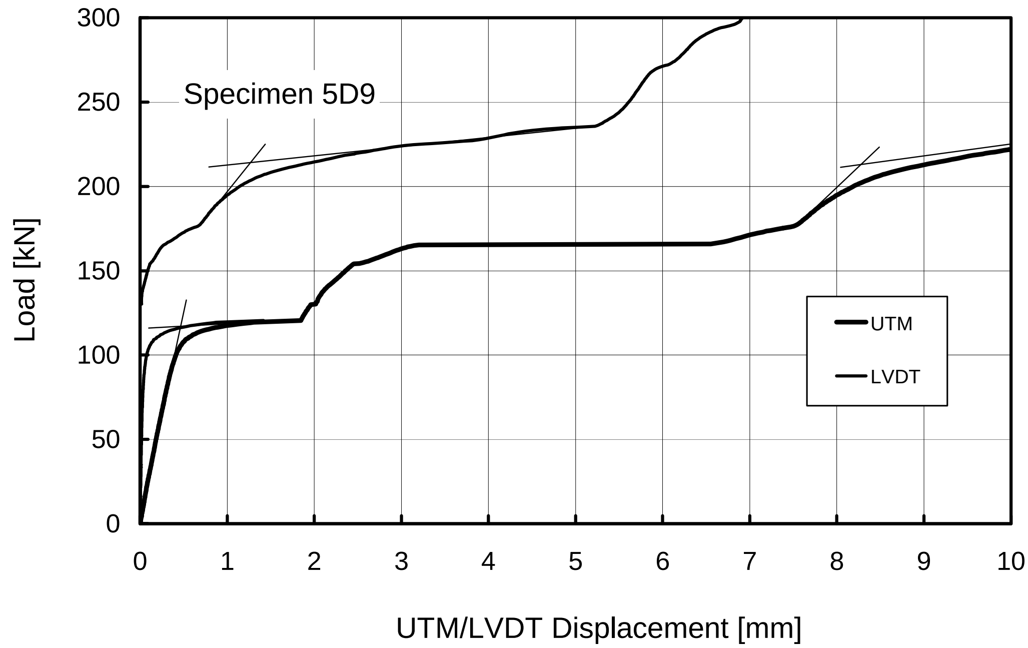

Figure 143 *– Load vs. displacement, 5D9.*

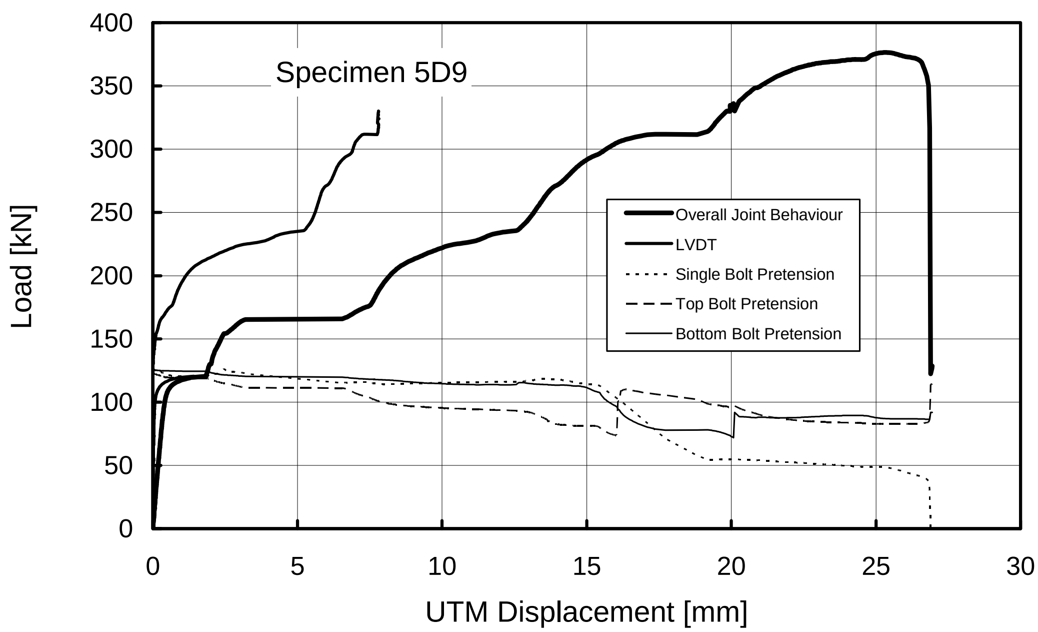

Figure 144 *– Load vs. displacement, 5D9.*

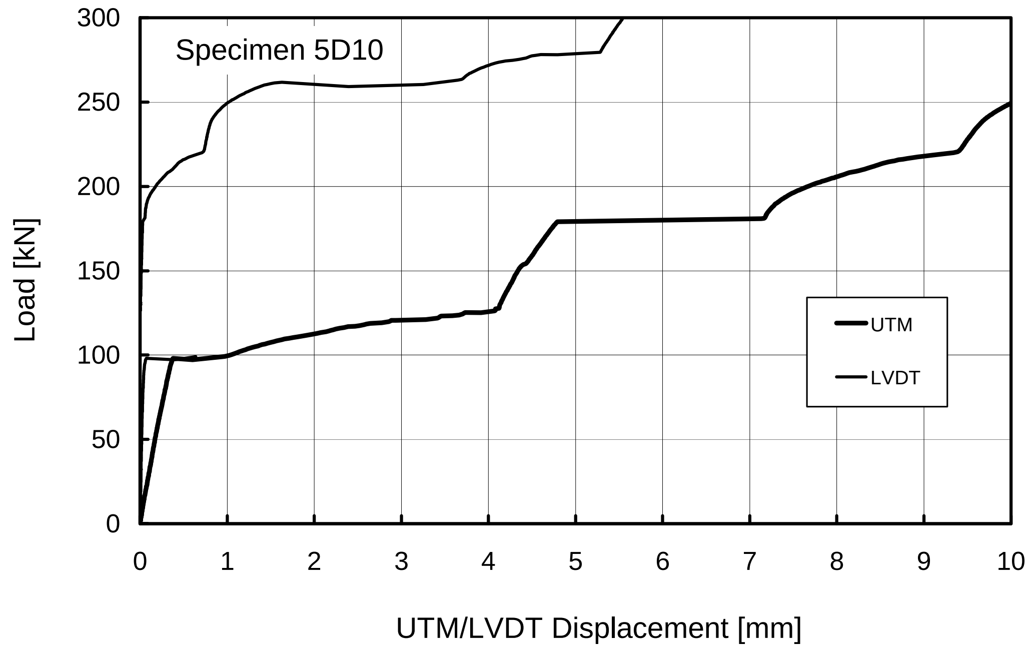

__Figure 145__ – Load vs. displacement, 5D10.

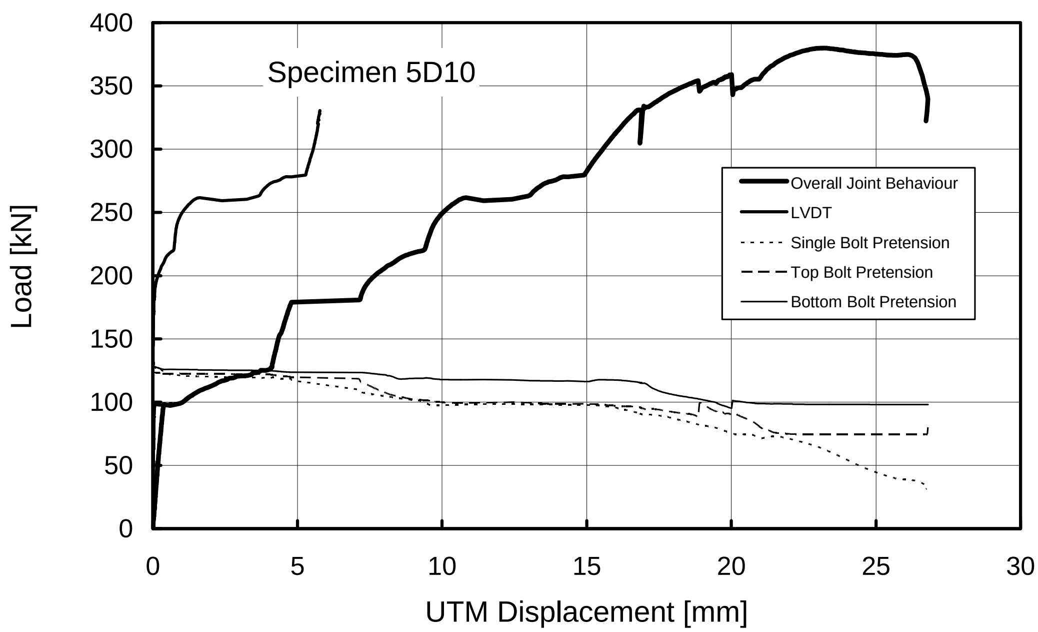

__Figure 146__ – Load vs. displacement, 5D10.

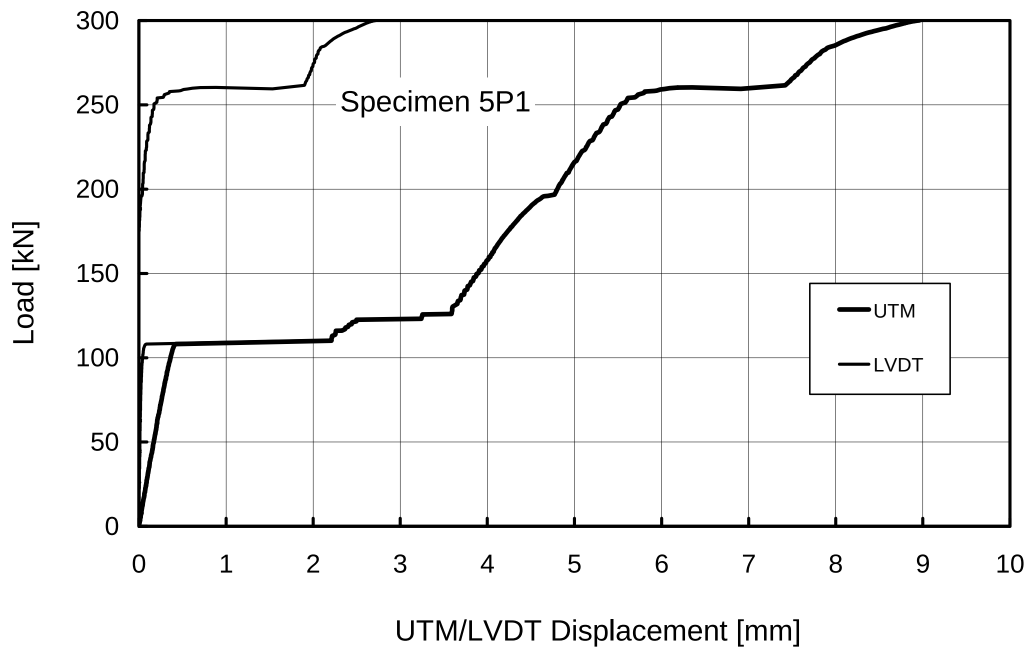

Figure 147 *– Load vs. displacement, 5P1.*

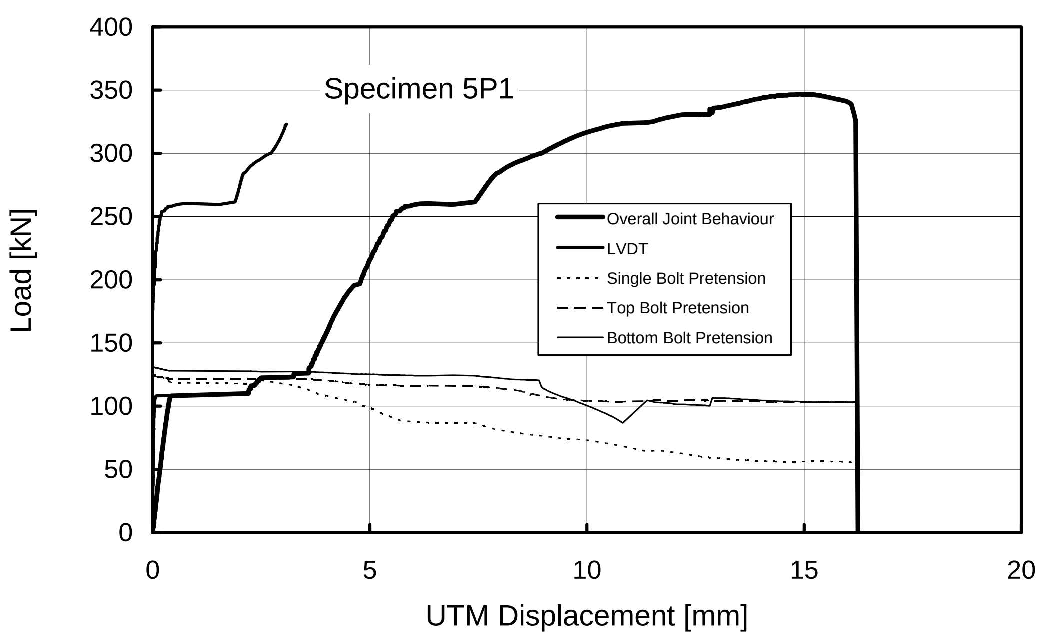

Figure 148 *– Load vs. displacement, 5P1.*

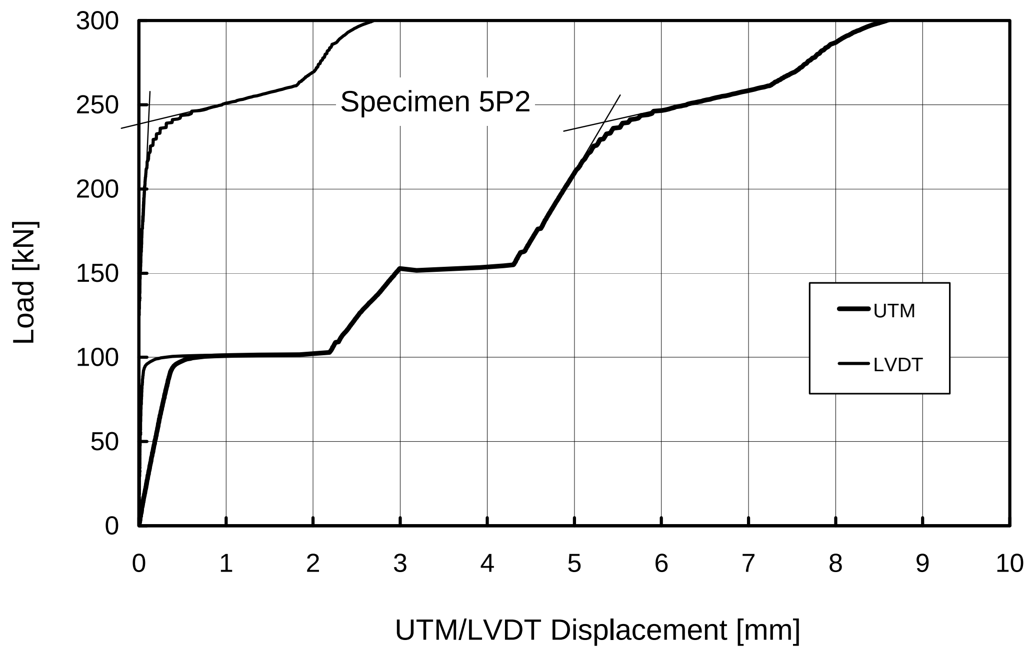

***Figure 149** – Load vs. displacement, 5P2.*

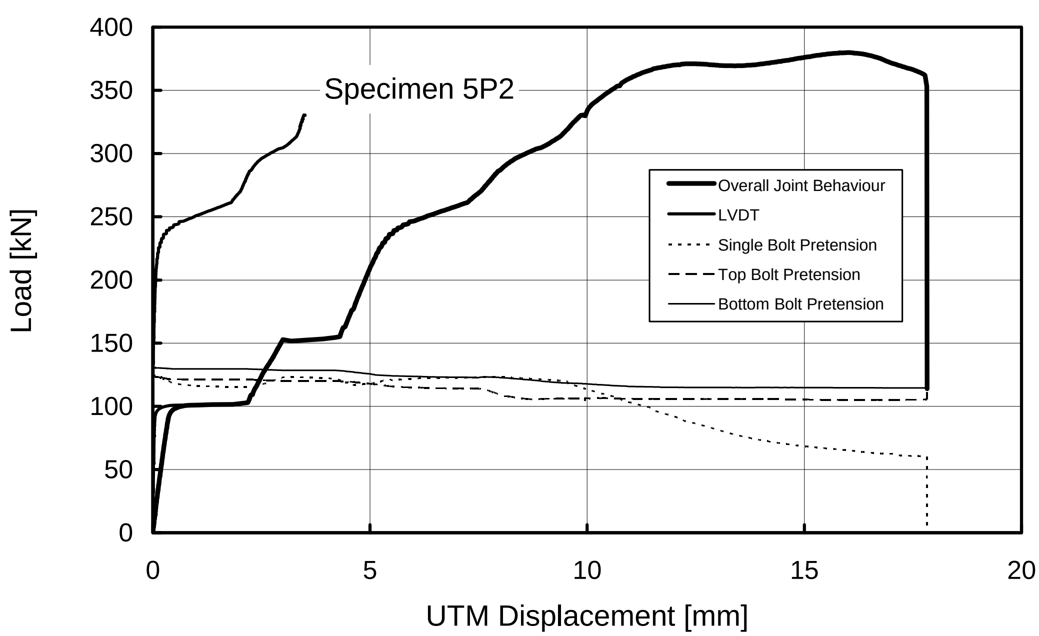

***Figure 150** – Load vs. displacement, 5P2.*

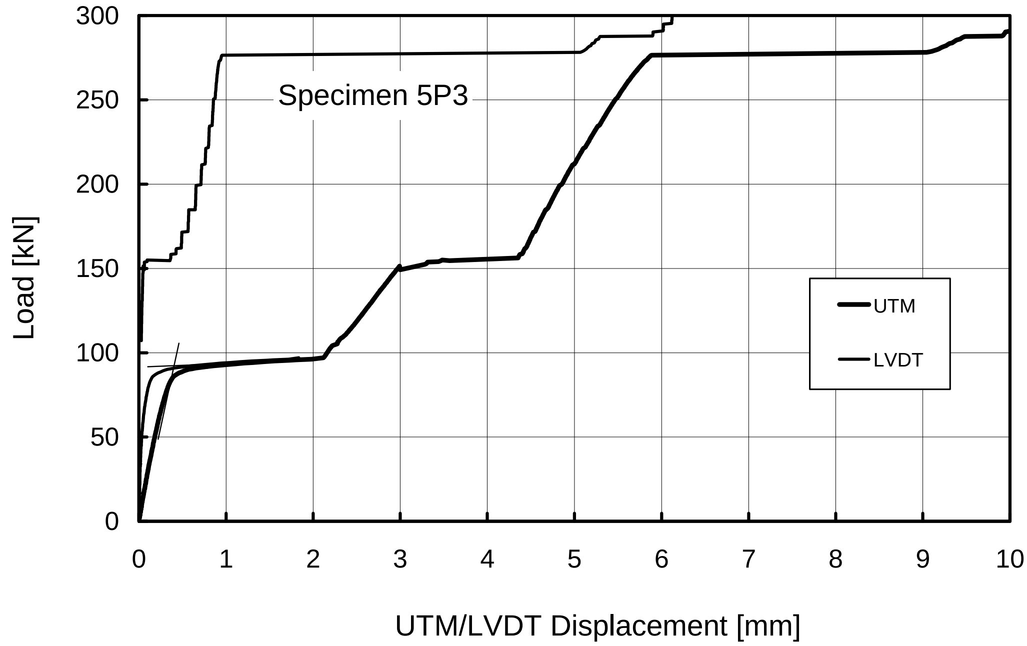

***Figure 151** – Load vs. displacement, 5P3.*

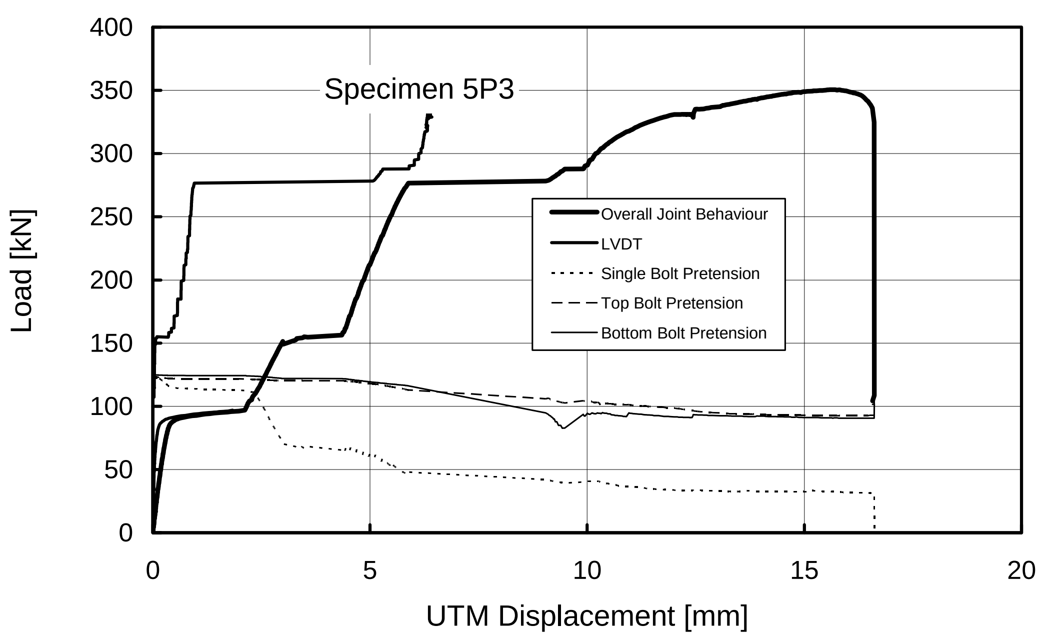

***Figure 152** – Load vs. displacement, 5P3.*

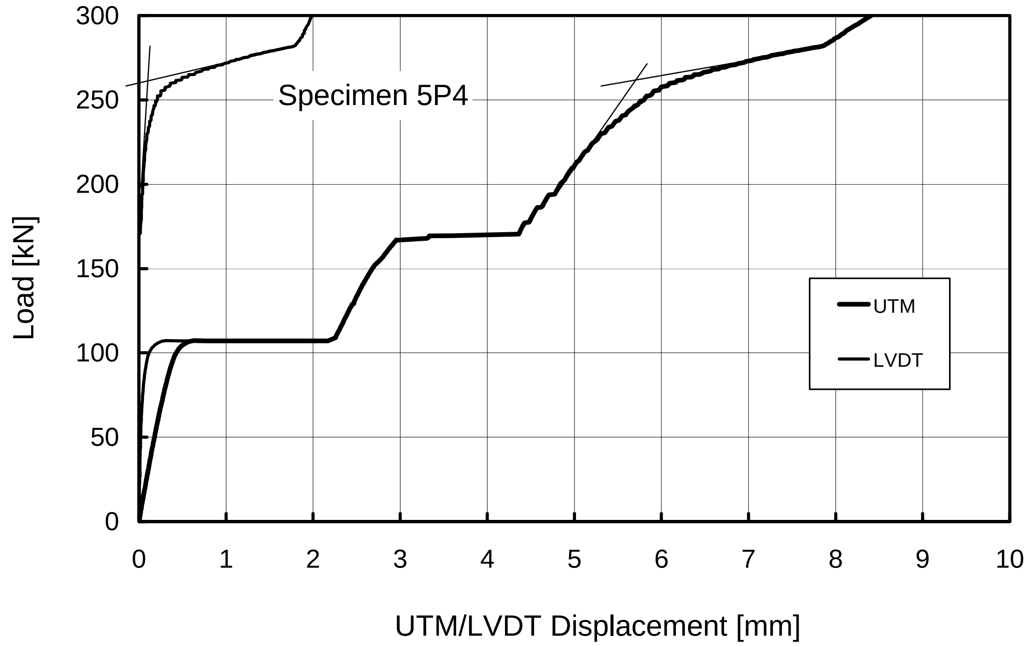

***Figure 153** – Load vs. displacement, 5P4.*

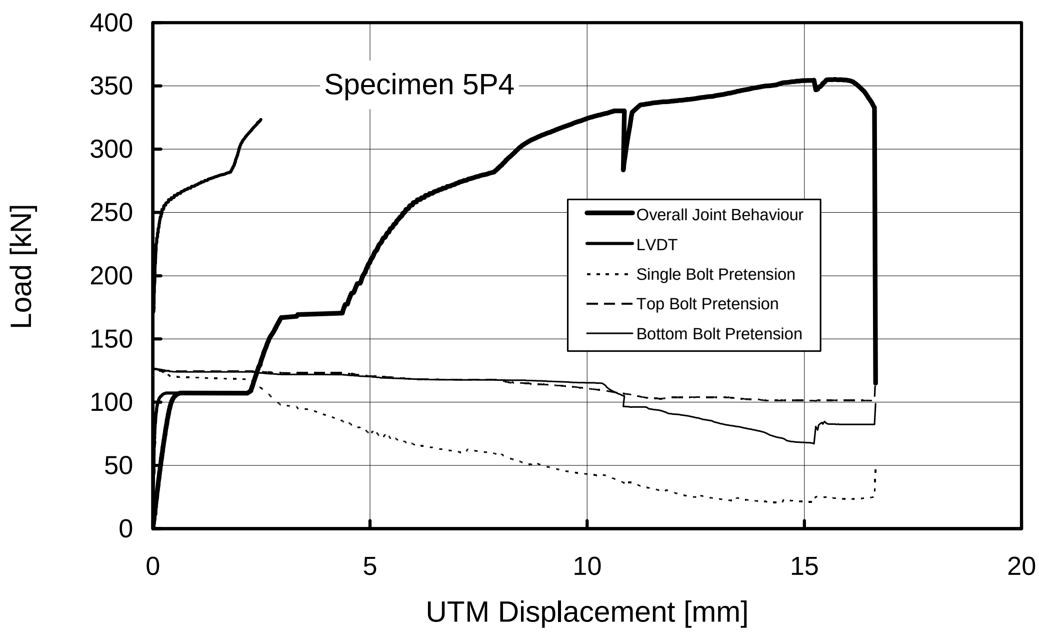

***Figure 154** – Load vs. displacement, 5P4.*

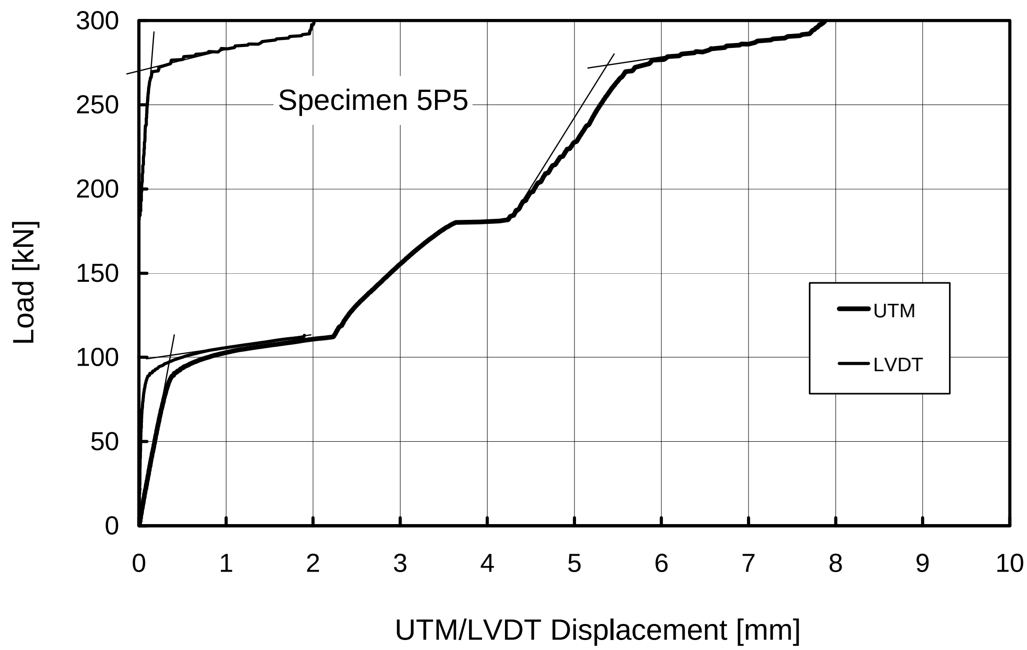

Figure 155 *– Load vs. displacement, 5P5.*

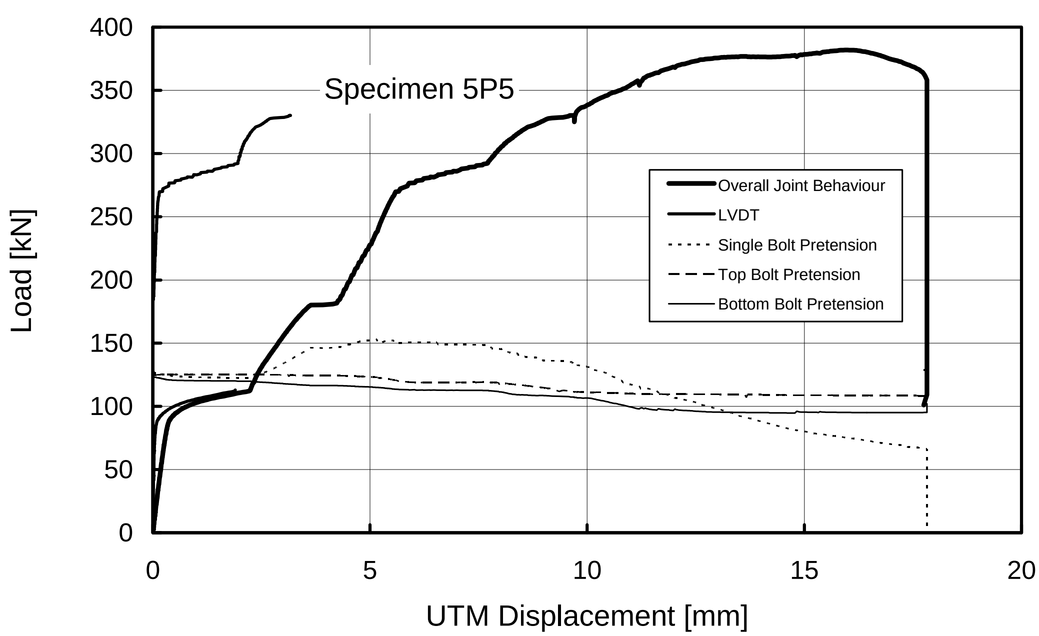

Figure 156 *– Load vs. displacement, 5P5.*

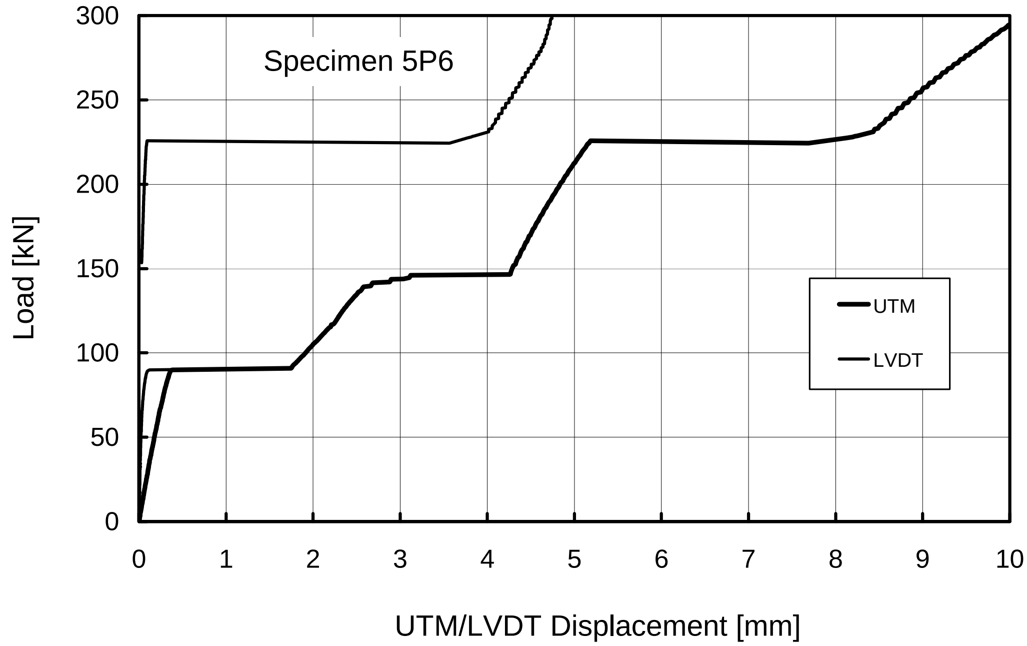

Figure 157 *– Load vs. displacement, 5P6.*

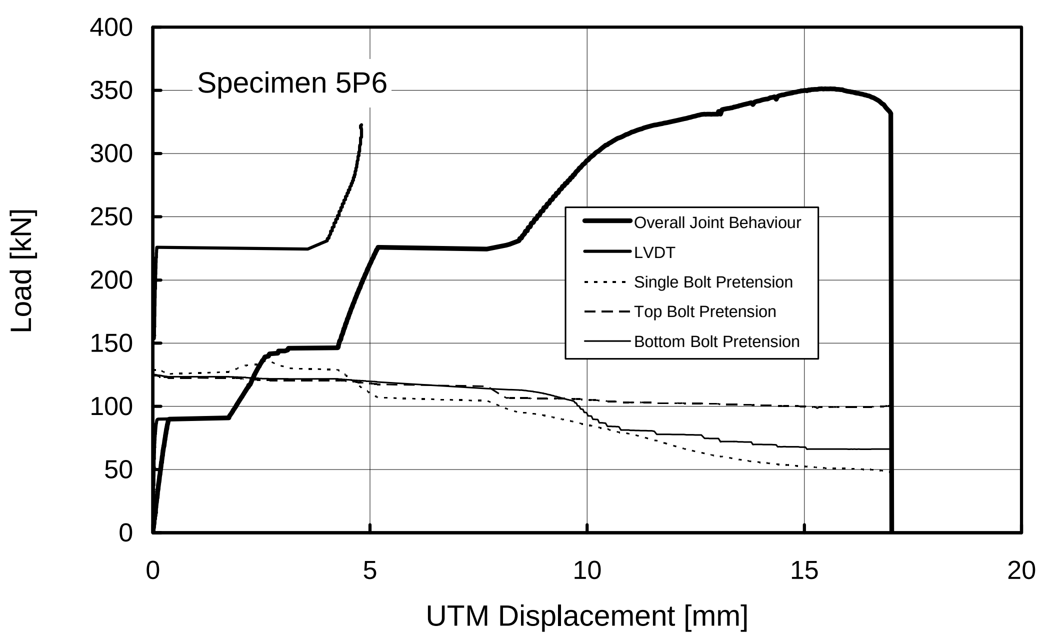

Figure 158 *– Load vs. displacement, 5P6.*

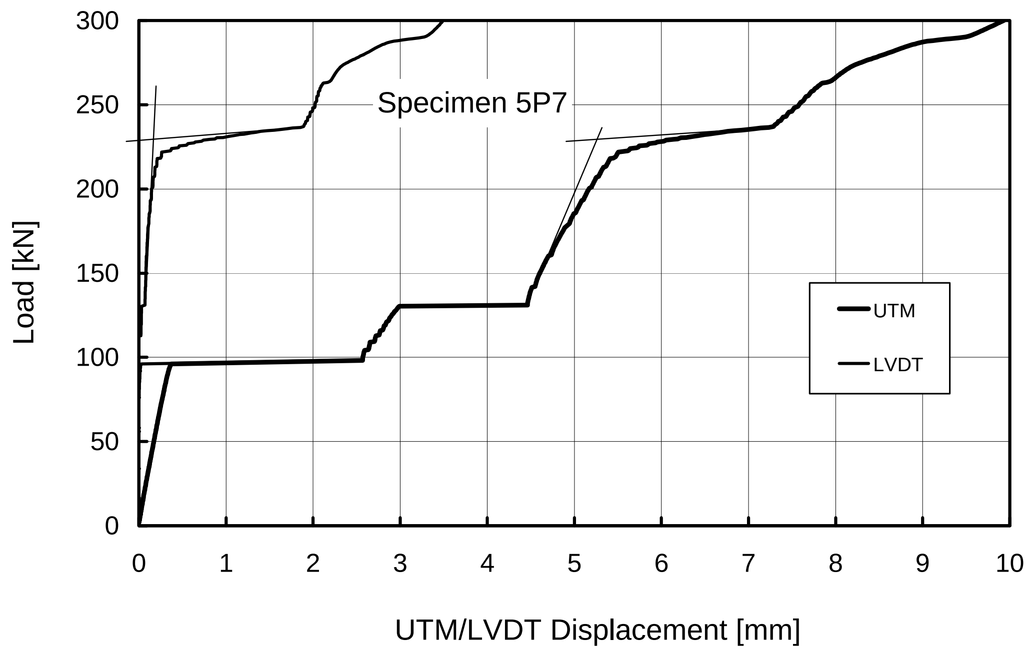

***Figure 159** – Load vs. displacement, 5P7.*

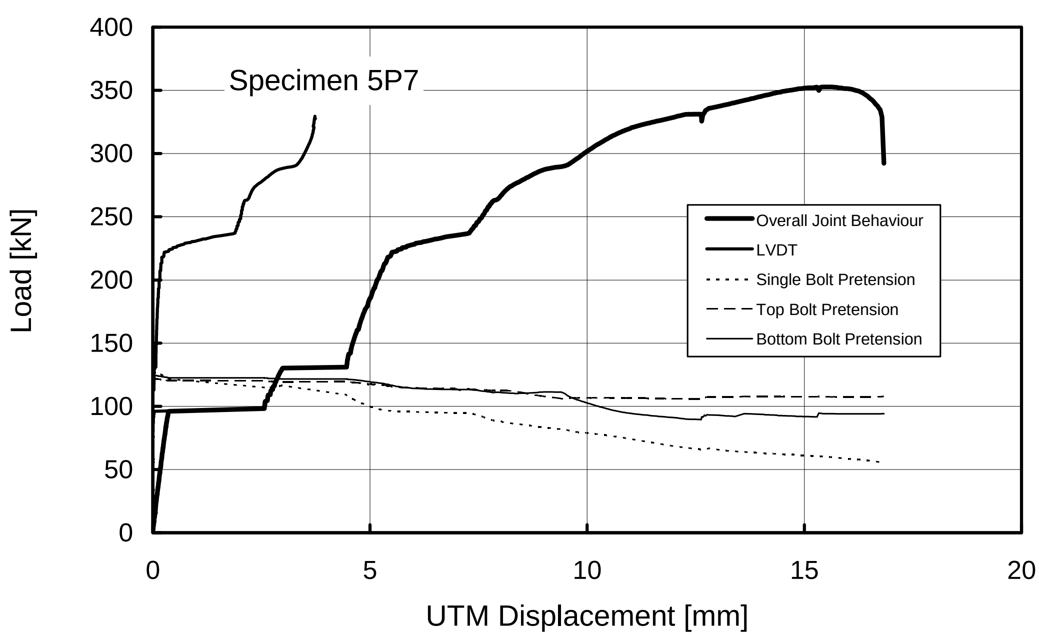

***Figure 160** – Load vs. displacement, 5P7.*

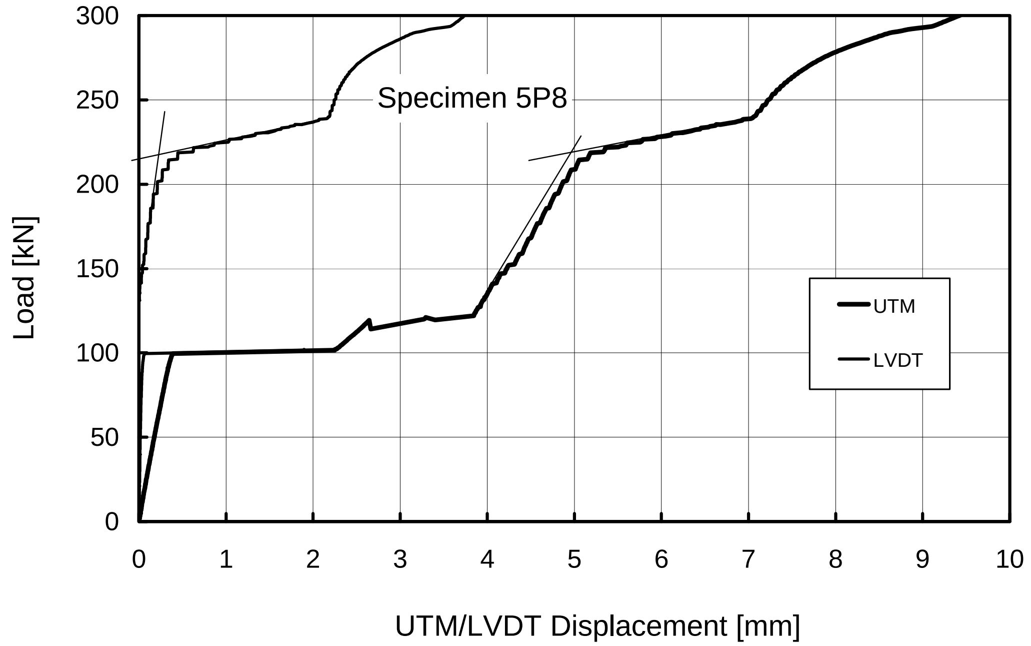

***Figure 161** – Load vs. displacement, 5P8.*

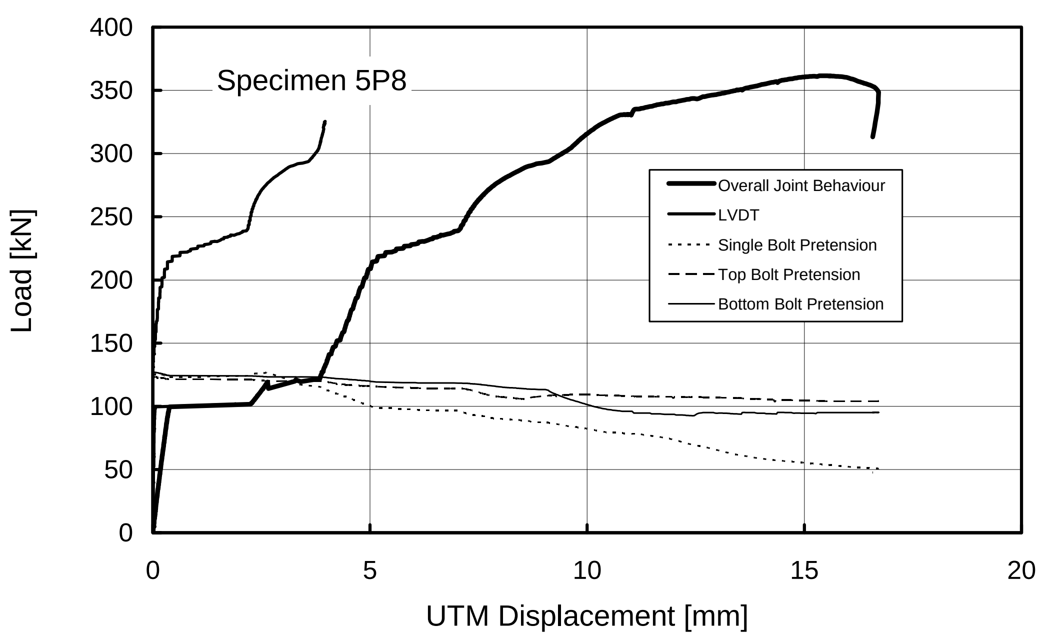

***Figure 162** – Load vs. displacement, 5P8.*

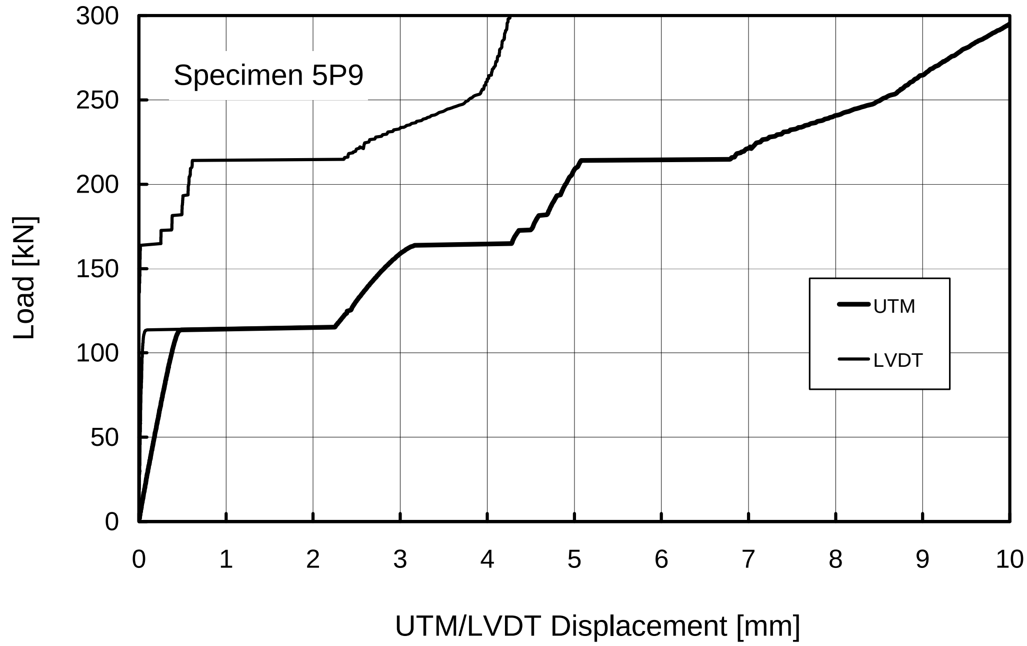

***Figure 163** – Load vs. displacement, 5P9.*

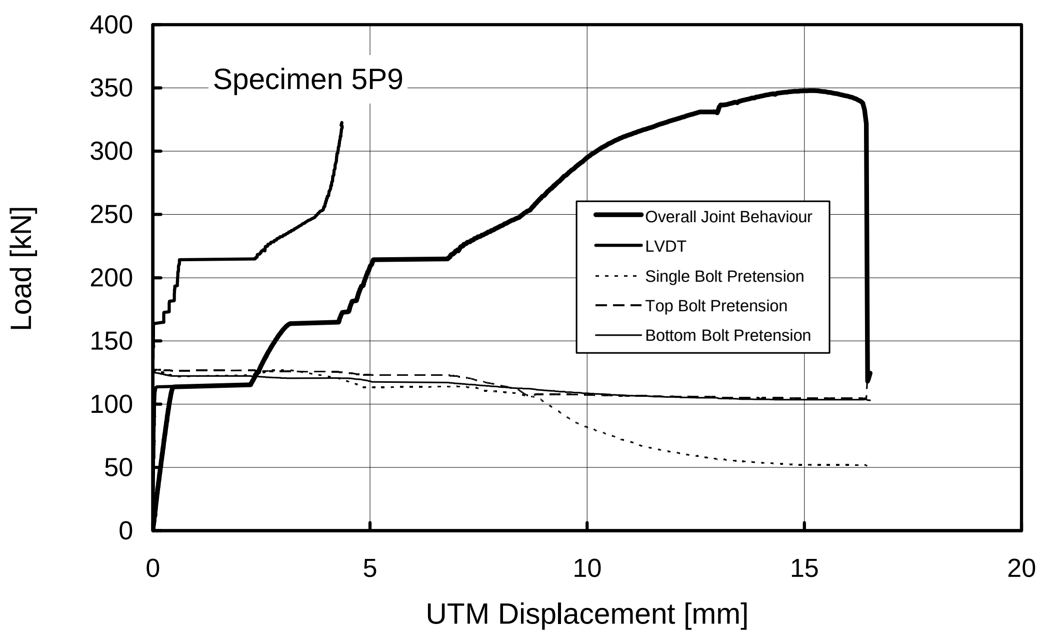

***Figure 164** – Load vs. displacement, 5P9.*

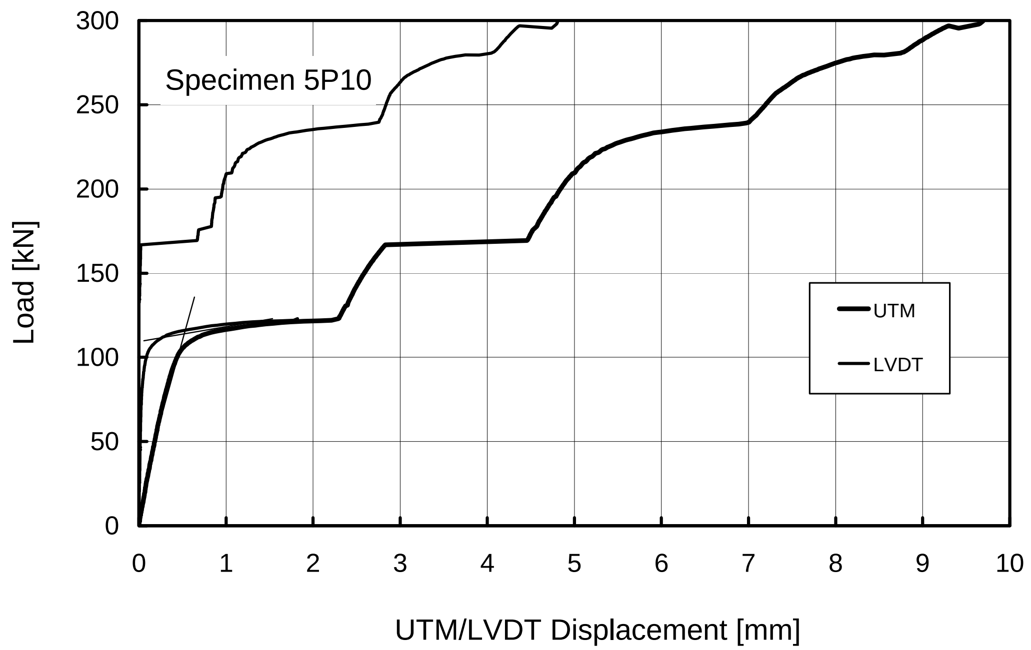

***Figure 165** – Load vs. displacement, 5P10.*

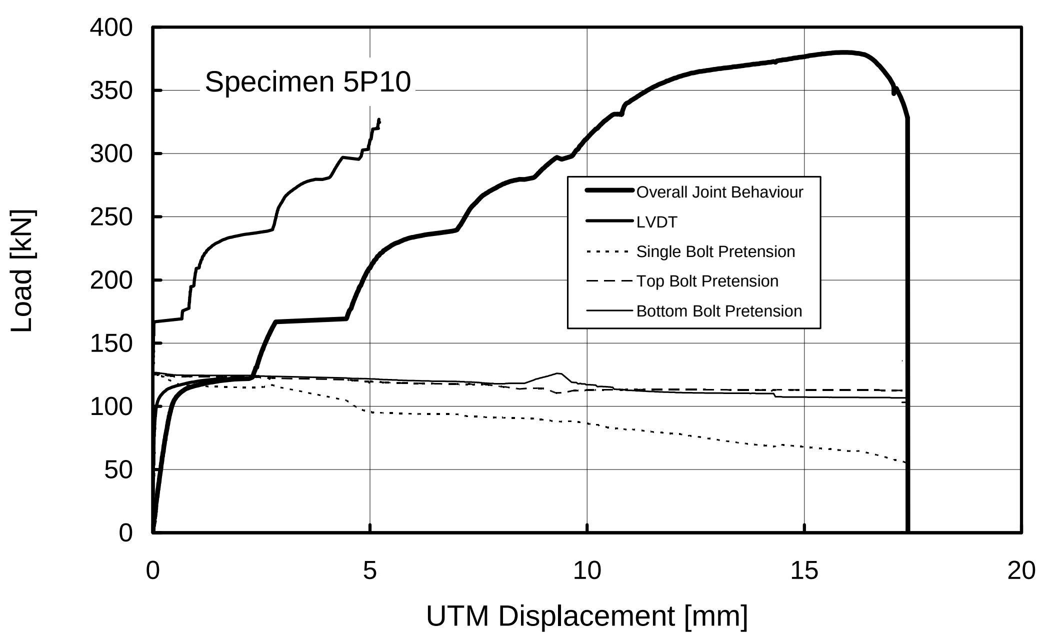

***Figure 166** – Load vs. displacement, 5P10.*

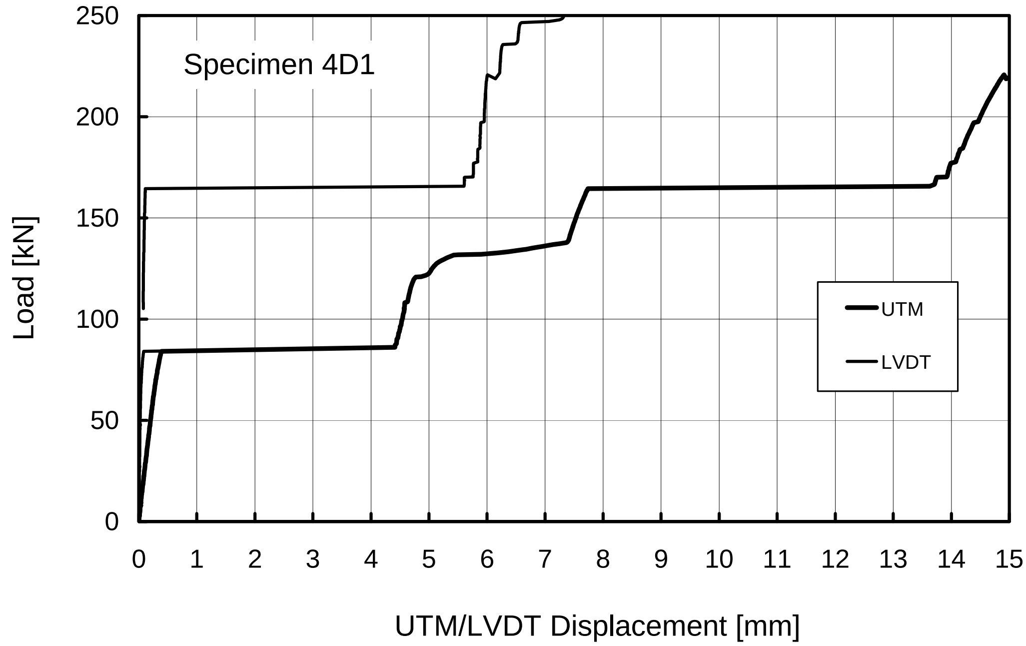

Figure 167 – Load vs. displacement, 4D1.

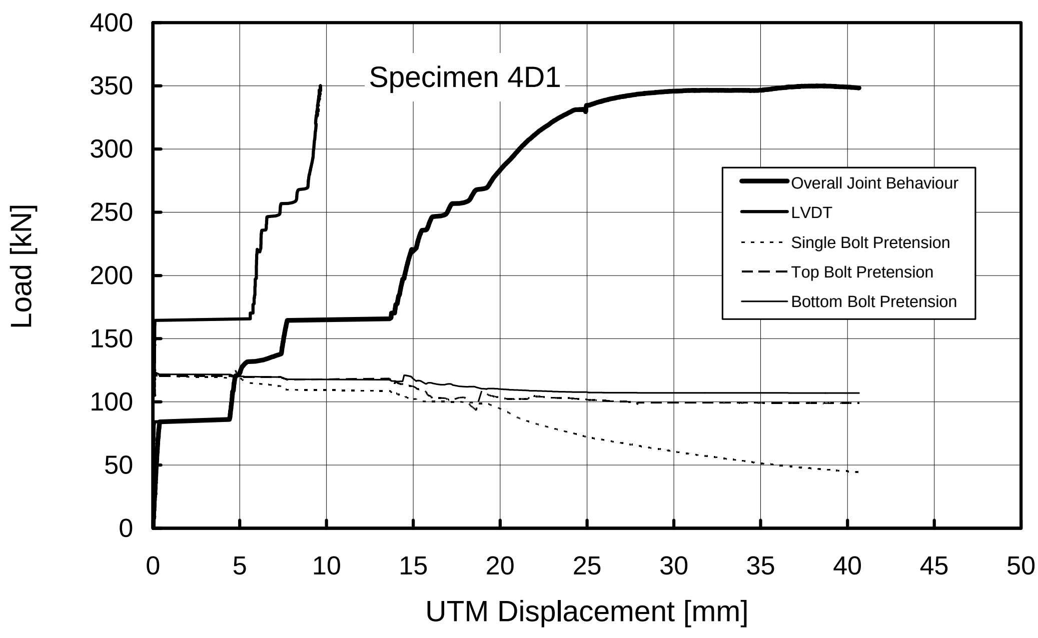

Figure 168 – Load vs. displacement, 4D1.

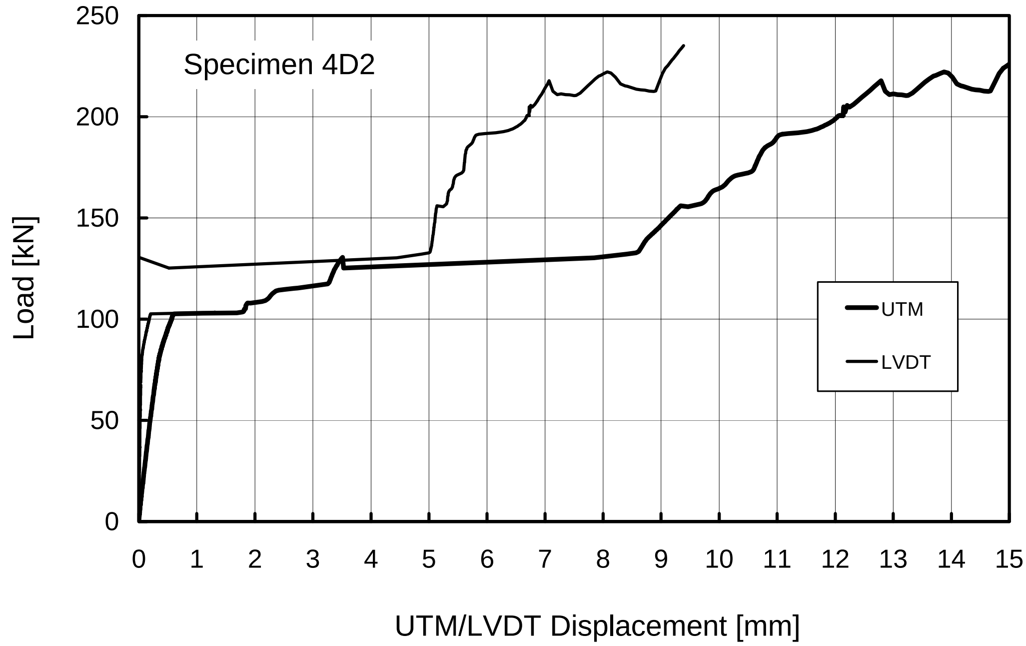

Figure 169 *– Load vs. displacement, 4D2.*

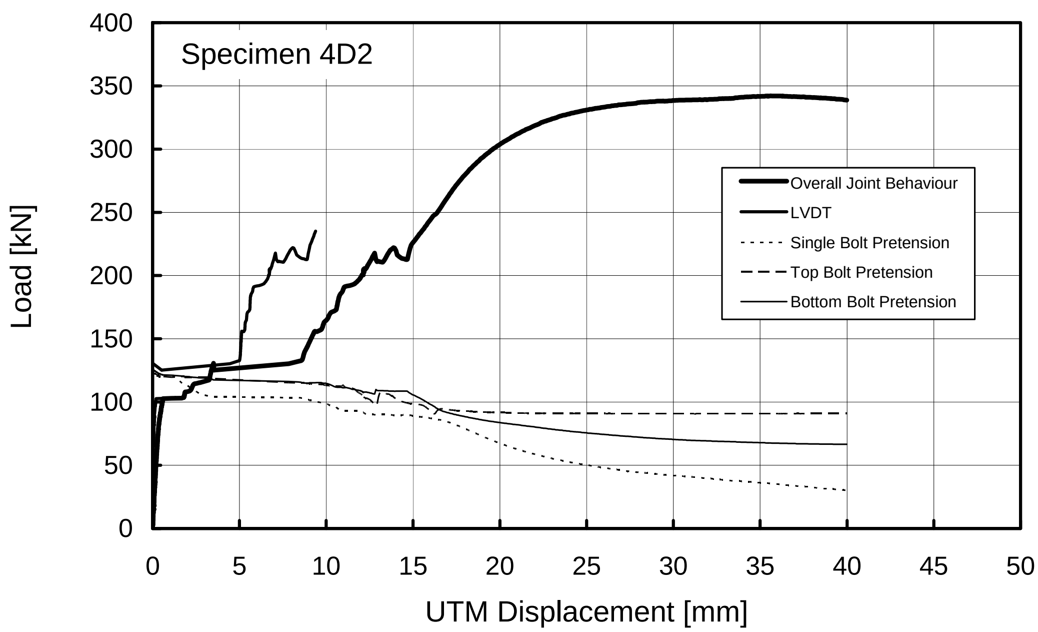

Figure 170 *– Load vs. displacement, 4D2.*

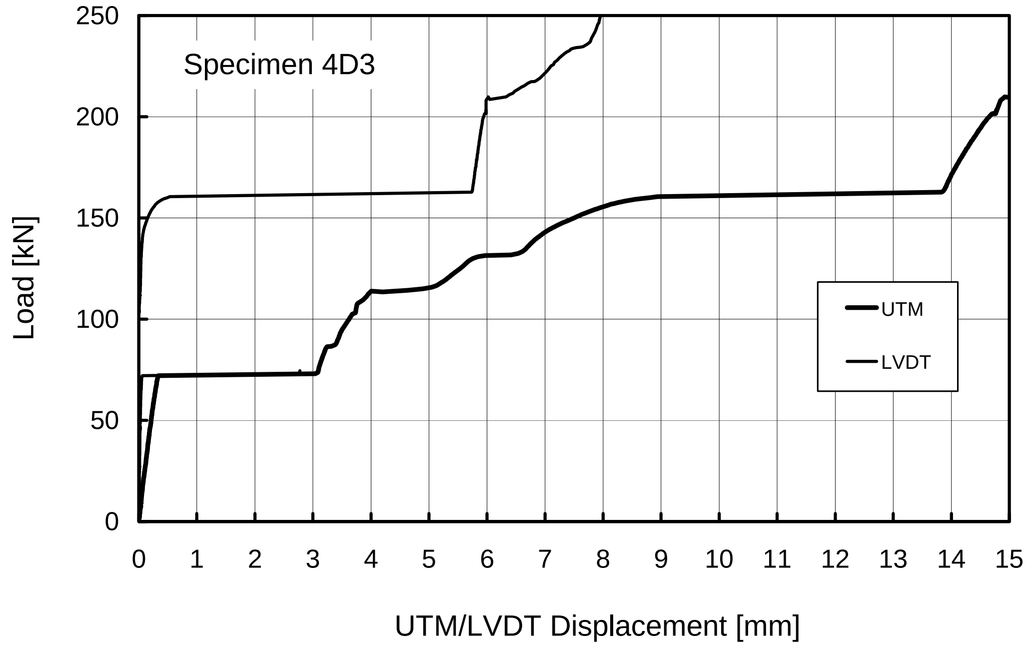

Figure 171 *– Load vs. displacement, 4D3.*

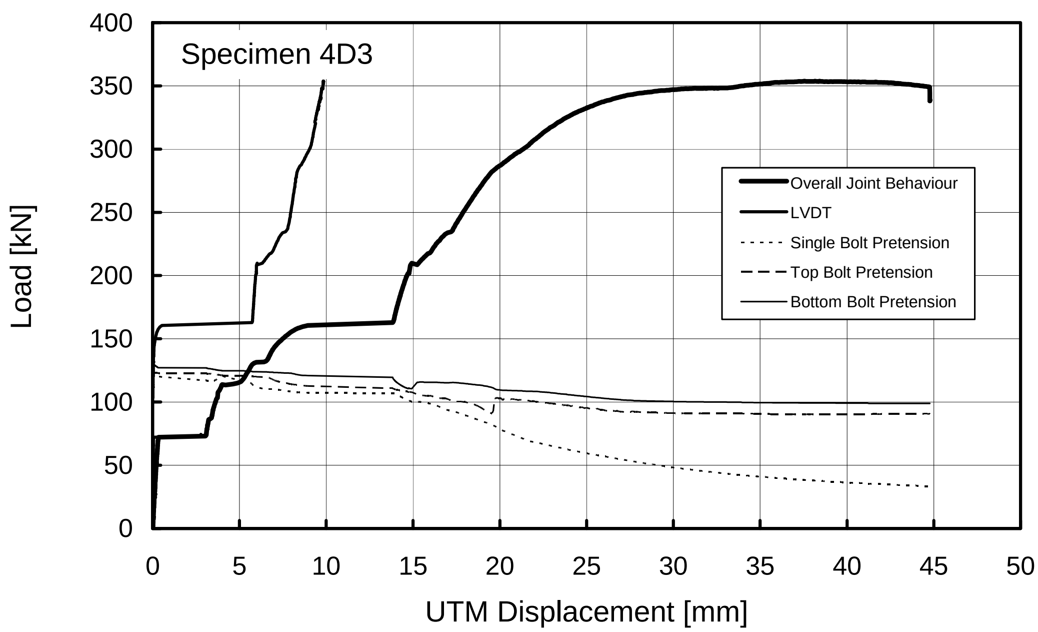

Figure 172 *– Load vs. displacement, 4D3.*

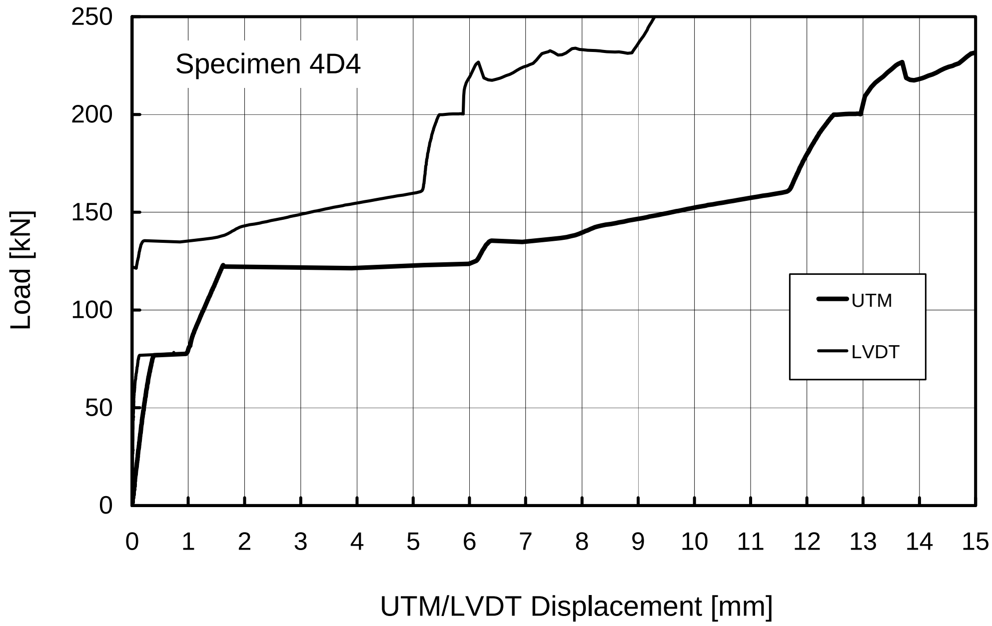

Figure 173 *– Load vs. displacement, 4D4.*

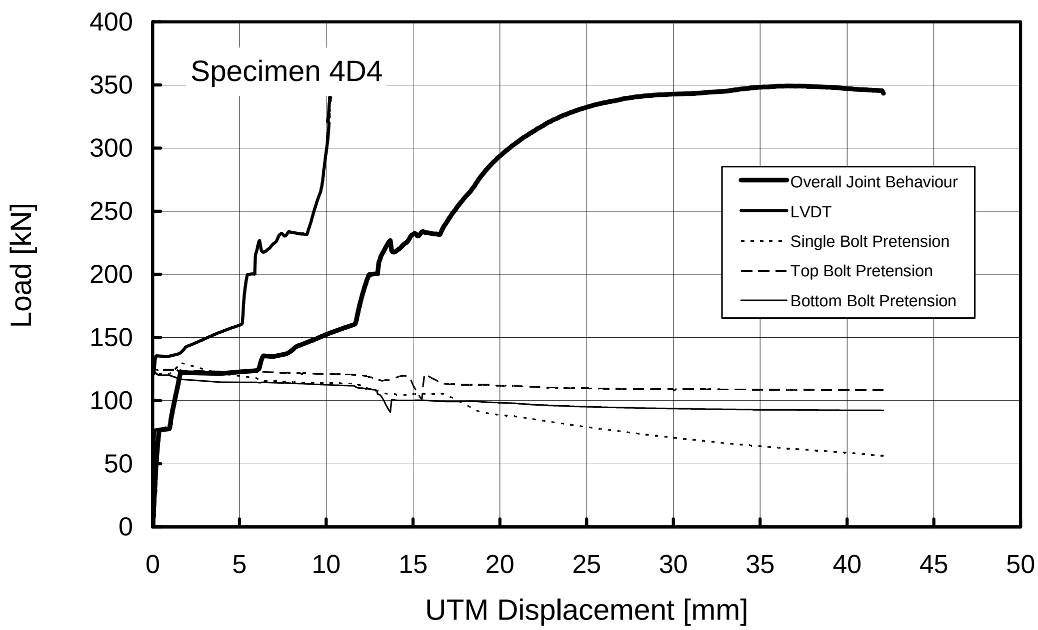

Figure 174 *– Load vs. displacement, 4D4.*

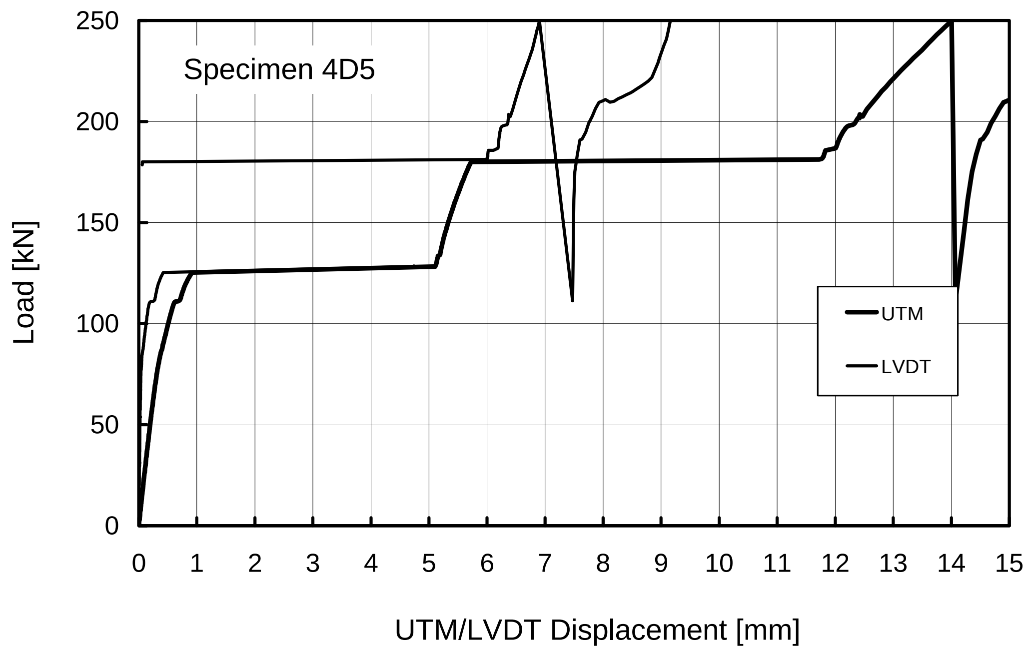

***Figure 175** – Load vs. displacement, 4D5.*

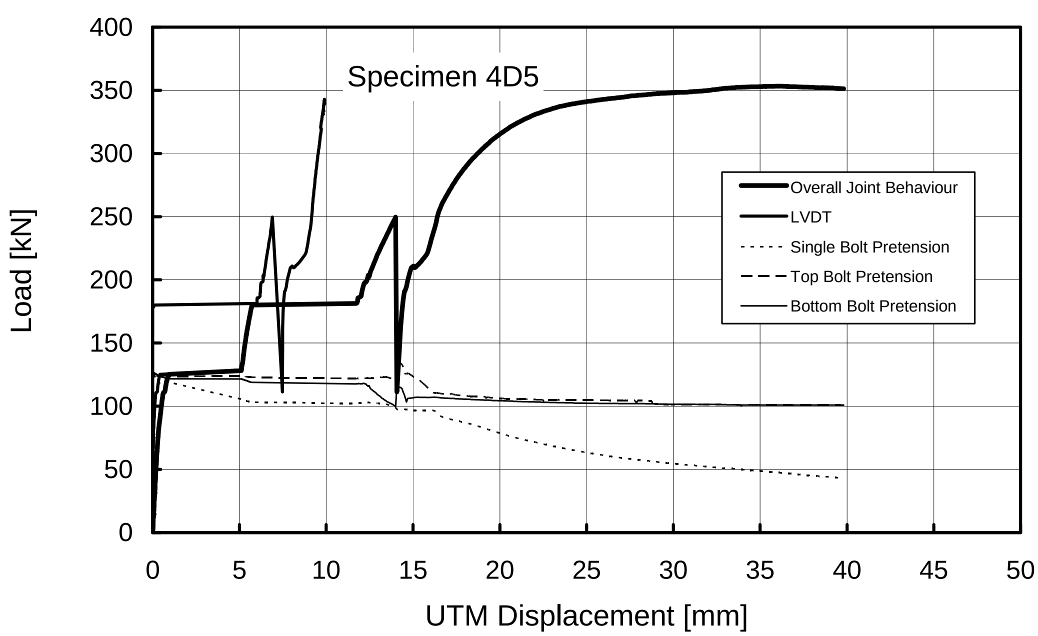

***Figure 176** – Load vs. displacement, 4D5.*

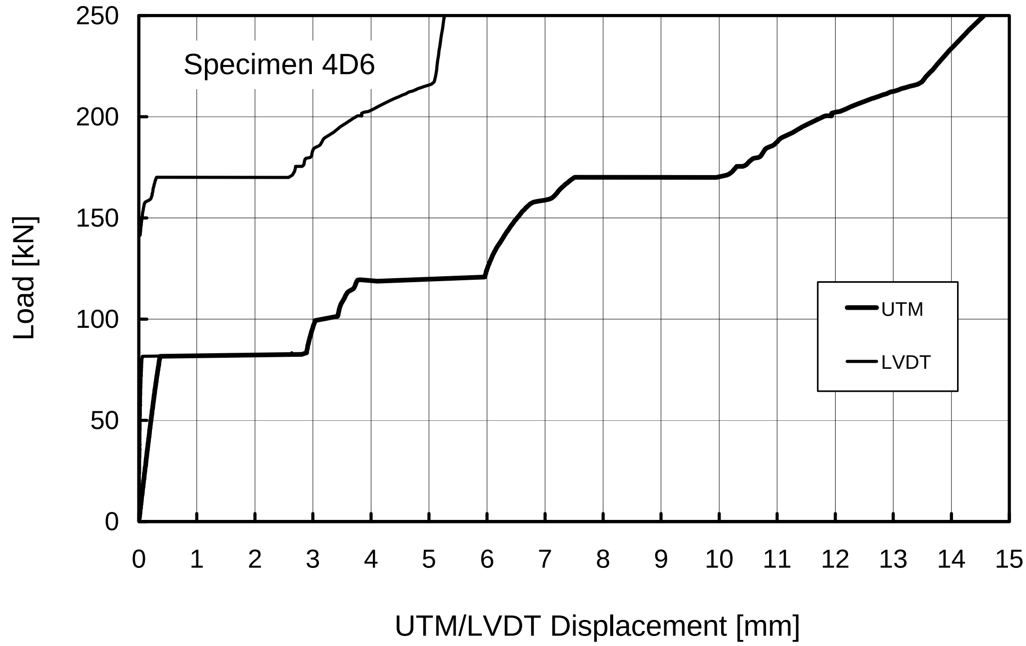

***Figure 177** – Load vs. displacement, 4D6.*

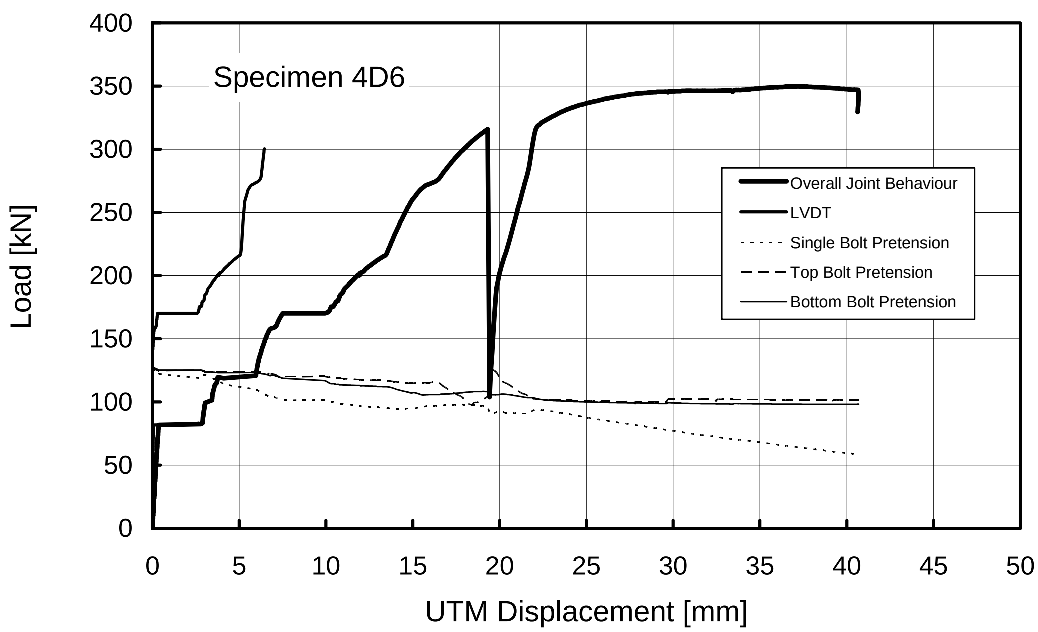

***Figure 178** – Load vs. displacement, 4D6.*

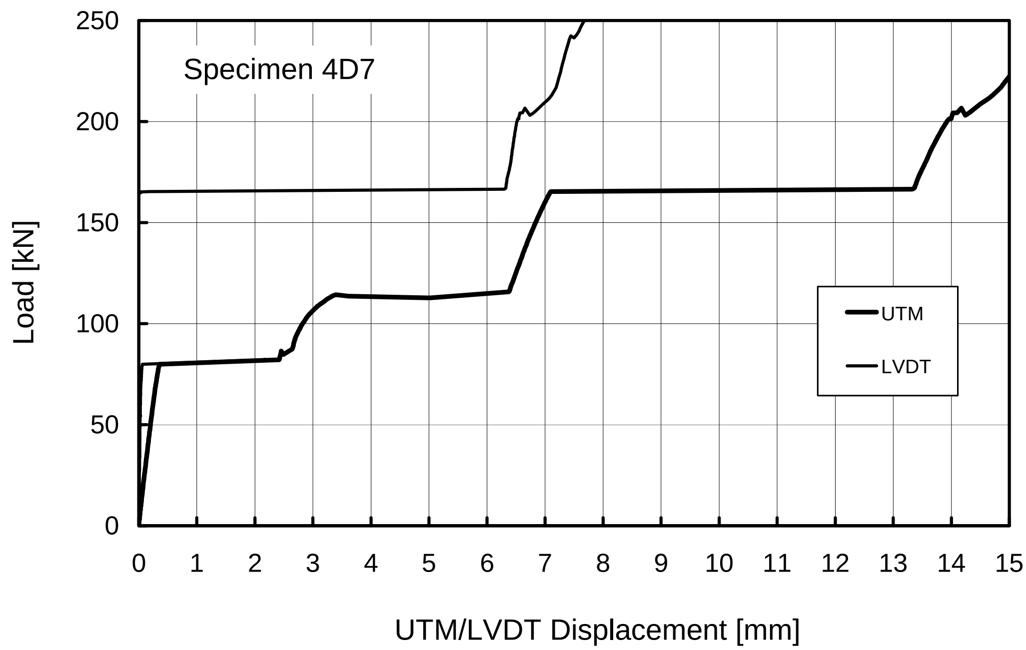

Figure 179 *– Load vs. displacement, 4D7.*

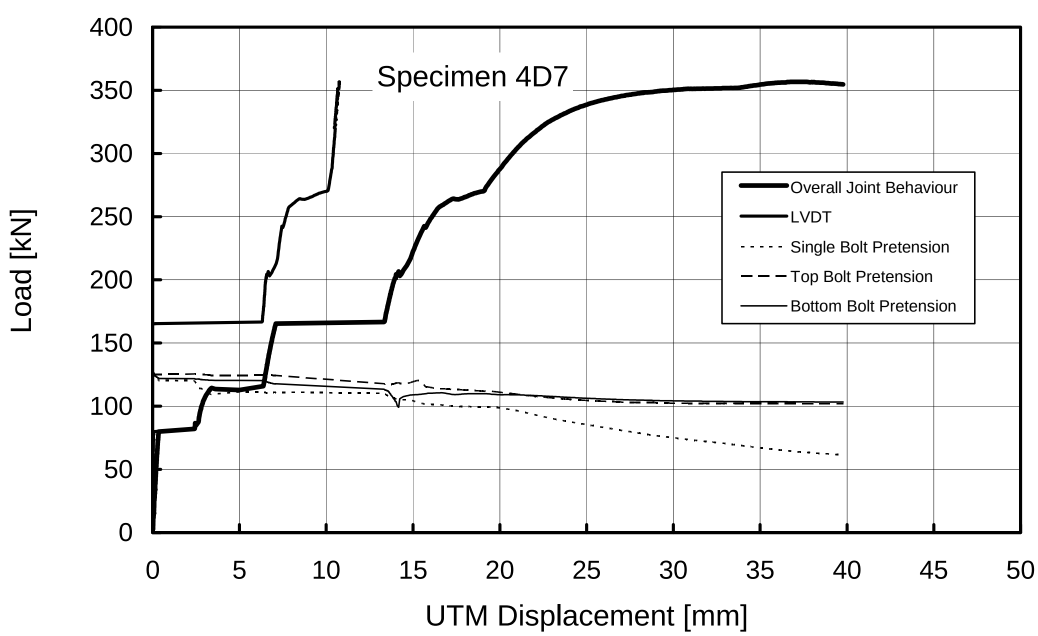

Figure 180 *– Load vs. displacement, 4D7.*

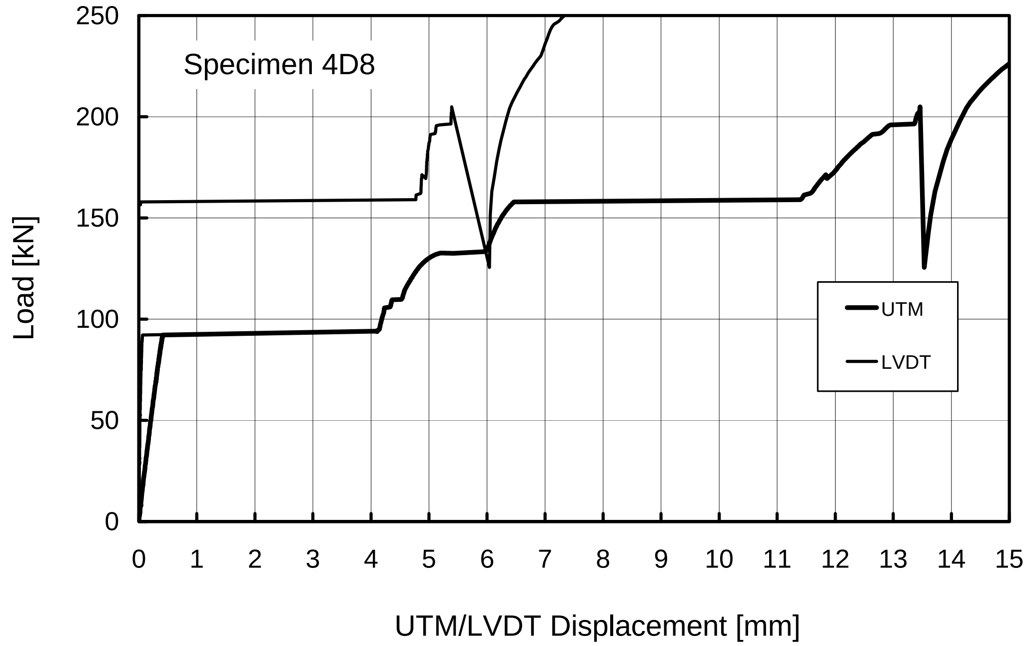

Figure 181 *– Load vs. displacement, 4D8.*

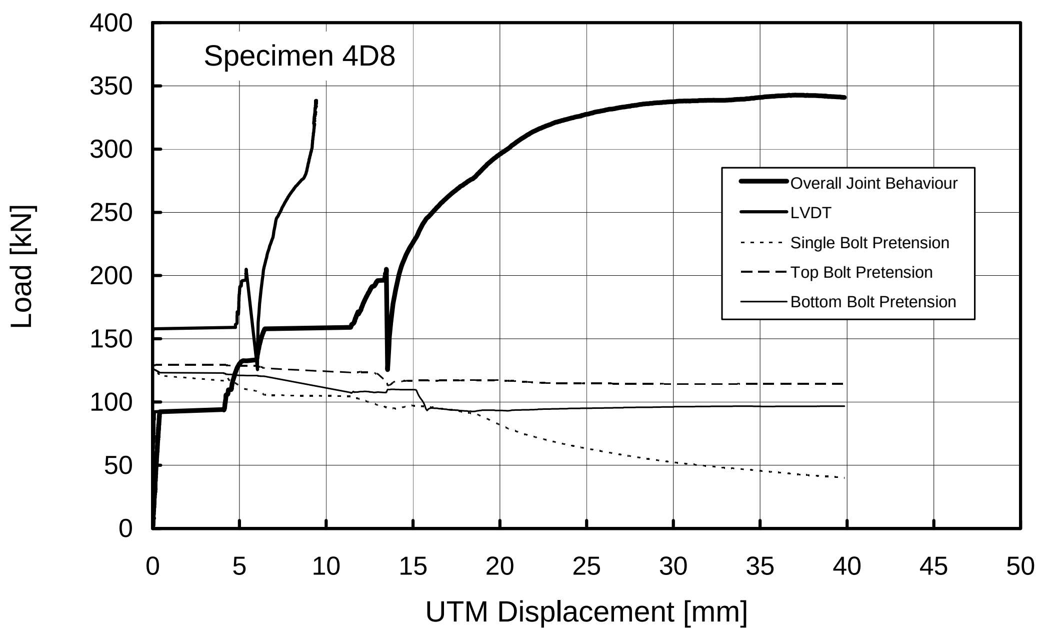

Figure 182 *– Load vs. displacement, 4D8.*

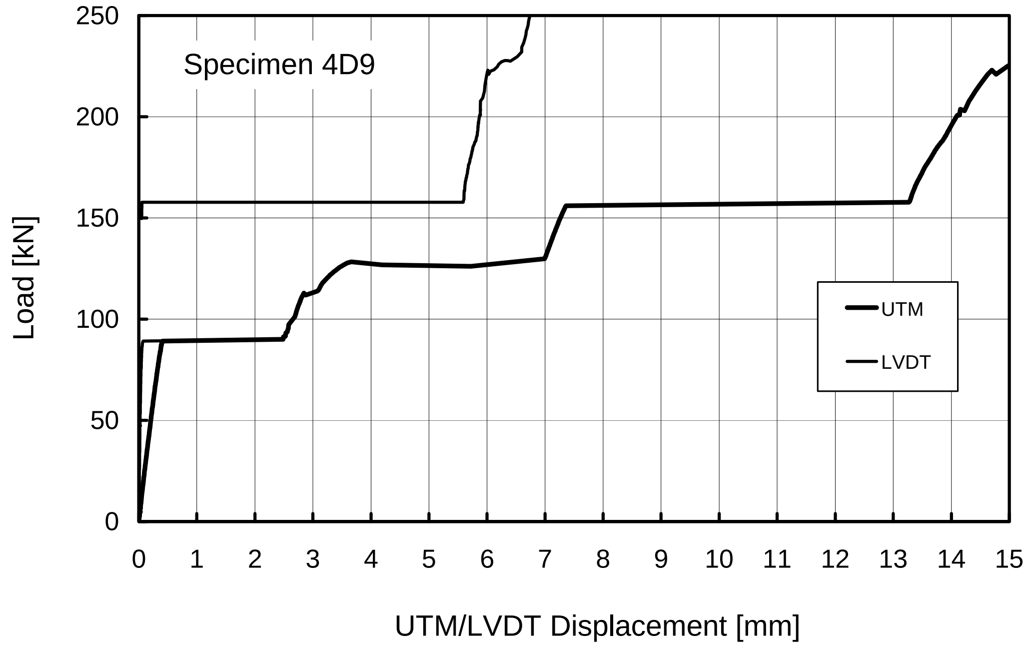

Figure 183 *– Load vs. displacement, 4D9.*

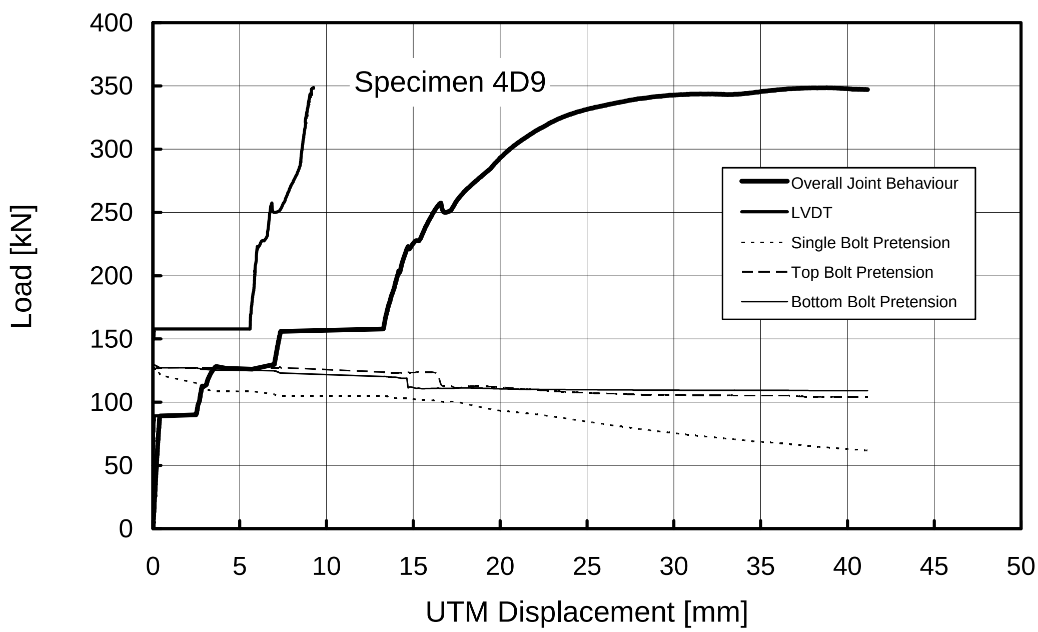

Figure 184 *– Load vs. displacement, 4D9.*

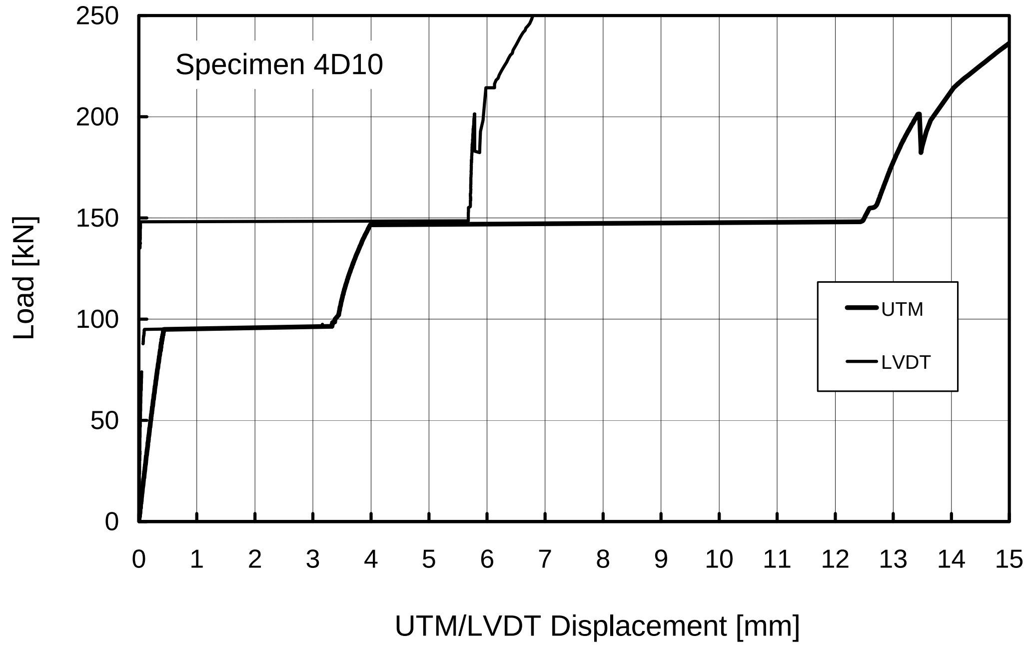

***Figure 185** – Load vs. displacement, 4D10.*

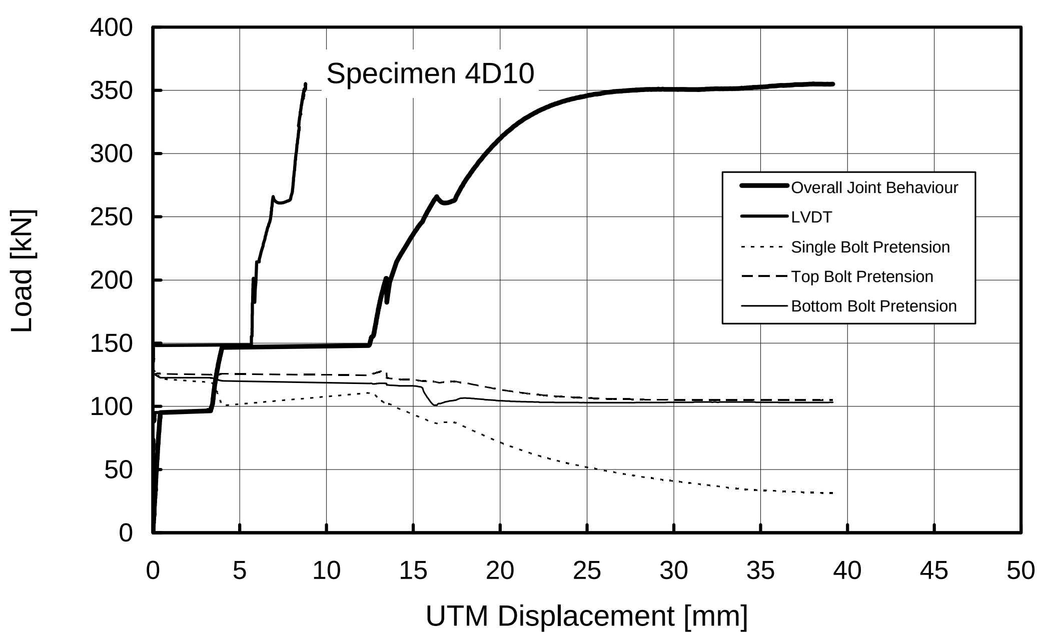

***Figure 186** – Load vs. displacement, 4D10.*

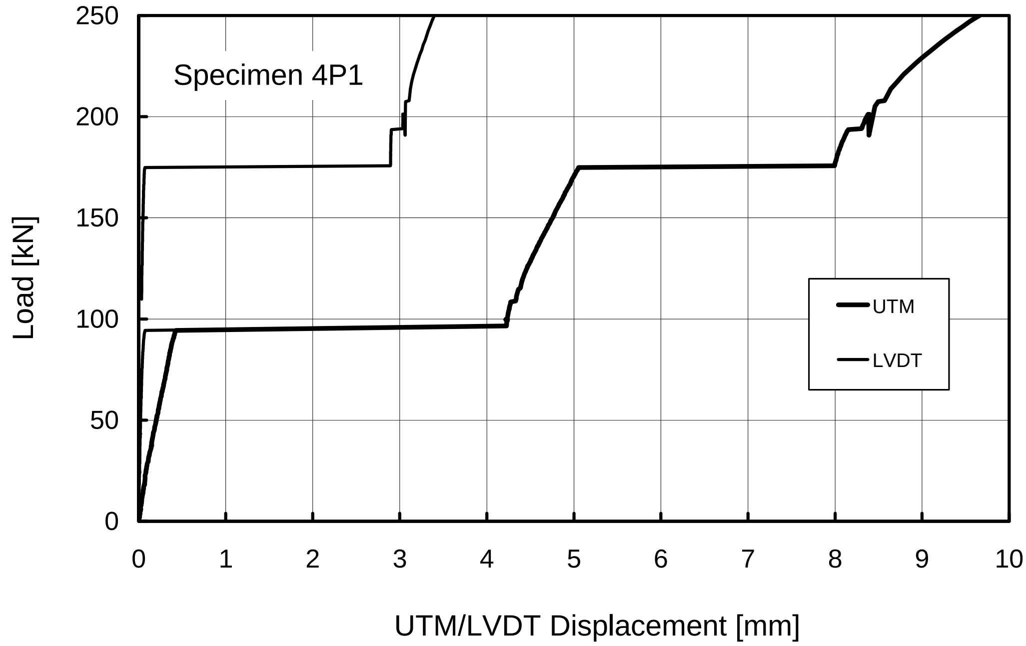

***Figure 187** – Load vs. displacement, 4P1.*

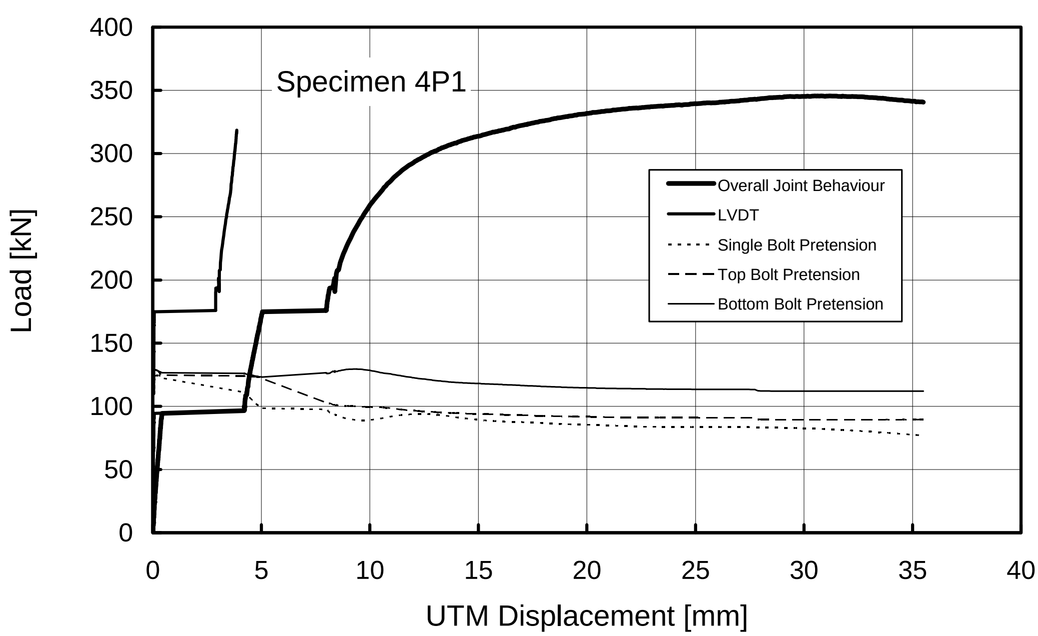

***Figure 188** – Load vs. displacement, 4P1.*

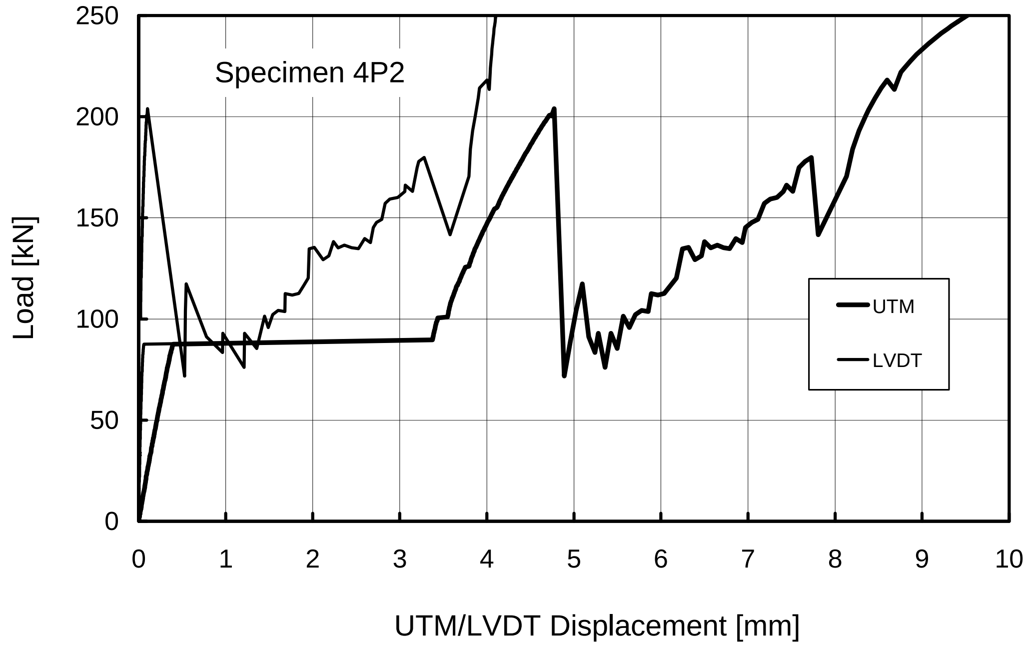

Figure 189 *– Load vs. displacement, 4P2.*

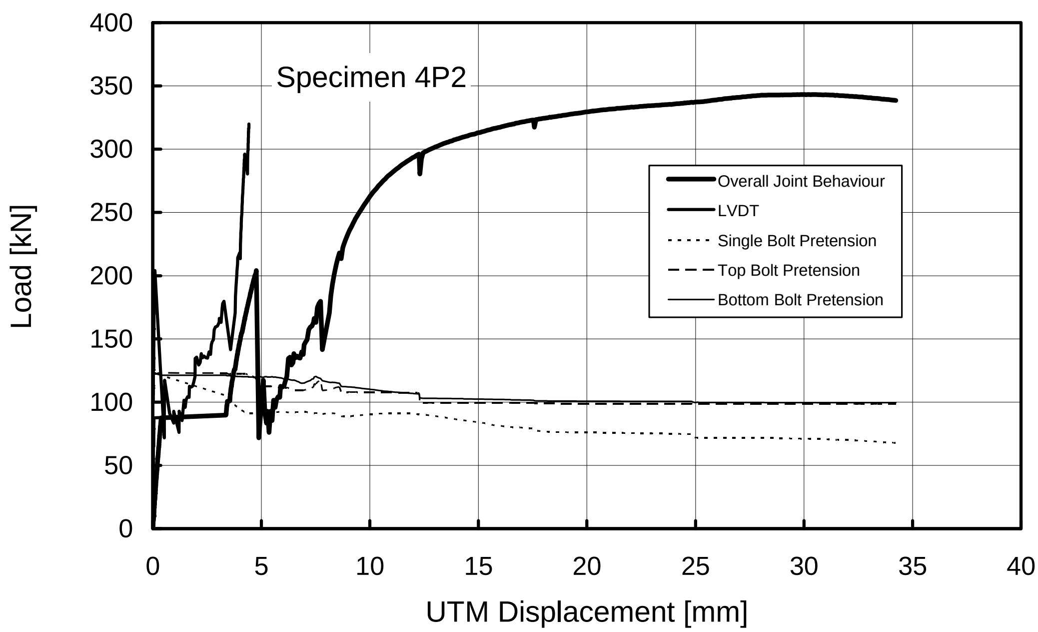

Figure 190 *– Load vs. displacement, 4P2.*

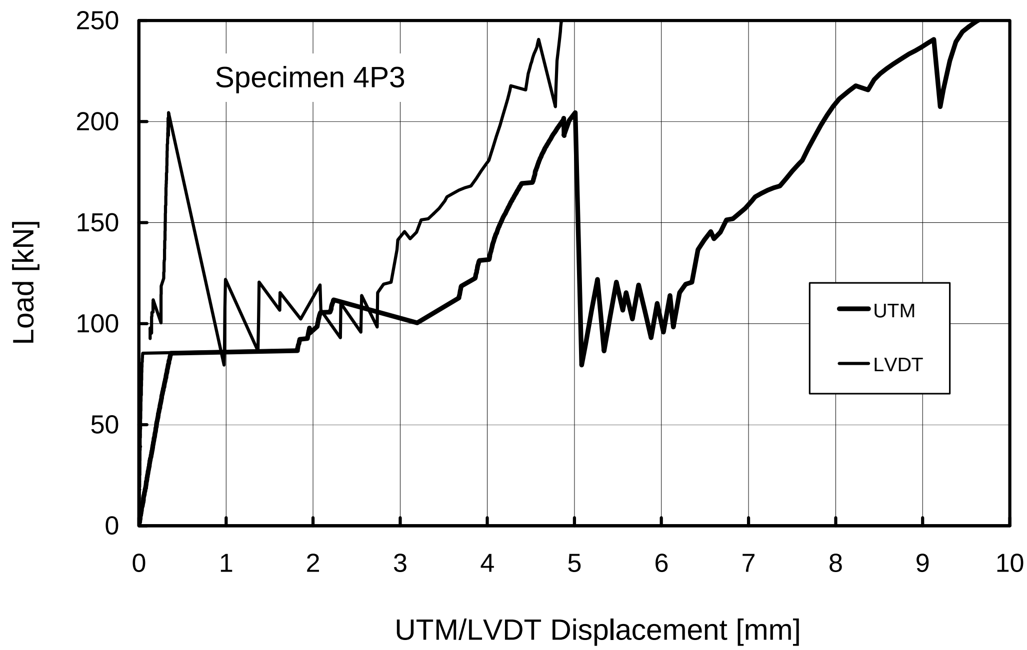

***Figure 191** – Load vs. displacement, 4P3.*

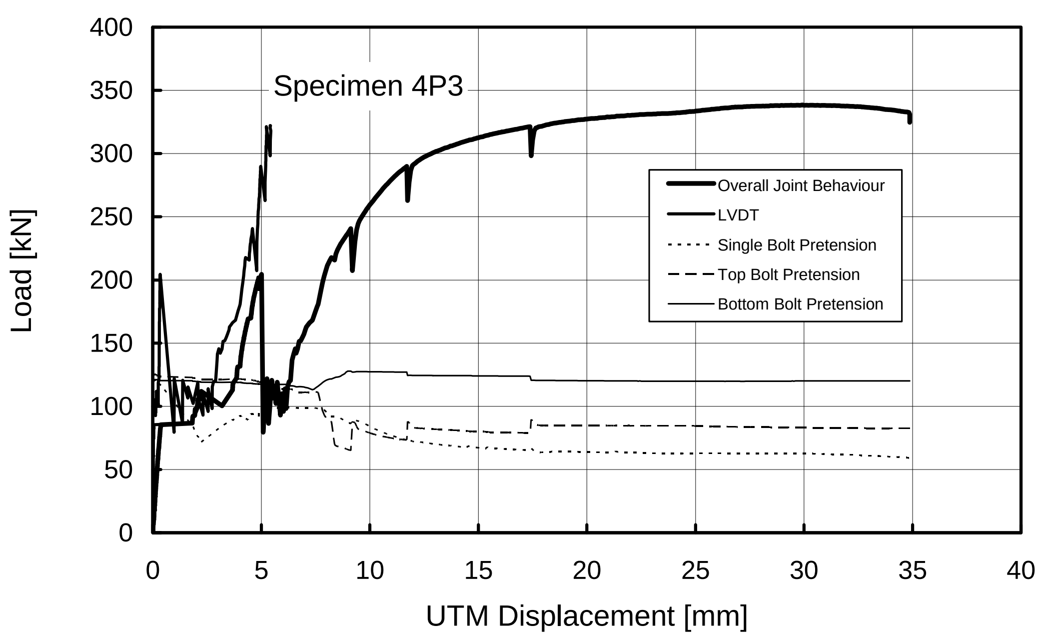

***Figure 192** – Load vs. displacement, 4P3.*

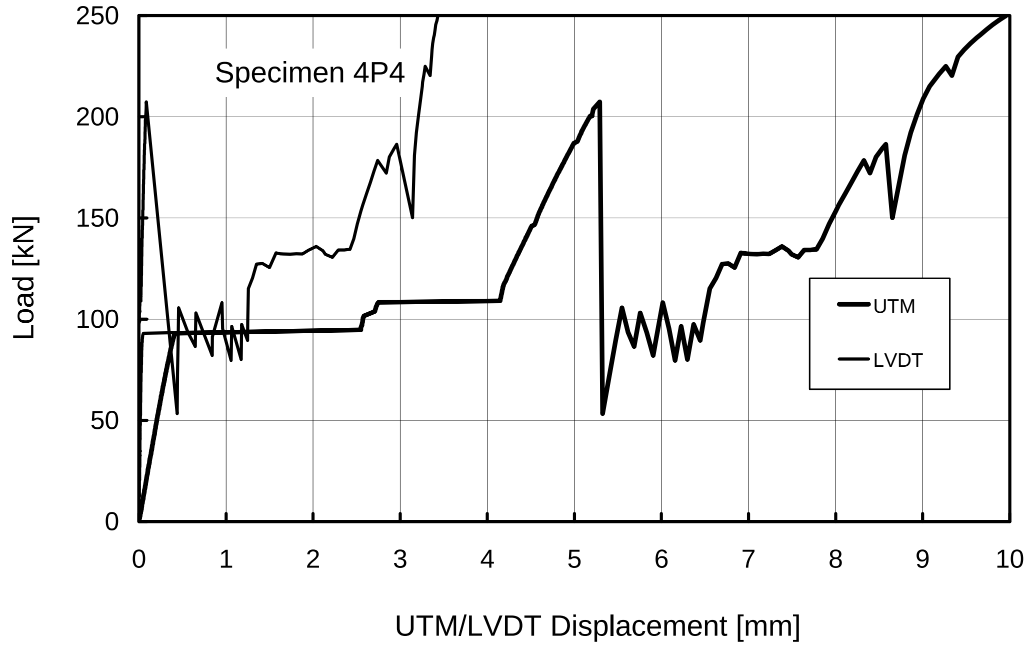

__Figure 193__ – Load vs. displacement, 4P4.

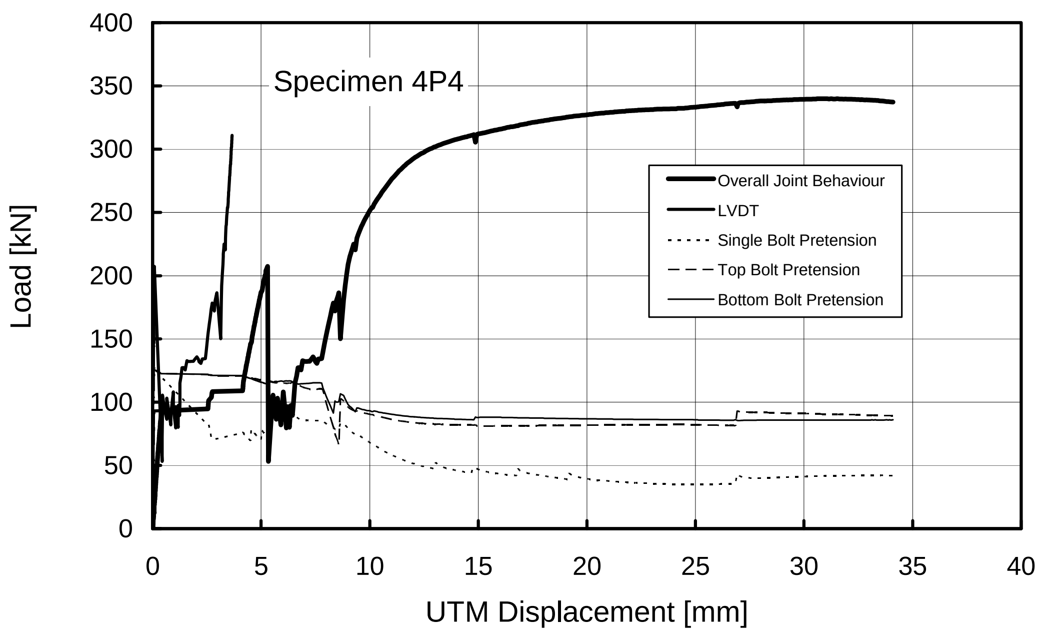

__Figure 194__ – Load vs. displacement, 4P4.

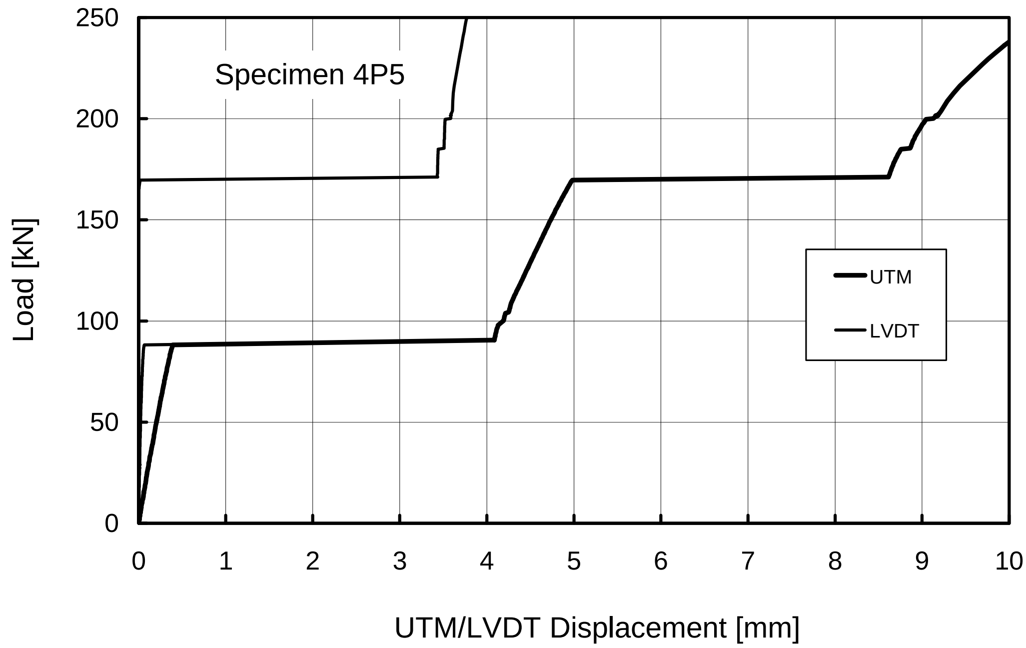

***Figure 195** – Load vs. displacement, 4P5.*

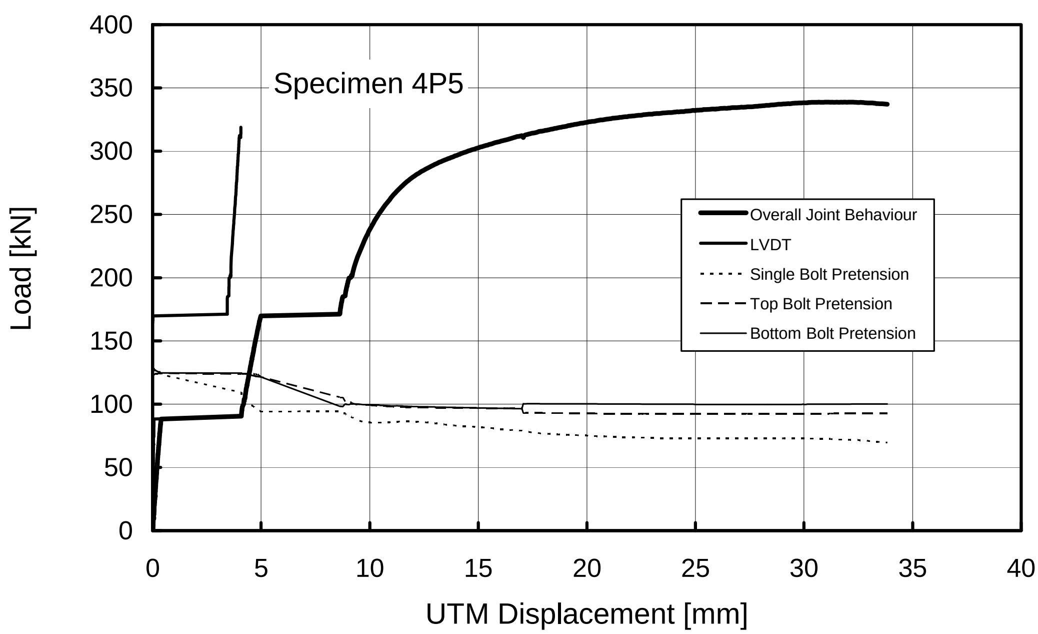

***Figure 196** – Load vs. displacement, 4P5.*

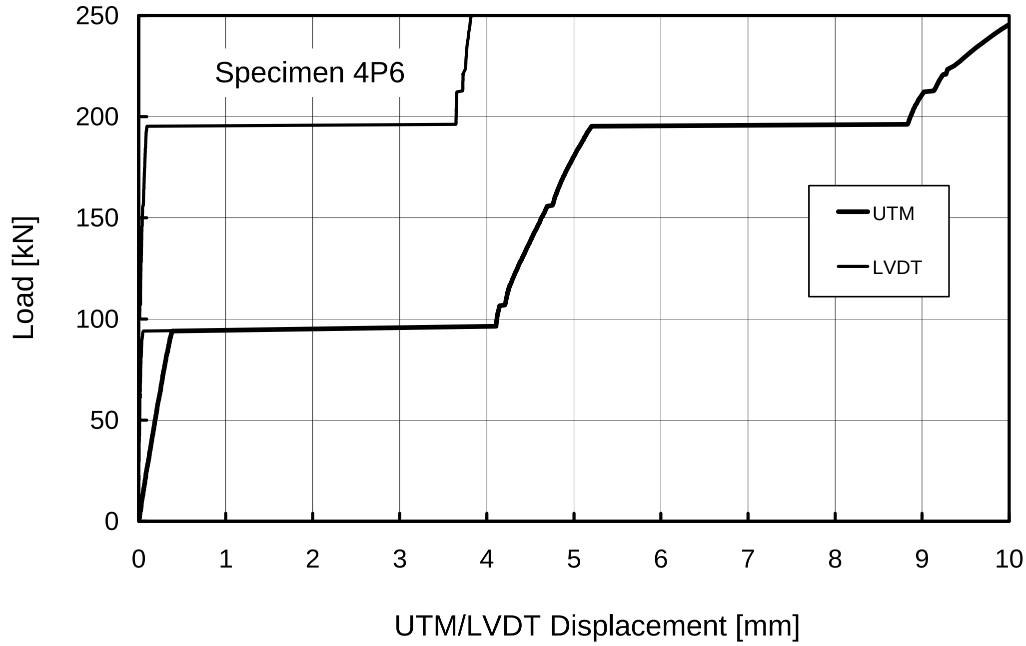

Figure 197 *– Load vs. displacement, 4P6.*

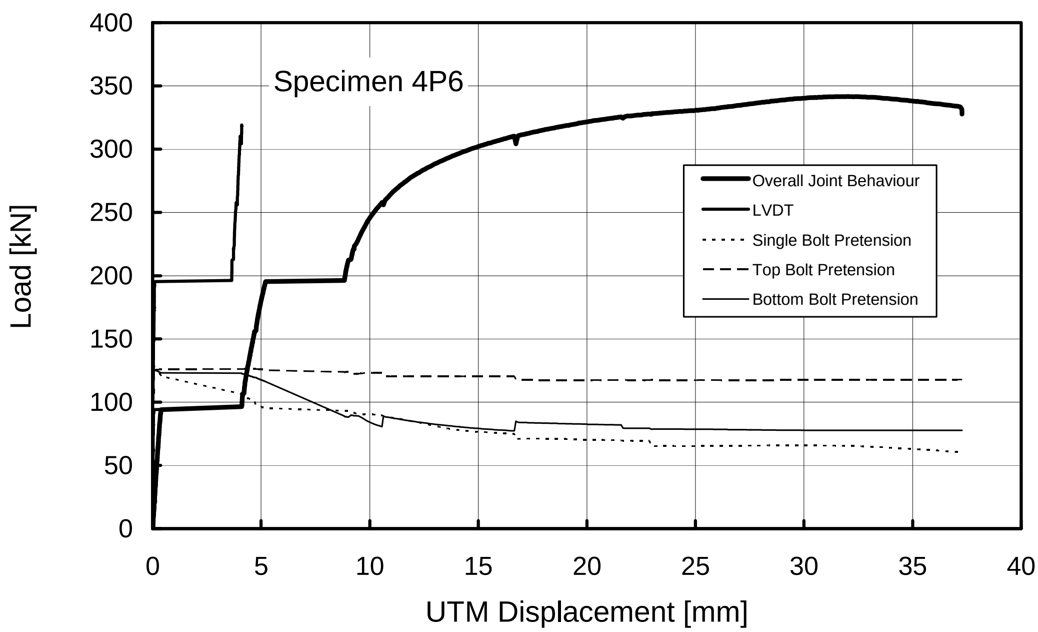

Figure 198 *– Load vs. displacement, 4P6.*

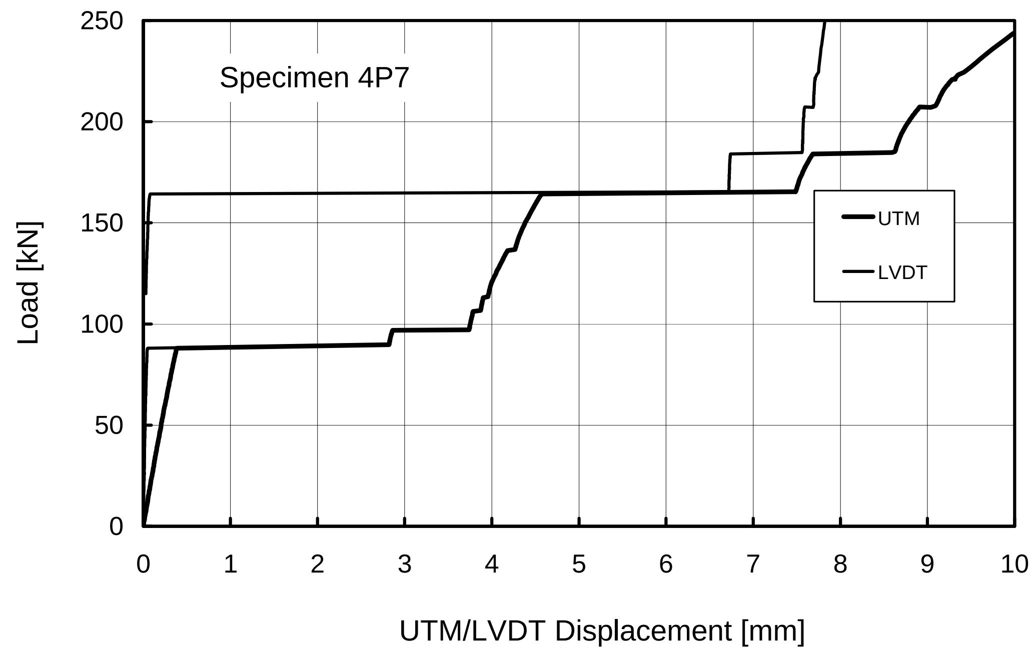

Figure 199 *– Load vs. displacement, 4P7.*

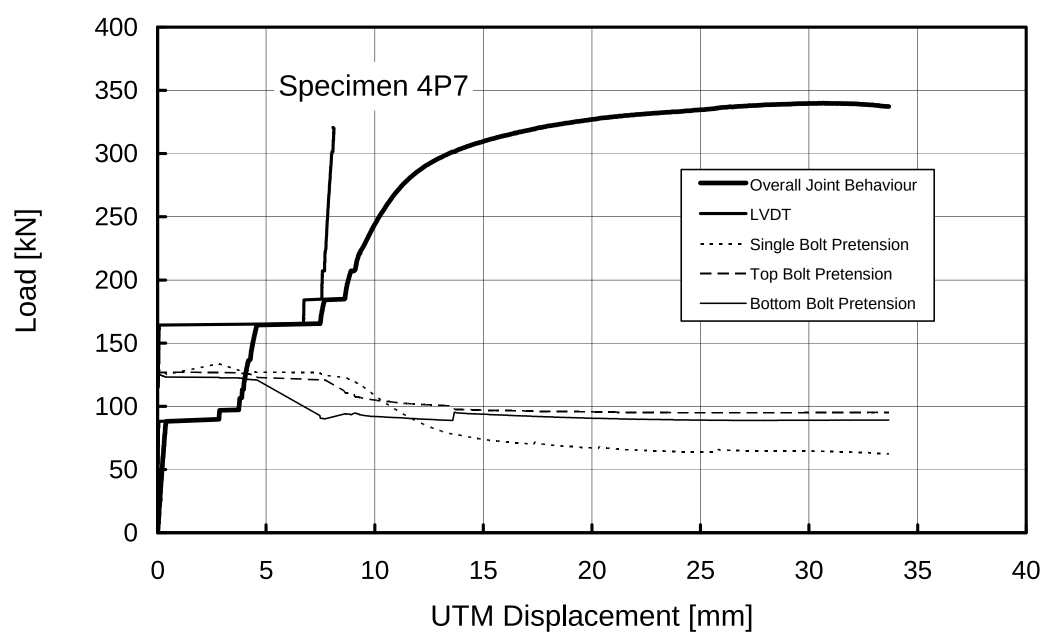

Figure 200 *– Load vs. displacement, 4P7.*

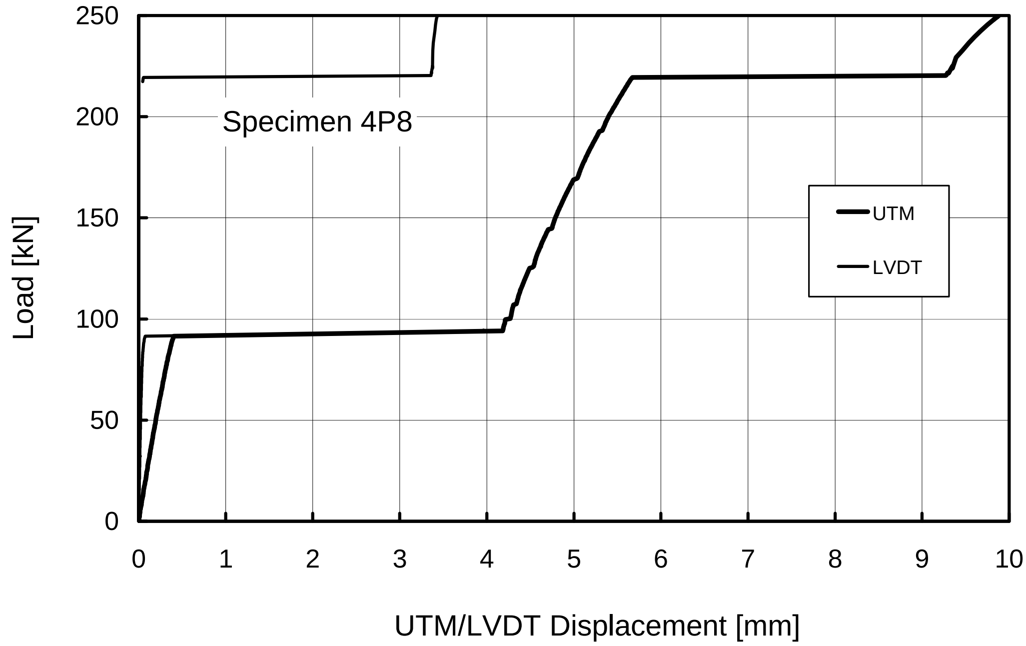

***Figure 201** – Load vs. displacement, 4P81.*

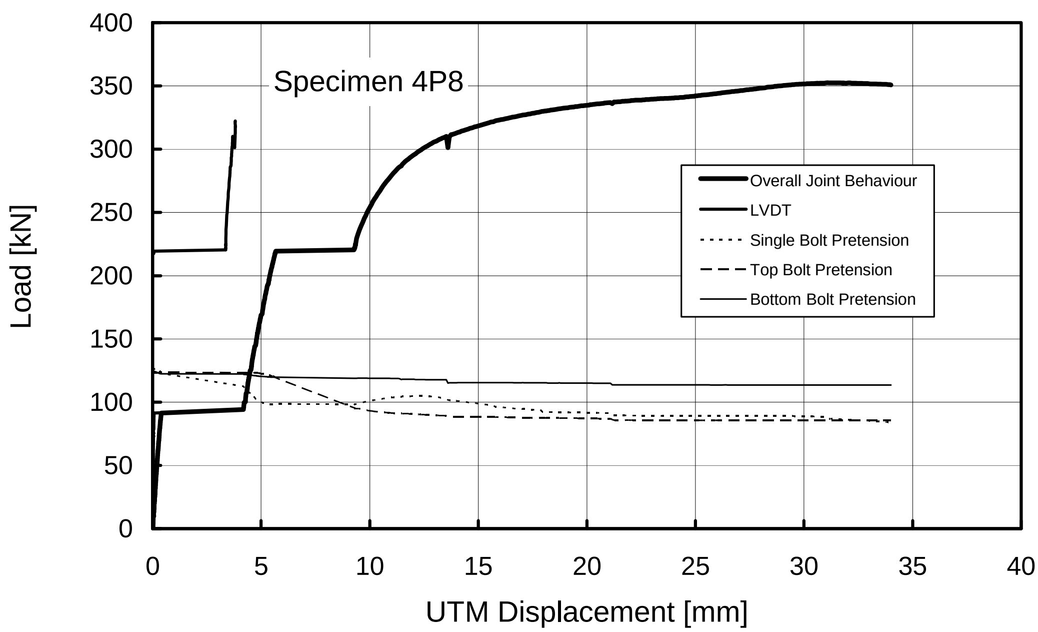

***Figure 202** – Load vs. displacement, 4P8.*

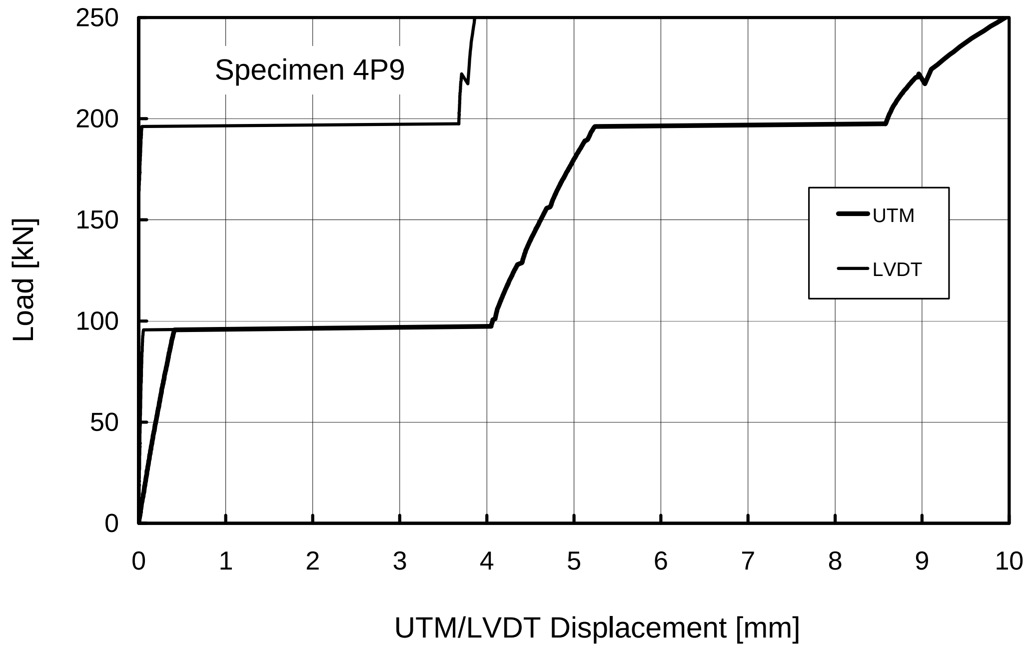

Figure 203 *– Load vs. displacement, 4P9.*

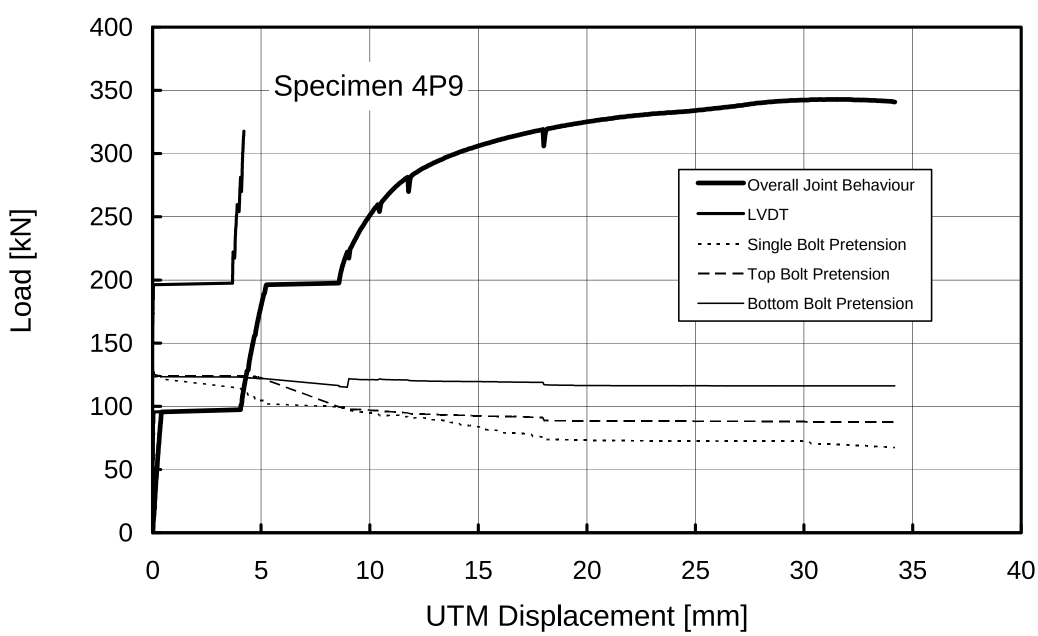

Figure 204 *– Load vs. displacement, 4P9.*

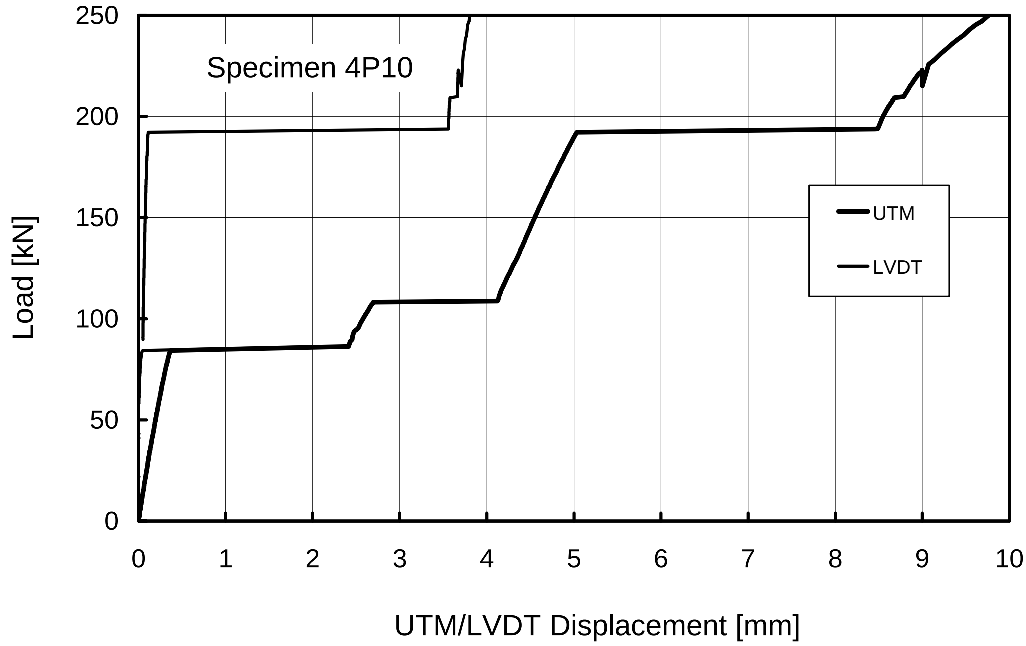

***Figure 205** – Load vs. displacement, 4P10.*

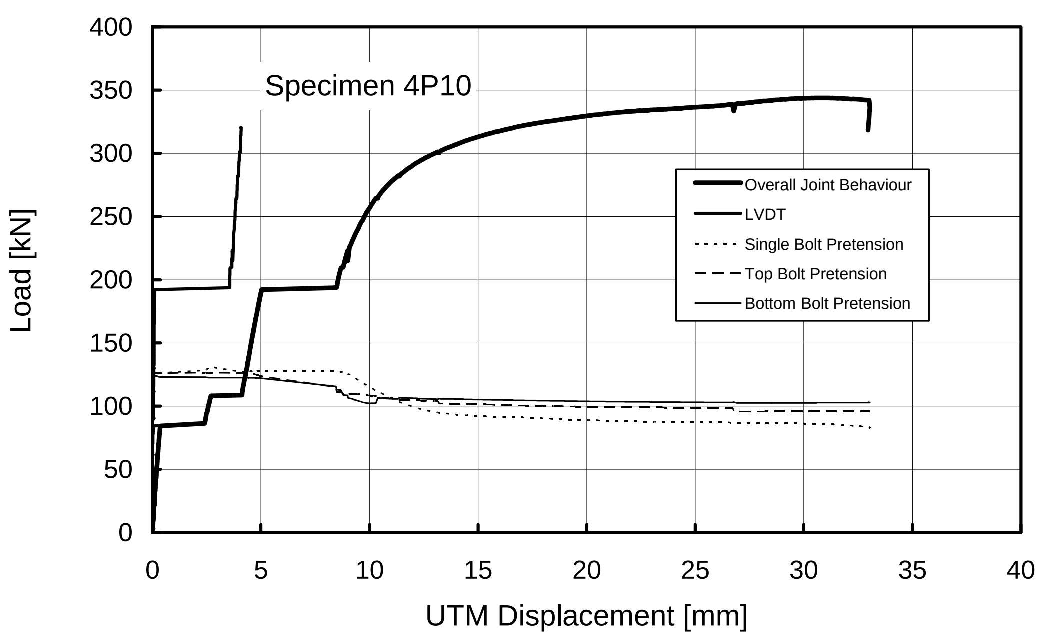

***Figure 206** – Load vs. displacement, 4P10.*

APPENDIX B

DETAILED TEST RESULTS

Table 12 presents the detailed test results for the slips of the one–bolt and two–bolt joints. “Single” refers to the one–bolt joint, “Two” to the two–bolt joint. “Top” and “Bottom” refer to the bolts on the two–bolt joint, where the top bolt is the one farther from the joint between the two main plates (see Figure 2). The slip coefficients are obtained as follows:

$$\mu_{One} = \frac{P_{slip,One}}{T_{b,Single}} \quad \text{for the one–bolt joint} \tag{4}$$

$$\mu_{Two} = \frac{P_{slip,Two}}{T_{b,Top} + T_{b,Bottom}} \quad \text{for the two–bolt joint} \tag{5}$$

***Table 12** – Detailed results of the slip coefficients for all specimens.*

No.	Desig-nation	Preload $T_{b,i}$ [kN]			Slip Load P_{slip} [kN]		Slip Coefficient μ [-]	
		Single	Top	Bottom	Single	Two	Single	Two
1	4N1	124	129	139	101	170	0.41	0.32
2	4N2	125	127	139	82	---	0.33	---
3	4N3	125	130	140	97	190	0.39	0.35
4	4N4	129	126	138	90	185	0.35	0.35
5	4N5	126	126	139	117	---	0.47	---
6	4N6	127	128	140	110	---	0.43	---
7	4N7	127	124	138	84	---	0.33	---
8	4N8	120	126	137	86	173	0.36	0.33
9	4N9	127	126	126	87	---	0.34	---
10	4N10	127	124	126	117	169	0.46	0.34
11	4N11	128	126	126	104	---	0.41	---
12	4N12	128	130	127	106	193	0.42	0.38
---	4N13	Damaged Plates, Specimen not Tested						
13	4N14	131	128	128	106	173	0.41	0.34
14	4N15	133	127	126	136	181	0.51	0.36
15	4S1	128	127	130	73	141	0.29	0.27
16	4S2	126	126	127	83	130	0.33	0.26
17	4S3	127	127	126	85	126	0.33	0.25
18	4S4	128	127	124	84	148	0.33	0.30
19	4S5	129	126	130	79	132	0.31	0.26
20	4S6	126	129	127	77	158	0.31	0.31
21	4S7	130	127	126	83	150	0.32	0.30
22	4S8	126	126	128	72	143	0.29	0.28
23	4S9	133	125	130	78	174	0.29	0.34
24	4S10	126	125	126	88	153	0.35	0.31

No.	Desig-nation	Preload $T_{b,i}$ [kN]			Slip Load P_{slip} [kN]		Slip Coefficient μ [-]	
		Single	Top	Bottom	Single	Two	Single	Two
25	4T1	164	161	161	108	228	0.33	0.35
26	4T2	163	161	161	140	185	0.43	0.29
27	4T3	166	161	161	130	188	0.39	0.29
28	4T4	163	161	162	131	183	0.40	0.28
29	4T5	163	163	160	136	214	0.42	0.33
30	5N1	127	125	127	83	222	0.33	0.44
31	5N2	127	128	125	91	288	0.36	0.57
32	5N3	130	124	128	94	182	0.36	0.36
33	5N4	129	127	126	110	235	0.43	0.47
34	5N5	128	126	126	115	252	0.45	0.50
35	5N6	127	126	127	104	259	0.41	0.51
36	5N7	128	127	126	99	250	0.39	0.49
37	5N8	128	125	127	85	250	0.33	0.50
38	5N9	127	125	127	120	210	0.47	0.42
39	5N10	130	126	128	107	---	0.41	---
40	5S1	133	127	126	106	170	0.40	0.34
41	5S2	129	125	127	94	176	0.37	0.35
42	5S3	124	129	127	92	181	0.37	0.35
43	5S4	128	128	125	107	159	0.42	0.31
44	5S5	127	126	126	80	186	0.31	0.37
45	5S6	130	124	127	76	196	0.29	0.39
46	5S7	126	125	125	71	206	0.28	0.41
47	5S8	126	125	128	105	213	0.42	0.42
48	5S9	129	126	125	95	171	0.37	0.34
49	5S10	126	126	126	108	182	0.43	0.36
50	5T1	162	161	161	155	---	0.48	---
51	5T2	164	163	162	156	250	0.48	0.38
52	5T3	162	161	161	139	300	0.43	0.47
53	5T4	161	160	164	105	320	0.33	0.49
54	5T5	160	160	159	155	280	0.48	0.44
55	5T6	163	160	163	155	275	0.48	0.43
56	5T7	161	161	162	115	300	0.36	0.46
57	5T8	161	161	163	145	325	0.45	0.50
58	5T9	162	163	163	145	320	0.45	0.49
59	5T10	162	161	163	170	275	0.52	0.42
60	5D1	129	132	126	120	245	0.47	0.48
61	5D2	130	127	127	100	267	0.39	0.53
62	5D3	129	126	127	100	261	0.39	0.52
63	5D4	127	125	126	105	165	0.41	0.33
64	5D5	131	125	125	115	245	0.44	0.49
65	5D6	127	131	127	93	260	0.37	0.50
66	5D7	128	125	124	120	246	0.47	0.49
67	5D8	127	125	129	135	225	0.53	0.44
68	5D9	128	124	127	115	220	0.45	0.44
69	5D10	130	125	129	98	262	0.38	0.52
70	5P1	127	125	132	108	260	0.43	0.51
71	5P2	127	125	132	100	240	0.40	0.47
72	5P3	126	124	126	90	277	0.36	0.56

No.	Desig-nation	Preload $T_{b,i}$ [kN]			Slip Load P_{slip} [kN]		Slip Coefficient μ [-]	
		Single	Top	Bottom	Single	Two	Single	Two
73	5P4	129	127	128	107	260	0.42	0.51
74	5P5	129	126	124	100	270	0.39	0.54
75	5P6	131	126	126	90	226	0.34	0.45
76	5P7	129	123	126	96	230	0.37	0.46
77	5P8	127	124	128	100	220	0.39	0.44
78	5P9	129	128	126	114	214	0.44	0.42
79	5P10	127	127	128	115	167	0.45	0.33
80	4D1	126	124	125	84	165	0.34	0.33
81	4D2	126	124	126	103	131	0.41	0.26
82	4D3	124	124	131	72	161	0.29	0.32
83	4D4	126	127	124	77	135	0.31	0.27
84	4D5	126	126	128	124	180	0.49	0.35
85	4D6	127	127	128	82	170	0.32	0.33
86	4D7	129	125	126	80	165	0.31	0.33
87	4D8	128	132	127	92	158	0.36	0.31
88	4D9	129	129	131	89	156	0.35	0.30
89	4D10	131	128	127	95	147	0.36	0.29
90	4P1	131	127	131	94	175	0.36	0.34
91	4P2	128	125	124	88	204	0.34	0.41
92	4P3	122	129	122	85	205	0.35	0.41
93	4P4	130	129	127	93	207	0.36	0.40
94	4P5	130	126	128	88	170	0.34	0.34
95	4P6	127	128	127	94	195	0.37	0.38
96	4P7	131	130	127	88	164	0.34	0.32
97	4P8	129	126	125	92	219	0.36	0.44
98	4P9	129	126	126	96	196	0.37	0.39
99	4P10	131	128	126	84	192	0.32	0.38

APPENDIX C

STATISTICAL TESTS

C.1 Introduction

Statistical tests were used to compare the different series of tests conducted in this research program. It was assumed that the test results follow a normal distribution. Two tests, the Student *t*–Test to compare the mean values, and the *F*–Test to compare standard deviations, were carried out. These are briefly explained in the following. Since for both tests it is not of importance which one of the samples has the smaller parameters, two-sided tests were used. A sample calculation for the comparison between the one–bolt and the two–bolt joints is presented in section C.4.

C.2 Comparison of Mean Values Using the Student *t*–Test

A statistical comparison of the mean values of two sets of test results ($\mu_{av,1}$ and $\mu_{av,2}$) can be carried out using the Student t–test, where t is defined as [Kennedy & Neville 1986]:

$$t = \frac{\left|\mu_{av,1} - \mu_{av,2}\right|}{\sqrt{\sigma_c^{\ 2}\left(\dfrac{n_1 + n_2}{n_1 n_2}\right)}} \tag{6}$$

where $\sigma_c^{\ 2}$ is the combined population variance estimated from the two samples, given by:

$$\sigma_c^{\ 2} = \frac{(n_1 - 1)\sigma_1^{\ 2} + (n_2 - 1)\sigma_2^{\ 2}}{(n_1 - 1) + (n_2 - 1)} = \frac{\sum_{i=1}^{n_1}(\mu_{1,i} - \mu_{av,1})^2 + \sum_{j=1}^{n_2}(\mu_{2,j} - \mu_{av,2})^2}{(n_1 - 1) + (n_2 - 1)} \tag{7}$$

In this test the null hypothesis is that the two sample means are not significantly different.

From tables or with a computer program such as Excel, a level of significance, α, for the calculated *t*–value can be obtained as a function of the number of degrees of freedom for the total number of the tests, $DOF = n_1 + n_2 - 2$. If the obtained level of significance is smaller than a reference level of significance, the hypothesis that the two mean values are not significantly different has to be rejected.

C.3 Comparison of Variances Using the *F*–Test

In order to be able to compare two sets of tests, it also has to be shown with some degree of certainty that the standard deviations of both samples do not differ significantly. If there are only two standard deviations (σ_1 and σ_2) the F test can be applied, where the value of F is calculated as [Kennedy & Neville 1986]:

$$F = \left(\frac{\sigma_1}{\sigma_2}\right)^2 \qquad \text{where } \sigma_1 > \sigma_2 \tag{8}$$

Subscript 1 corresponds to the set of data with the largest standard deviation and subscript 2 refers to the other set of data. In this test the null hypothesis is that the two sample standard deviations are not significantly different.

From tables or with a computer program such as Excel, a level of significance, α, for the calculated *F*–value can be obtained as a function of the number of degrees of freedom, DOF, for each sample ($DOF_i = n_i - 1$ where n_i is the sample size of the sample *i*). If the obtained level of significance is smaller than a reference level of significance, the hypothesis that the two standard deviations are not significantly different has to be rejected.

C.4 Sample Calculation for the Comparison between the One– and Two–Bolt Joints

Given:

	One–bolt joints	Two–bolt joints
Number of tests n	99	91
Mean slip coefficient μ_{av}	0.3852	0.3901
Standard deviation σ	0.0588	0.0827

Student t–Test

For the Student *t*–test, it does not matter which of the two samples is taken as sample 1. In this example, we take the one–bolt joints data set as sample 1.

The pooled variance has to be determined:

$$\sigma_c{}^2 = \frac{(n_1 - 1)\sigma_1{}^2 + (n_2 - 1)\sigma_2{}^2}{(n_1 - 1) + (n_2 - 1)} = \frac{(99-1)0.0588^2 + (91-1)0.0827^2}{(99-1)+(91-1)} = 0.00508$$

The *t*–value then becomes:

$$t = \frac{|\mu_{av,1} - \mu_{av,2}|}{\sqrt{\sigma_c{}^2\left(\frac{n_1 + n_2}{n_1 n_2}\right)}} = \frac{|0.3852 - 0.3901|}{\sqrt{0.00508\left(\frac{99+91}{99 \cdot 91}\right)}} = 0.474$$

The number of degrees of freedom for the pooled data is: $DOF = 99 + 91 - 2 = 188$.

The level of significance, α, was obtained with Excel (=TDIST(*t*, *DOF*,2)*100, where the parameter 2 takes into account that a two-sided test is used and the factor 100 transforms the result in %):

$$\alpha = t\,\text{INV}(0.474{,}188) = 63.2\%$$

The probability that the two means are the same is 63.2%. It therefore seems that the mean slip coefficient obtained from the one–bolt joints is not significantly different from the mean slip coefficient obtained from the two–bolt joints. According to our definition (see Section 4.1), the assigned degree of difference in this case is “insignificant.”

F–Test

For the F–Test, it first has to be established which one of the two samples is sample 1 and which one is sample 2 (the one with the larger standard deviation is sample 1).

$\sigma_{2bolt} > \sigma_{1bolt} \Rightarrow$ the two–bolt joints are from sample 1 while the one–bolt joints are from sample 2

$$F = \left(\frac{\sigma_{2bolt}}{\sigma_{1bolt}}\right)^2 = \left(\frac{0.0827}{0.0588}\right)^2 = 1.97$$

The number of degrees of freedom are: $DOF_{2bolt} = 91 - 1 = 90$ and $DOF_{1bolt} = 99 - 1 = 98$.

The level of significance, α, was obtained with Excel (=2*FDIST(F, DOF_{2bolt}, DOF_{1bolt}) * 100, where the factor 2 takes into account that a two-sided test is used and the factor 100 transforms the result in %):

$$\alpha = F\,\text{INV}(1.97{,}90{,}98) = 0.11\%$$

The probability that the two standard deviations are the same is only 0.11%. We can therefore conclude with a high degree of confidence that the two standard deviations are different. According to our definition (see Section 4.1), the assigned degree of difference in this case is “significant.”

APPENDIX D

FAILURE OF JOINTS BY BOLT SHEAR OR PLATE BEARING

D.1 Introduction

A reliability analysis on the bearing and shear failure results obtained from the test specimens was performed to examine the validity of the resistance factor in the equations given by CAN/CSA S16-01, *Limit States Design of Steel Structures* [CSA 2001], subsequently referred to as S16. Bolt shear failure occurred in the specimens using the 5/8-in. thick plates and bearing failure occurred in the specimens with the 1/2-in. thick plates. A typical bearing failure is illustrated in Figure 207. The following sections briefly outline the derivation of the reliability analysis theory and show its application to the results obtained from the testing procedure.

***Figure 207** – Bearing failure in 1/2-in. thick plate.*

D.2 Reliability Analysis Theory

The probability of structural failure is related to the safety index defined as follows:

$$\beta = \frac{ln\left(\bar{R} / \bar{Q} \right)}{\sqrt{{V_R}^2 + {V_Q}^2}} \tag{9}$$

where $\bar{R}$ and V_R are the mean value and the coefficient of variation of the resistance, respectively. $\bar{Q}$ and V_Q are the mean value and the coefficient of variation of the total load effect.

Lind [1971] proposed an approximation for $\sqrt{{V_R}^2 + {V_Q}^2}$ using a separation factor, α, as follows:

$$\sqrt{{V_R}^2 + {V_Q}^2} = \alpha \left(V_R + V_Q \right) \tag{10}$$

For a range of V_R / V_Q between 1/3 and 3, with $\alpha = 0.75$ the approximation provided by the right hand side of equation (10) is within 6% of the exact value provided by the left hand side of equation (10). Galambos and Ravindra [1973] extended this concept further by introducing two separation factors, α_R and α_Q, such that

$$\sqrt{{V_R}^2 + {V_Q}^2} = \alpha_R V_R + \alpha_Q V_Q \tag{11}$$

Using this approximation, the expression for the safety index, β, can now be rewritten as:

$$\beta = \frac{ln \bar{R} / \bar{Q}}{\alpha_R V_R + \alpha_Q V_Q} \tag{12}$$

from which we can obtain:

$$\bar{R}\, exp\left(-\beta\, \alpha_R V_R \right) = \bar{Q}\, exp\left(\beta\, \alpha_Q V_Q \right) \tag{13}$$

This equation relates the mean values of the resistance and the load effect. In order to re-write the equation in terms of the associated nominal values, $\tilde{R}$ and $\tilde{Q}$, we set:

$$\rho_R = \frac{\bar{R}}{\tilde{R}} \qquad and \qquad \rho_Q = \frac{\bar{Q}}{\tilde{Q}} \tag{14}$$

where ρ_R and ρ_Q are the bias coefficient for the resistance and the bias coefficient for the load effect, respectively. The relationship between the nominal values of R and Q becomes:

$$\rho_R\, exp(-\beta\, \alpha_R\, V_R)\ \tilde{R} \ = \ \rho_Q\, exp(\beta\, \alpha_Q\, V_Q)\ \tilde{Q} \tag{15}$$

The nominal values of R and Q are related as follows:

$$\phi\, \tilde{R} = \alpha'\, \tilde{Q} \tag{16}$$

where ϕ is the *resistance factor* and α' is the *load factor*. Therefore, from comparison of equations (10) and (11) we can deduce:

$$\phi = \rho_R\, exp(-\beta\, \alpha_R\, V_R) \tag{17}$$

Galambos and Ravindra [1977] proposed a separation factor α_R = 0.55.

Equation (17) is based on a target safety index of 3.0. However, because of the interdependence of the resistance and load factors an adjustment factor C is required for safety indices different from 3.0. An adjustment factor less than 1.0 is applied when the safety index is greater than 3.0. Conversely, an adjustment factor greater than 1.0 is used when the safety index is less than 3.0. Thus, equation (17) becomes:

$$\phi = C\, \rho_R\, exp(-\beta\, \alpha_R\, V_R) \tag{18}$$

where the adjustment factor C can be derived using the procedure described by Fisher *et al.* [1978]. The following expression was derived using this procedure:

$$C = \frac{1.086(1.0933 + 1.3936\, L/D)}{e^{0.0275\beta}[1 + 0.03111\beta + (1 + 0.1313\beta)\, L/D]} \tag{19}$$

where L/D is the live over dead load ratio.

Fisher *et al.* [1978] have shown that this factor varies only from 0.86 to 0.90 for a safety index of 4.5 and a wide range of live to dead load ratios. Figure 208 illustrates the variation of the correction factor as a function of the safety index for different values of live load to dead load ratio varying from 0.5 to 3.0. A simple polynomial expression can be fitted through any one of the curves shown in Figure 208 using a least square regression analysis. For a live to dead load ratio, *L/D*, of 3.0, which was adopted in the present reliability analysis, the correction factor can be obtained from:

$$C = 0.008\,\beta^2 - 0.1584\,\beta + 1.4056 \tag{20}$$

The correlation coefficient, r^2, for this approximation to equation (19) is 1.00, indicating that there is no loss of accuracy when equation (20) is used in lieu of equation (19). The live to dead load ratio of 3.0 is consistent with the value used for the calibration of the allowable stress design from load and resistance factor design equations [Galambos, 2006].

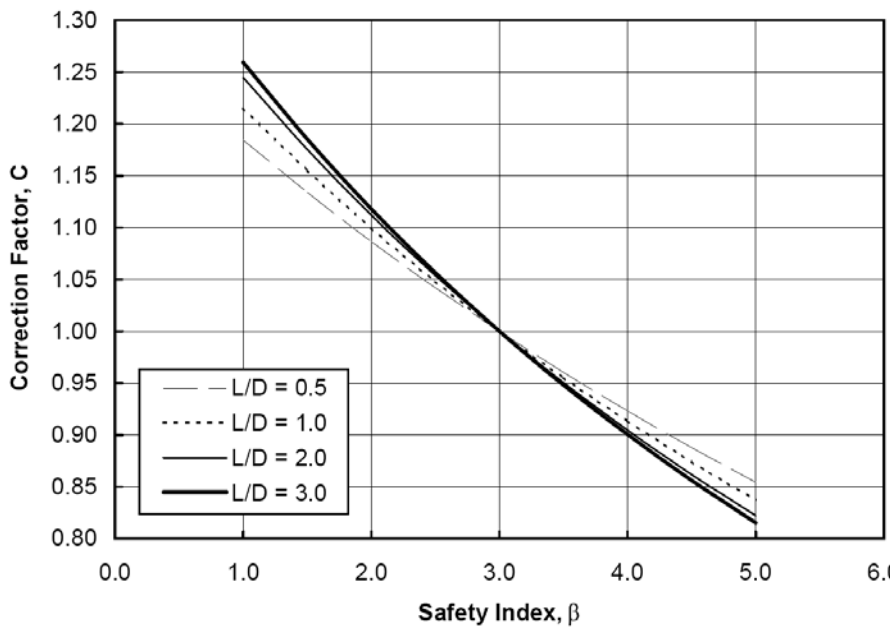

Figure 208 *– Variation of the correction factor C as a function of live to dead load ratio, L/D, and safety index,* β.

The bias coefficient for the resistance, ρ_R, and the corresponding coefficient of variation, V_R, reflect the various sources of variability in the predictions of the resistance. ρ_R is given by:

$$\rho_R = \rho_p \rho_m \rho_D \tag{21}$$

where ρ_p is the bias coefficient for the design equation, ρ_m is the bias coefficient for the material properties and ρ_D is the bias coefficient for the specimen dimensions.

The bias coefficient of the design equation, ρ_p, also referred to as the professional factor, is a measure of the accuracy of the equation, or model, used to predict the required results. This factor is calculated by taking the mean value of the ratio of test results to predicted results in a sample. The predicted results are calculated by using the S16 design equation with actual mean properties and omitting the resistance factor.

The bias coefficients of the material properties and specimen dimensions, ρ_m and ρ_D respectively, are a measure of the accuracy of the material and dimensional properties of the test specimen. These coefficients are calculated by taking the mean of the ratio of the measured values to the nominal values.

The coefficient of variation for the resistance, V_R, is given by:

$$V_R = \sqrt{V_p^2 + V_m^2 + V_D^2} \tag{22}$$

where V_p, V_m, and V_D are the coefficients of variation for the factors described above.

D.3 Bearing Failure

A reliability analysis was carried out on the test specimens that failed in bearing in order to examine the bearing resistance factor recommended by S16. For bearing failure in bolted connections, S16 uses the following formula:

$$B_r = 3\phi_{br} tdnF_u \tag{23}$$

where

B_r	:	factored bearing resistance
ϕ_{br}	:	resistance factor for bearing of bolts on steel
t	:	thickness of the connected material
d	:	diameter of the bolt(s)
n	:	number of bolts
F_u	:	specified minimum tensile strength of the connected material

The test results from the present test procedure (U of A tests), 6 results from Perry [1981] and 11 results from Monash [2007] are analysed and summarized in Table 13. Some of the tests performed by Monash [2007] have been omitted as they do not satisfy the minimum end distance requirement specified by CAN/CSA S16-01. Also given in Table 13 are the actual ultimate strength of the plates, F_u, the measured plate thicknesses, t, and bolt diameters, d, as well as the predicted failure loads, $B_{predicted}$, and the resulting professional factors, $\rho_p = B_{test} / B_{predicted}$. The resulting professional factor ρ_p (mean value of all $B_{test} / B_{predicted}$ ratios) was found to be 0.965 and the corresponding coefficient of variation, V_p, was found to be 0.048.

The values for t and d were measured directly from the plate and bolts used for each of the U of A tests while nominal values were used for the Perry [1981] and Monash [2007] tests. The number of bolts, n, was equal to 1 in for the U of A and Monash [2007] tests and 2 for the Perry [1981] tests. The value for F_u of the U of A tests was determined from tension tests performed on the plates according to ASTM A 370-05 [ASTM 2005a], *Standard Test Methods and Definitions for Mechanical Testing of Steel Products.* The average of three tests was found to be 500 MPa, see Table 1. The value for F_u of the Monash [2007] tests was 422 MPa and 397 MPa and 448MPa for the 2 heats from the Perry [1981] tests.

The bias coefficient and coefficient of variation for the material properties, $\rho_m = 1.19$ and $V_m = 0.034$ respectively, were obtained from [Schmidt & Bartlett 2002] and refer to the ultimate strength, F_u, of the plates.

The bias coefficient and coefficient of variation for the specimen dimensions for bearing failure is a combination of both specimen thickness and bolt diameter which can be calculated by:

$$\rho_D = \rho_t \rho_d \qquad (24)$$

and

$$V_D{}^2 = V_t^2 + V_d^2 \quad (25)$$

where ρ_t and ρ_d are the bias coefficient of the specimen thickness and bolt diameter respectively and V_t and V_d are the corresponding coefficients of variation.

The plate thickness bias coefficient and corresponding coefficient of variation, $\rho_t = 1.015$ and $V_t = 0.013$ respectively, were obtained from [Kennedy & Gad-Aly 1979].

The bias coefficient and coefficient of variation for the bolt diameter was determined from measurements of the tested bolts supplemented with measured dimensions from 11 other unused bolt lots. The characteristics for all the bolt measurements are given in Table 14. The calculated values for the bias and variation coefficients are $\rho_d = 0.993$ and $V_d = 0.003$, respectively. The bolt diameters for the first 29 U of A tests were not measured, instead the average of the measured diameters from the same lot was used for the calculations in Table 13. With these characteristics the bias coefficient for the specimen dimensions becomes $\rho_D = \rho_t \rho_d = 1.015 \cdot 0.993 = 1.01$. The corresponding coefficient of variation is $V_D = \sqrt{V_t^2 + V_d^2} = \sqrt{0.013^2 + 0.003^2} = 0.013$.

Table 13 *– Bearing failure test results.*

Test Specimen	d [mm]	t [mm]	F_u [MPa]	$B_{r,test}$ [kN]	$B_{r,predicted}$ [kN]	$B_{r,test}/B_{r,predicted}$ [-]
4N1	18.88	12.65	500	357	359	0.99
4N2	18.88	12.65	500	356	359	0.99
4N3	18.88	12.61	500	357	357	1.00
4N4	18.88	12.64	500	351	358	0.98
4N5	18.88	12.66	500	351	359	0.98
4N6	18.88	12.65	500	352	359	0.98
4N7	18.88	12.66	500	353	359	0.98
4N8	18.88	12.68	500	354	359	0.98
4N9	18.88	12.62	500	355	358	0.99
4N10	18.88	12.58	500	350	357	0.98
4N11	18.88	12.60	500	353	357	0.99
4N12	18.88	12.63	500	359	358	1.00
4N13				no data		
4N14	18.88	12.59	500	340	357	0.95
4N15	18.88	12.62	500	353	358	0.99
4S1	18.88	12.65	500	340	358	0.95

Test Specimen	d [mm]	t [mm]	F_u [MPa]	$B_{r,test}$ [kN]	$B_{r,predicted}$ [kN]	$B_{r,test}/B_{r,predicted}$ [-]
4S2	18.88	12.74	500	349	360	0.97
4S3	18.88	12.59	500	344	358	0.96
4S4	18.88	12.65	500	341	359	0.95
4S5	18.88	12.70	500	340	360	0.94
4S6	18.88	12.64	500	342	357	0.96
4S7	18.88	12.72	500	345	359	0.96
4S8	18.88	12.63	500	350	360	0.97
4S9	18.88	12.66	500	343	358	0.96
4S10	18.88	12.69	500	343	359	0.96
4T1	18.88	12.61	500	359	358	1.00
4T2	18.88	12.68	500	370	361	1.03
4T3	18.88	12.71	500	377	357	1.06
4T4	18.88	12.65	500	352	359	0.98
4T5	18.88	12.65	500	353	360	0.98
4D1	18.95	12.62	500	350	359	0.97
4D2	18.86	12.68	500	342	359	0.95
4D3	18.87	12.67	500	354	359	0.99
4D4	18.89	12.67	500	349	359	0.97
4D5	18.92	12.59	500	353	357	0.99
4D6	18.86	12.61	500	350	357	0.98
4D7	18.86	12.62	500	357	357	1.00
4D8	18.9	12.68	500	343	360	0.95
4D9	18.84	12.63	500	349	357	0.98
4D10	18.88	12.74	500	355	361	0.98
4P1	18.93	12.72	500	346	361	0.96
4P2	18.87	12.72	500	343	360	0.95
4P3	18.86	12.65	500	338	358	0.94
4P4	18.86	12.67	500	340	359	0.95
4P5	18.85	12.69	500	339	359	0.94
4P6	18.9	12.63	500	342	358	0.95
4P7	18.87	12.67	500	340	359	0.95
4P8	18.88	12.64	500	352	358	0.98
4P9	18.9	12.64	500	343	359	0.96
4P10	18.91	12.69	500	344	360	0.95
8-H1-2	25.4	6.20	397	376	375	1.00
8-H1-1C	25.4	6.20	397	378	375	1.01
8-H3-1	25.4	6.63	448	401	453	0.89
7-H3-1	25.4	6.63	448	386	453	0.85
8S-H3-1	25.4	6.63	448	385	453	0.85
7S-H3-1	25.4	6.63	448	336	453	0.74
MLP25-1	20.00	20.00	422	215	506	0.42
MLP25-2	20.00	20.00	422	210	506	0.42
MLP25-3	20.00	20.00	422	211	506	0.42
MLP30-1	20.00	20.00	422	271	506	0.54
MLP30-2	20.00	20.00	422	266	506	0.53
MLP30-3	20.00	20.00	422	265	506	0.52
MLP35-1	20.00	20.00	422	306	506	0.60
MLP35-2	20.00	20.00	422	312	506	0.62

Test Specimen	d [mm]	t [mm]	F_u [MPa]	$B_{r,test}$ [kN]	$B_{r,predicted}$ [kN]	$B_{r,test}/B_{r,predicted}$ [-]
MLP35-3	20.00	20.00	422	310	506	0.61
MLP45-1	20.00	20.00	422	384	506	0.76
MLP45-2	20.00	20.00	422	365	506	0.72

Table 14 *– Measured bolt diameters.*

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
4D1	18.95	19.05	0.99	282.04	285.02	0.99
4D2	18.86	19.05	0.99	279.37	285.02	0.98
4D3	18.87	19.05	0.99	279.66	285.02	0.98
4D4	18.89	19.05	0.99	280.26	285.02	0.98
4D5	18.92	19.05	0.99	281.15	285.02	0.99
4D6	18.86	19.05	0.99	279.37	285.02	0.98
4D7	18.86	19.05	0.99	279.37	285.02	0.98
4D8	18.90	19.05	0.99	280.55	285.02	0.98
4D9	18.84	19.05	0.99	278.77	285.02	0.98
4D10	18.88	19.05	0.99	279.96	285.02	0.98
4P1	18.93	19.05	0.99	281.44	285.02	0.99
4P2	18.87	19.05	0.99	279.66	285.02	0.98
4P3	18.86	19.05	0.99	279.37	285.02	0.98
4P4	18.86	19.05	0.99	279.37	285.02	0.98
4P5	18.85	19.05	0.99	279.07	285.02	0.98
4P6	18.90	19.05	0.99	280.55	285.02	0.98
4P7	18.87	19.05	0.99	279.66	285.02	0.98
4P8	18.88	19.05	0.99	279.96	285.02	0.98
4P9	18.90	19.05	0.99	280.55	285.02	0.98
4P10	18.91	19.05	0.99	280.85	285.02	0.99
5N6	18.83	19.05	0.99	278.48	285.02	0.98
5N7	18.83	19.05	0.99	278.48	285.02	0.98
5N8	18.88	19.05	0.99	279.96	285.02	0.98
5N9	18.83	19.05	0.99	278.48	285.02	0.98
5N10	18.99	19.05	1.00	283.23	285.02	0.99
5S1	18.83	19.05	0.99	278.48	285.02	0.98
5S2	18.85	19.05	0.99	279.07	285.02	0.98
5S3	18.82	19.05	0.99	278.18	285.02	0.98
5S4	18.83	19.05	0.99	278.48	285.02	0.98
5S5	18.82	19.05	0.99	278.18	285.02	0.98
5S6	18.82	19.05	0.99	278.18	285.02	0.98
5S7	18.82	19.05	0.99	278.18	285.02	0.98
5S8	18.83	19.05	0.99	278.48	285.02	0.98
5S9	18.80	19.05	0.99	277.59	285.02	0.97
5S10	18.82	19.05	0.99	278.18	285.02	0.98

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
5T1	18.83	19.05	0.99	278.48	285.02	0.98
5T2	18.88	19.05	0.99	279.96	285.02	0.98
5T3	18.93	19.05	0.99	281.44	285.02	0.99
5T4	18.85	19.05	0.99	279.07	285.02	0.98
5T5	18.87	19.05	0.99	279.66	285.02	0.98
5T6	18.88	19.05	0.99	279.96	285.02	0.98
5T7	18.85	19.05	0.99	279.07	285.02	0.98
5T8	18.90	19.05	0.99	280.55	285.02	0.98
5T9	18.88	19.05	0.99	279.96	285.02	0.98
5T10	18.88	19.05	0.99	279.96	285.02	0.98
5D1	18.92	19.05	0.99	281.15	285.02	0.99
5D2	18.93	19.05	0.99	281.44	285.02	0.99
5D3	18.93	19.05	0.99	281.44	285.02	0.99
5D4	18.88	19.05	0.99	279.96	285.02	0.98
5D5	18.89	19.05	0.99	280.26	285.02	0.98
5D6	18.88	19.05	0.99	279.96	285.02	0.98
5D7	18.89	19.05	0.99	280.26	285.02	0.98
5D8	18.92	19.05	0.99	281.15	285.02	0.99
5D9	18.89	19.05	0.99	280.26	285.02	0.98
5D10	18.87	19.05	0.99	279.66	285.02	0.98
5P1	18.96	19.05	1.00	282.34	285.02	0.99
5P2	18.88	19.05	0.99	279.96	285.02	0.98
5P3	19.02	19.05	1.00	284.13	285.02	1.00
5P4	18.87	19.05	0.99	279.66	285.02	0.98
5P5	18.88	19.05	0.99	279.96	285.02	0.98
5P6	18.92	19.05	0.99	281.15	285.02	0.99
5P7	18.91	19.05	0.99	280.85	285.02	0.99
5P8	18.93	19.05	0.99	281.44	285.02	0.99
5P9	18.97	19.05	1.00	282.63	285.02	0.99
5P10	18.89	19.05	0.99	280.26	285.02	0.98
1-1	18.89	19.05	0.99	280.26	285.02	0.98
1-2	18.88	19.05	0.99	279.96	285.02	0.98
1-3	18.89	19.05	0.99	280.26	285.02	0.98
1-4	18.89	19.05	0.99	280.26	285.02	0.98
1-5	18.89	19.05	0.99	280.26	285.02	0.98
1-6	18.91	19.05	0.99	280.85	285.02	0.99
1-7	18.90	19.05	0.99	280.55	285.02	0.98
1-8	18.91	19.05	0.99	280.85	285.02	0.99
1-9	18.91	19.05	0.99	280.85	285.02	0.99
1-10	18.90	19.05	0.99	280.55	285.02	0.98
1-11	18.90	19.05	0.99	280.55	285.02	0.98
1-12	18.90	19.05	0.99	280.55	285.02	0.98
1-13	18.91	19.05	0.99	280.85	285.02	0.99
1-14	18.90	19.05	0.99	280.55	285.02	0.98
1-15	18.90	19.05	0.99	280.55	285.02	0.98
1-16	18.90	19.05	0.99	280.55	285.02	0.98

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
1-17	18.89	19.05	0.99	280.26	285.02	0.98
1-18	18.89	19.05	0.99	280.26	285.02	0.98
1-19	18.89	19.05	0.99	280.26	285.02	0.98
1-20	18.88	19.05	0.99	279.96	285.02	0.98
2-1	22.27	22.23	1.00	389.52	387.95	1.00
2-2	22.23	22.23	1.00	388.12	387.95	1.00
2-3	22.23	22.23	1.00	388.12	387.95	1.00
2-4	22.22	22.23	1.00	387.77	387.95	1.00
2-5	22.26	22.23	1.00	389.17	387.95	1.00
2-6	22.20	22.23	1.00	387.08	387.95	1.00
2-7	22.24	22.23	1.00	388.47	387.95	1.00
2-8	22.22	22.23	1.00	387.77	387.95	1.00
2-9	22.24	22.23	1.00	388.47	387.95	1.00
2-10	22.22	22.23	1.00	387.77	387.95	1.00
2-11	22.22	22.23	1.00	387.77	387.95	1.00
2-12	22.23	22.23	1.00	388.12	387.95	1.00
2-13	22.25	22.23	1.00	388.82	387.95	1.00
2-14	22.22	22.23	1.00	387.77	387.95	1.00
2-15	22.23	22.23	1.00	388.12	387.95	1.00
2-16	22.25	22.23	1.00	388.82	387.95	1.00
2-17	22.24	22.23	1.00	388.47	387.95	1.00
2-18	22.24	22.23	1.00	388.47	387.95	1.00
2-19	22.25	22.23	1.00	388.82	387.95	1.00
2-20	22.25	22.23	1.00	388.82	387.95	1.00
3-1	22.07	22.23	0.99	382.56	387.95	0.99
3-2	22.08	22.23	0.99	382.90	387.95	0.99
3-3	22.05	22.23	0.99	381.86	387.95	0.98
3-4	22.07	22.23	0.99	382.56	387.95	0.99
3-5	22.06	22.23	0.99	382.21	387.95	0.99
3-6	22.05	22.23	0.99	381.86	387.95	0.98
3-7	22.05	22.23	0.99	381.86	387.95	0.98
3-8	22.06	22.23	0.99	382.21	387.95	0.99
3-9	22.04	22.23	0.99	381.52	387.95	0.98
3-10	22.02	22.23	0.99	380.82	387.95	0.98
3-11	22.06	22.23	0.99	382.21	387.95	0.99
3-12	22.06	22.23	0.99	382.21	387.95	0.99
3-13	22.03	22.23	0.99	381.17	387.95	0.98
3-14	22.06	22.23	0.99	382.21	387.95	0.99
3-15	22.05	22.23	0.99	381.86	387.95	0.98
3-16	22.08	22.23	0.99	382.90	387.95	0.99
3-17	22.06	22.23	0.99	382.21	387.95	0.99
3-18	22.03	22.23	0.99	381.17	387.95	0.98
3-19	22.06	22.23	0.99	382.21	387.95	0.99
3-20	22.06	22.23	0.99	382.21	387.95	0.99
4-1	18.88	19.05	0.99	279.96	285.02	0.98
4-2	18.89	19.05	0.99	280.26	285.02	0.98

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
4-3	18.89	19.05	0.99	280.26	285.02	0.98
4-4	18.88	19.05	0.99	279.96	285.02	0.98
4-5	18.86	19.05	0.99	279.37	285.02	0.98
4-6	18.87	19.05	0.99	279.66	285.02	0.98
4-7	18.87	19.05	0.99	279.66	285.02	0.98
4-8	18.86	19.05	0.99	279.37	285.02	0.98
4-9	18.87	19.05	0.99	279.66	285.02	0.98
4-10	18.86	19.05	0.99	279.37	285.02	0.98
4-11	18.86	19.05	0.99	279.37	285.02	0.98
4-12	18.88	19.05	0.99	279.96	285.02	0.98
4-13	18.84	19.05	0.99	278.77	285.02	0.98
4-14	18.86	19.05	0.99	279.37	285.02	0.98
4-15	18.85	19.05	0.99	279.07	285.02	0.98
4-16	18.86	19.05	0.99	279.37	285.02	0.98
4-17	18.86	19.05	0.99	279.37	285.02	0.98
4-18	18.88	19.05	0.99	279.96	285.02	0.98
4-19	18.85	19.05	0.99	279.07	285.02	0.98
4-20	18.85	19.05	0.99	279.07	285.02	0.98
5-1	18.88	19.05	0.99	279.96	285.02	0.98
5-2	18.88	19.05	0.99	279.96	285.02	0.98
5-3	18.90	19.05	0.99	280.55	285.02	0.98
5-4	18.87	19.05	0.99	279.66	285.02	0.98
5-5	18.86	19.05	0.99	279.37	285.02	0.98
5-6	18.88	19.05	0.99	279.96	285.02	0.98
5-7	18.88	19.05	0.99	279.96	285.02	0.98
5-8	18.87	19.05	0.99	279.66	285.02	0.98
5-9	18.85	19.05	0.99	279.07	285.02	0.98
5-10	18.88	19.05	0.99	279.96	285.02	0.98
5-11	18.87	19.05	0.99	279.66	285.02	0.98
5-12	18.85	19.05	0.99	279.07	285.02	0.98
5-13	18.87	19.05	0.99	279.66	285.02	0.98
5-14	18.86	19.05	0.99	279.37	285.02	0.98
5-15	18.86	19.05	0.99	279.37	285.02	0.98
5-16	18.88	19.05	0.99	279.96	285.02	0.98
5-17	18.87	19.05	0.99	279.66	285.02	0.98
5-18	18.87	19.05	0.99	279.66	285.02	0.98
5-19	18.86	19.05	0.99	279.37	285.02	0.98
5-20	18.87	19.05	0.99	279.66	285.02	0.98
6-1	25.19	25.40	0.99	498.36	506.71	0.98
6-2	25.20	25.40	0.99	498.76	506.71	0.98
6-3	25.18	25.40	0.99	497.97	506.71	0.98
6-4	25.18	25.40	0.99	497.97	506.71	0.98
6-5	25.21	25.40	0.99	499.16	506.71	0.99
6-6	25.21	25.40	0.99	499.16	506.71	0.99
6-7	25.22	25.40	0.99	499.55	506.71	0.99
6-8	25.22	25.40	0.99	499.55	506.71	0.99

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
6-9	25.22	25.40	0.99	499.55	506.71	0.99
6-10	25.21	25.40	0.99	499.16	506.71	0.99
6-11	25.22	25.40	0.99	499.55	506.71	0.99
6-12	25.21	25.40	0.99	499.16	506.71	0.99
6-13	25.24	25.40	0.99	500.34	506.71	0.99
6-14	25.24	25.40	0.99	500.34	506.71	0.99
6-15	25.24	25.40	0.99	500.34	506.71	0.99
6-16	25.21	25.40	0.99	499.16	506.71	0.99
6-17	25.21	25.40	0.99	499.16	506.71	0.99
6-18	25.20	25.40	0.99	498.76	506.71	0.98
6-19	25.22	25.40	0.99	499.55	506.71	0.99
6-20	25.21	25.40	0.99	499.16	506.71	0.99
7-1	22.14	22.23	1.00	384.99	387.95	0.99
7-2	22.13	22.23	1.00	384.64	387.95	0.99
7-3	22.10	22.23	0.99	383.60	387.95	0.99
7-4	22.08	22.23	0.99	382.90	387.95	0.99
7-5	22.11	22.23	0.99	383.94	387.95	0.99
7-6	22.07	22.23	0.99	382.56	387.95	0.99
7-7	22.08	22.23	0.99	382.90	387.95	0.99
7-8	22.07	22.23	0.99	382.56	387.95	0.99
7-9	22.11	22.23	0.99	383.94	387.95	0.99
7-10	22.05	22.23	0.99	381.86	387.95	0.98
7-11	22.07	22.23	0.99	382.56	387.95	0.99
7-12	22.06	22.23	0.99	382.21	387.95	0.99
7-13	22.04	22.23	0.99	381.52	387.95	0.98
7-14	22.08	22.23	0.99	382.90	387.95	0.99
7-15	22.08	22.23	0.99	382.90	387.95	0.99
7-16	22.10	22.23	0.99	383.60	387.95	0.99
7-17	22.08	22.23	0.99	382.90	387.95	0.99
7-18	22.11	22.23	0.99	383.94	387.95	0.99
7-19	22.12	22.23	1.00	384.29	387.95	0.99
7-20	22.08	22.23	0.99	382.90	387.95	0.99
8-1	25.28	25.40	1.00	501.93	506.71	0.99
8-2	25.33	25.40	1.00	503.92	506.71	0.99
8-3	25.31	25.40	1.00	503.12	506.71	0.99
8-4	25.37	25.40	1.00	505.51	506.71	1.00
8-5	25.27	25.40	0.99	501.53	506.71	0.99
8-6	25.30	25.40	1.00	502.73	506.71	0.99
8-7	25.29	25.40	1.00	502.33	506.71	0.99
8-8	25.32	25.40	1.00	503.52	506.71	0.99
8-9	25.26	25.40	0.99	501.14	506.71	0.99
8-10	25.34	25.40	1.00	504.32	506.71	1.00
8-11	25.32	25.40	1.00	503.52	506.71	0.99
8-12	25.28	25.40	1.00	501.93	506.71	0.99
8-13	25.26	25.40	0.99	501.14	506.71	0.99
8-14	25.31	25.40	1.00	503.12	506.71	0.99

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
8-15	25.33	25.40	1.00	503.92	506.71	0.99
8-16	25.30	25.40	1.00	502.73	506.71	0.99
8-17	25.28	25.40	1.00	501.93	506.71	0.99
8-18	25.31	25.40	1.00	503.12	506.71	0.99
8-19	25.32	25.40	1.00	503.52	506.71	0.99
8-20	25.31	25.40	1.00	503.12	506.71	0.99
9-1	25.31	25.40	1.00	503.12	506.71	0.99
9-2	25.29	25.40	1.00	502.33	506.71	0.99
9-3	25.32	25.40	1.00	503.52	506.71	0.99
9-4	25.31	25.40	1.00	503.12	506.71	0.99
9-5	25.25	25.40	0.99	500.74	506.71	0.99
9-6	25.27	25.40	0.99	501.53	506.71	0.99
9-7	25.28	25.40	1.00	501.93	506.71	0.99
9-8	25.29	25.40	1.00	502.33	506.71	0.99
9-9	25.29	25.40	1.00	502.33	506.71	0.99
9-10	25.32	25.40	1.00	503.52	506.71	0.99
9-11	25.33	25.40	1.00	503.92	506.71	0.99
9-12	25.32	25.40	1.00	503.52	506.71	0.99
9-13	25.29	25.40	1.00	502.33	506.71	0.99
9-14	25.30	25.40	1.00	502.73	506.71	0.99
9-15	25.31	25.40	1.00	503.12	506.71	0.99
9-16	25.31	25.40	1.00	503.12	506.71	0.99
9-17	25.30	25.40	1.00	502.73	506.71	0.99
9-18	25.34	25.40	1.00	504.32	506.71	1.00
9-19	25.30	25.40	1.00	502.73	506.71	0.99
9-20	25.27	25.40	0.99	501.53	506.71	0.99
10-1	25.31	25.40	1.00	503.12	506.71	0.99
10-2	25.33	25.40	1.00	503.92	506.71	0.99
10-3	25.32	25.40	1.00	503.52	506.71	0.99
10-4	25.32	25.40	1.00	503.52	506.71	0.99
10-5	25.33	25.40	1.00	503.92	506.71	0.99
10-6	25.34	25.40	1.00	504.32	506.71	1.00
10-7	25.31	25.40	1.00	503.12	506.71	0.99
10-8	25.35	25.40	1.00	504.71	506.71	1.00
10-9	25.33	25.40	1.00	503.92	506.71	0.99
10-10	25.30	25.40	1.00	502.73	506.71	0.99
10-11	25.30	25.40	1.00	502.73	506.71	0.99
10-12	25.31	25.40	1.00	503.12	506.71	0.99
10-13	25.32	25.40	1.00	503.52	506.71	0.99
10-14	25.32	25.40	1.00	503.52	506.71	0.99
10-15	25.34	25.40	1.00	504.32	506.71	1.00
10-16	25.32	25.40	1.00	503.52	506.71	0.99
10-17	25.30	25.40	1.00	502.73	506.71	0.99
10-18	25.31	25.40	1.00	503.12	506.71	0.99
10-19	25.32	25.40	1.00	503.52	506.71	0.99
10-20	25.32	25.40	1.00	503.52	506.71	0.99

Bolt Number	d			A_b		
	Measured [mm]	Nominal [mm]	ρ_d [-]	Measured [mm^2]	Nominal [mm^2]	ρ_A [-]
11-1	25.24	25.40	0.99	500.34	506.71	0.99
11-2	25.22	25.40	0.99	499.55	506.71	0.99
11-3	25.23	25.40	0.99	499.95	506.71	0.99
11-4	25.24	25.40	0.99	500.34	506.71	0.99
11-5	25.26	25.40	0.99	501.14	506.71	0.99
11-6	25.28	25.40	1.00	501.93	506.71	0.99
11-7	25.21	25.40	0.99	499.16	506.71	0.99
11-8	25.22	25.40	0.99	499.55	506.71	0.99
11-9	25.22	25.40	0.99	499.55	506.71	0.99
11-10	25.21	25.40	0.99	499.16	506.71	0.99
11-11	25.21	25.40	0.99	499.16	506.71	0.99
11-12	25.23	25.40	0.99	499.95	506.71	0.99
11-13	25.24	25.40	0.99	500.34	506.71	0.99
11-14	25.24	25.40	0.99	500.34	506.71	0.99
11-15	25.22	25.40	0.99	499.55	506.71	0.99
11-16	25.24	25.40	0.99	500.34	506.71	0.99
11-17	25.20	25.40	0.99	498.76	506.71	0.98
11-18	25.21	25.40	0.99	499.16	506.71	0.99
11-19	25.23	25.40	0.99	499.95	506.71	0.99
11-20	25.22	25.40	0.99	499.55	506.71	0.99

All the statistical coefficients for the bearing failures are summarized in Table 15.

***Table 15** – Summary of statistical coefficients for the bearing failures.*

Parameter	Bias Coefficient	Coefficient of Variation
"Professional"	$\rho_p = 0.965$	$V_p = 0.048$
Material	$\rho_m = 1.19$	$V_m = 0.034$
Dimensions	$\rho_D = 1.01$	$V_D = 0.013$

Based on the test results from Table 13, the resistance factor for bearing of bolts on steel, ϕ_{Br}, becomes (equation (18)):

$$\begin{aligned}\phi_{Br} &= C\rho_R \exp(-\beta\alpha_R V_R) \\ &= C\cdot(0.965\cdot 1.19\cdot 1.01)\exp\left(-\beta\cdot 0.55\cdot\sqrt{0.048^2+0.034^2+0.013^2}\right) \\ &= 1.16C\exp(-0.033\beta)\end{aligned} \tag{26}$$

Figure 209 shows the resistance factor for bearing of bolts on steel, ϕ_{Br}, as a function of the targeted safety index, β, for different live over dead load ratios, L/D. The resistance factor according to [CSA 2001], $\phi_{Br} = 0.67$, is also shown on the graph.

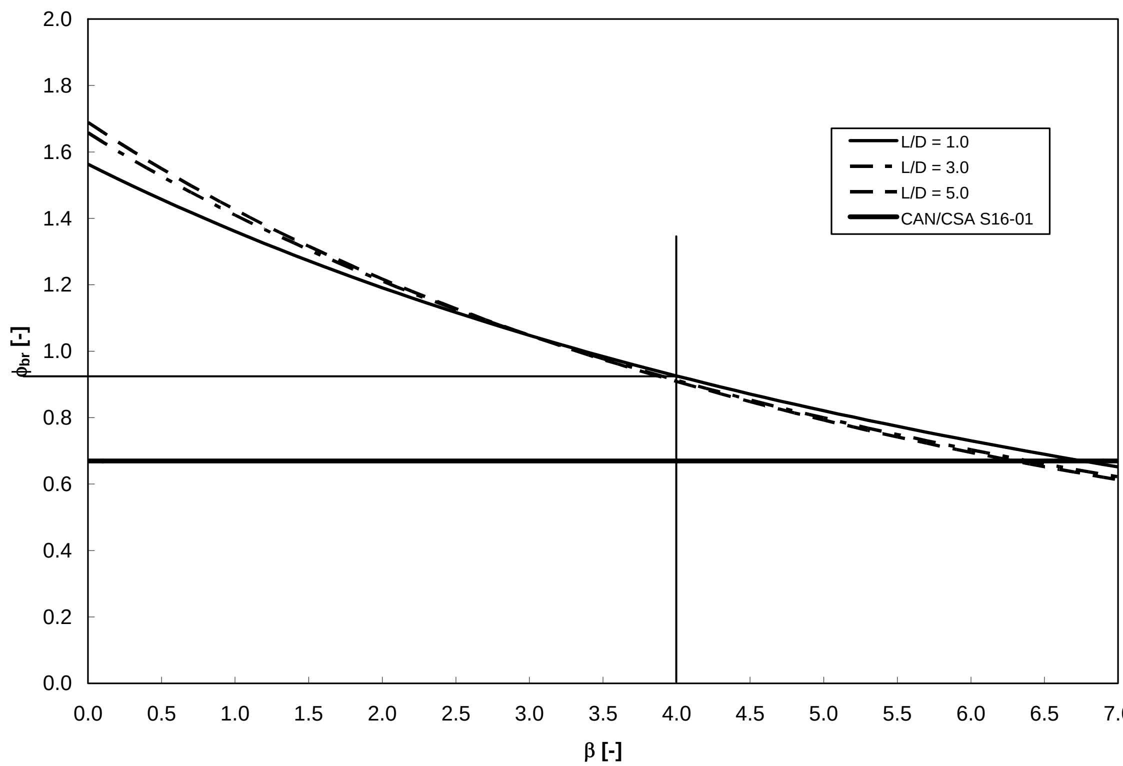

***Figure 209** – Results for the resistance factor, ϕ_{br}, as a function of the safety index, β, and of the live to dead load ratio, L/D.*

D.4 Bolt Shear Failure

A reliability analysis was carried out on the test specimens that failed due to bolt shear in order to examine the resistance factor recommended by S16. For bolts in shear, S16 uses the following formula:

$$V_r = 0.60\phi_b nmA_b F_u \tag{27}$$

where V_r : factored bolt shear resistance of the connection

ϕ_b : resistance factor for bolts

n	:	number of bolts
m	:	number of shear planes
A_b	:	nominal cross sectional area of a bolt
F_u	:	specified minimum tensile strength of the bolt(s)

The test results from the U of A tests are analysed and summarized in Table 17. The table also presents the actual tensile strength of the bolts, F_u, and the measured bolt diameters, d, used to calculate A_b as well as the predicted failure loads, $V_{predicted}$, and the resulting professional factors, ρ_p.

The value for n and m were 1 and 2 respectively for all specimens while A_b was calculated from the bolt diameter measurements of Table 14. The value for F_u was determined to be 945 MPa from the average of three tension tests performed according to ASTM A 370-05 [ASTM 2005a] on bolts taken from the same lot, see Figure 210 and Table 16.

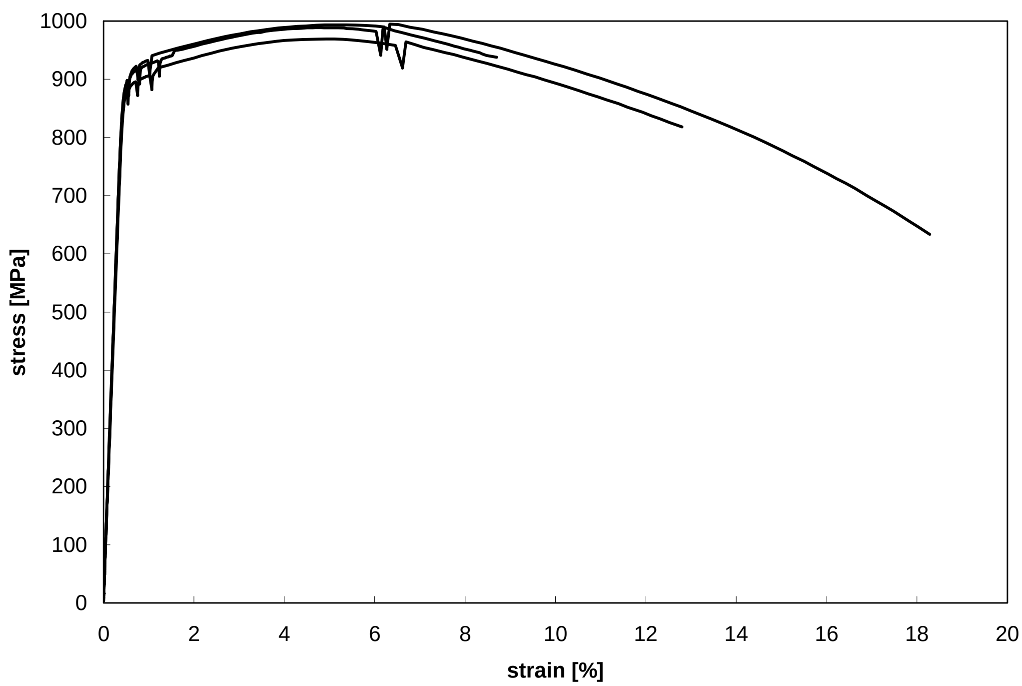

***Figure 210** – Engineering stress vs. strain curve for three ASTM A325 bolts.*

Table 16 *– Results of tension coupon tests of the three tested ASTM A325 bolts.*

Tension Coupon	F_u **[MPa]**	E **[MPa]**	ε_r **[%]**
1	952	213,000	---
2	930	215,000	---
3	954	206,000	18

The resulting professional factor ρ_p was found to be 1.145 and the corresponding coefficient of variation V_p was found to be 0.042.

The bias coefficient and coefficient of variation for the material properties, $\rho_m = 1.20$ and $V_m = 0.070$ respectively, were obtained from [Fisher *et al.* 1978].

The bias coefficient and coefficient of variation for the bolt area were determined from Table 14 to be $\rho_A = 0.987$ and $V_A = 0.006$ respectively.

Table 17 *– Bolt shear failure test results.*

Test Specimen	A_b [mm]	t [mm]	F_u [MPa]	$V_{r,test}$ [kN]	$V_{r,predicted}$ [kN]	$V_{r,test}/V_{r,predicted}$ [-]
5N1	280.89	15.986	945	349	318	1.10
5N2	280.89	15.996	945	362	318	1.14
5N3	280.89	15.912	945	371	318	1.17
5N4	280.89	15.959	945	338	318	1.06
5N5	280.89	15.995	945	382	318	1.20
5N6	278.48	15.89	945	402	316	1.27
5N7	278.48	15.98	945	375	316	1.19
5N8	279.96	16.03	945	391	317	1.23
5N9	278.48	15.95	945	351	316	1.11
5N10	283.23	15.97	945	352	321	1.10
5S1	278.48	16.02	945	352	316	1.12
5S2	279.07	15.98	945	351	316	1.11
5S3	278.18	15.91	945	362	315	1.15
5S4	278.48	16.00	945	357	316	1.13
5S5	278.18	15.93	945	349	315	1.11
5S6	278.18	16.00	945	355	315	1.12
5S7	278.18	15.96	945	355	315	1.12
5S8	278.48	16.01	945	368	316	1.17

Table 17 – (Cont'd)

Test Specimen	A_b [mm]	t [mm]	F_u [MPa]	$V_{r,test}$ [kN]	$V_{r,predicted}$ [kN]	$V_{r,test}/V_{r,predicted}$ [-]
5S9	277.59	15.97	945	349	315	1.11
5S10	278.18	15.99	945	359	315	1.14
5T1	278.48	15.95	945	373	316	1.18
BT2	279.96	15.980	945	381	317	1.20
5T3	281.44	16.01	945	358	319	1.12
5T4	279.07	16.01	945	346	316	1.09
5T5	279.66	16.02	945	361	317	1.14
5T6	279.96	16.01	945	367	317	1.16
5T7	279.07	15.92	945	347	316	1.10
5T8	280.55	15.95	945	366	318	1.15
5T9	279.96	15.99	945	379	317	1.19
5T10	279.96	15.98	945	395	317	1.25
5D1	281.15	15.98	945	346	319	1.09
5D2	281.44	16.00	945	347	319	1.09
5D3	281.44	15.95	945	388	319	1.21
5D4	279.96	16.01	945	379	317	1.19
5D5	280.26	16.02	945	360	318	1.13
5D6	279.96	15.94	945	372	317	1.17
5D7	280.26	15.97	945	355	318	1.12
5D8	281.15	16.02	945	356	319	1.12
5D9	280.26	15.95	945	377	318	1.19
5D10	279.66	16.01	945	380	317	1.20
5P1	282.34	15.97	945	347	320	1.08
5P2	279.96	15.98	945	380	317	1.20
5P3	284.13	16.01	945	351	322	1.09
5P4	279.66	15.99	945	355	317	1.12
5P5	279.96	15.97	945	379	317	1.19
5P6	281.15	16.00	945	351	319	1.10
5P7	280.85	16.02	945	352	318	1.11
5P8	281.44	15.95	945	362	319	1.13
5P9	282.63	16.00	945	348	320	1.09
5P10	280.26	16.02	945	380	318	1.20

All the statistical coefficients for the bolt shear failures are summarized in Table 18.

***Table 18** – Summary of statistical coefficients for the bolt shear failures.*

Parameter	Bias Coefficient	Coefficient of Variation
"Professional"	$\rho_p = 1.15$	$V_p = 0.042$
Material	$\rho_m = 1.20$	$V_m = 0.070$
Dimensions	$\rho_A = 0.987$	$V_A = 0.006$

Based on the test results from Table 17, the resistance factor for bolts, ϕ_b, becomes (equation (18)):

$$\begin{aligned}\phi_B &= C\rho_R \exp(-\beta\alpha_R V_R) \\ &= C\cdot(1.15\cdot 1.20\cdot 0.987)\exp\left(-\beta\cdot 0.55\cdot\sqrt{0.042^2+0.070^2+0.006^2}\right) \\ &= 1.36C\exp(-0.045\beta)\end{aligned} \quad (28)$$

Figure 211 shows the resistance factor for bolts, ϕ_B, as a function of the targeted safety index, β, for different live to dead load ratios, L/D. The resistance factor according to CSA [2001], $\phi_B = 0.80$, is also shown on the graph.

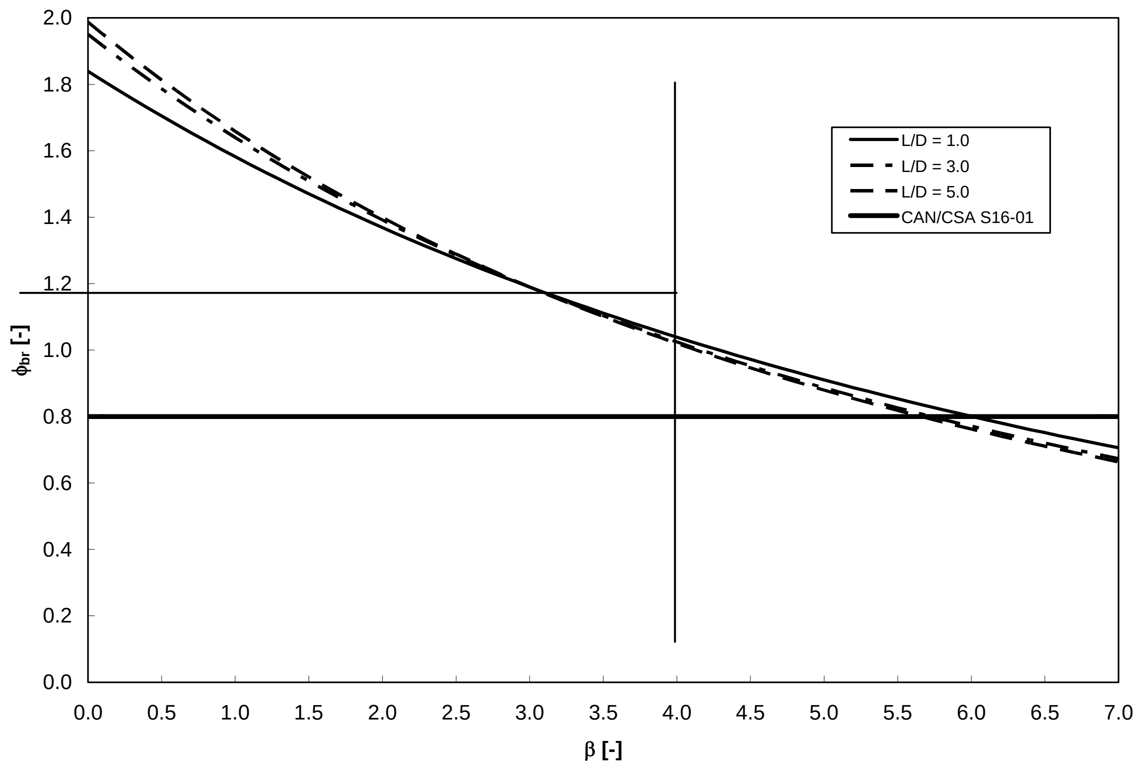

Figure 211 *– Results for the resistance factor, ϕ_b, as a function of the safety index, β, and of the live to dead load ratio, L/D.*