Gusset Plate Connection to Round HSS Tension Members

J. J. ROGER CHENG and GEOFFREY L. KULAK

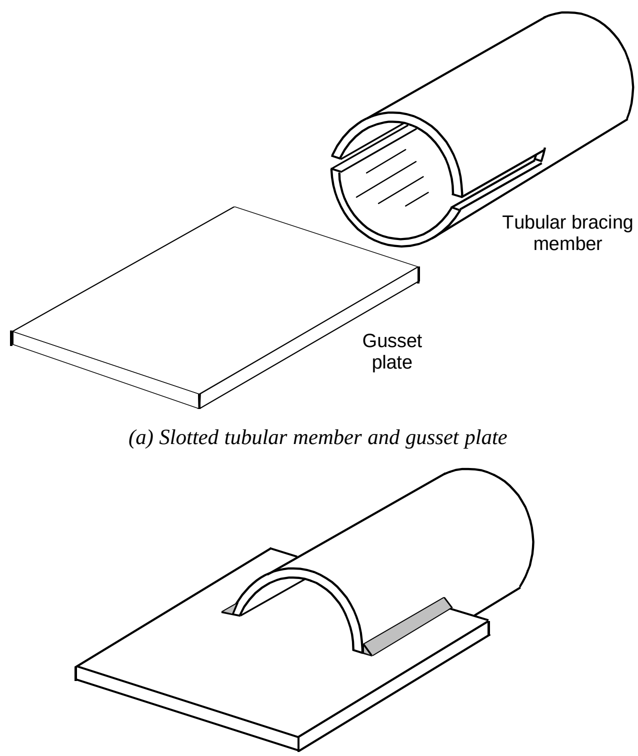
ABSTRACT

An experimental program and associated numerical analysis were undertaken to study the shear lag effect in round hollow structural section (HSS) tension members that are welded to gusset plates. The connection is made by slotting the tube longitudinally, inserting the gusset plate, and then placing longitudinal fillet welds at the tube-to-gusset interface. Transverse welds at the junction of the slot and the gusset plate may or may not be present. A total of nine specimens with three different tube sizes and various weld lengths were tested in the program. The majority of the specimens failed by fracture of the tube somewhere between the two gusset plates, and there was considerable ductility prior to fracture. Numerical analyses of the connections were carried out using an elasto-plastic model and measured material properties. Based on the tests and the numerical analyses, it is concluded that shear lag does not significantly affect the ultimate strength of the slotted tube connection, even with a weld length as little as 80 percent of the distance between the welds. The studies showed that the restraint provided by the gusset plate at the slotted end effectively increases the load-carrying capacity of the tube as compared to the unrestrained portion of the member. In the numerical analysis, fracture is assumed to have occurred when the equivalent plastic strain reaches a critical value. The test results are discussed in light of the requirements in the American Institute of Steel Construction (AISC) *Specification for Design of Steel Hollow Structural Sections* (AISC, 1997).

INTRODUCTION

Tubular sections are used frequently in fabricated steel construction as tension members, for example, as bracing members. An inexpensive and easy way of making the end connections is to slot the tube longitudinally and insert a gusset plate, which is then welded to the tube using fillet welds. This arrangement is shown pictorially in Figure 1. Part (a) of the figure shows the slotted tube and a representation of the gusset plate. The connected tube and gusset plate are shown in Part (b). In addition to the four longitudinal fillet welds that will be present, there also may be fillet welds across the thickness of the gusset plate at the top of the slot. An alternative to this arrangement is to slot the gusset plate rather than the tube. Fabricators prefer slotting the tube, however, since alignment of the elements and subsequent welding are more convenient with this arrangement.

Only the slotted tube option is discussed in this paper and only circular tubes are treated. The work has implications when square or rectangular tubes are used, but those cases are not treated specifically.



(a) Slotted tubular member and gusset plate

(b) Assembled tubular member and gusset plate

Fig. 1. Slotted tube connection.

J. J. Roger Cheng, Ph.D., P.Eng. is C. W. Carry professor of steel structures, Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Canada.

Geoffrey L. Kulak, Ph.D., P.Eng. is professor emeritus at the Department of Civil & Environmental Engineering, University of Alberta, Edmonton, Canada.

AISC LRFD DESIGN REQUIREMENTS

Only a relatively small portion of the cross-section of a tube can be connected to the gusset plate. It has to be assumed, then, that shear lag will be present and must be taken into account by the designer. The effective area of tension members is discussed in Section B3 of the AISC LRFD Specification (AISC, 1993). Calculation of the effective area according to B3 acknowledges the possibility of shear lag and prescribes a reduction coefficient, U, that is to be applied to the calculated cross-sectional area when computing the factored resistance based on fracture. However, the values suggested for U in this section of the Specification do not specifically treat the type of connection shown in Figure 1. The AISC *Specification for the Design of Hollow Structural Sections* (AISC, 1997) does cover this case, though, and it is those rules for shear lag that will be treated here. This specification will be referred to as the HSS Specification.

According to Section 2.1 of the HSS Specification, the effective net area for tension members is to be calculated as:

$$A_e = AU \tag{1}$$

where $A = A_n$. In the case of a slotted tube connected to a gusset plate, the net area is that of the tube as reduced by the slots. For the arrangement shown in Figure 2, the HSS Specification gives the shear lag reduction factor as:

$$U = 1 - (\bar{x} / L) \leq 0.9 \tag{2}$$

The terms $\bar{x}$ and L are shown in Figure 2. The term $\bar{x}$ is intended to be the distance from the centerline of the gusset plate to the centroid of one-half of the tube cross-section. A good approximation is obtained using the recommendation given in the HSS Specification, namely:

$$\bar{x} = D / \pi \tag{3}$$

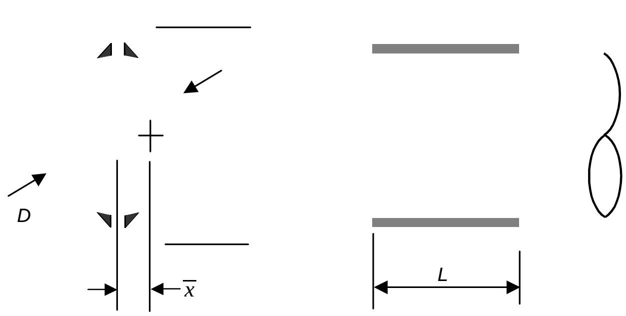


Fig. 2. AISC shear lag nomenclature.

There is an implication in the net area calculation that fillet welds will not be used where the gusset plate meets the end of the slot in the tubular member (transverse welds). Indeed, the Commentary to the HSS Specification states that, “welding around the end of the gusset plate is not recommended.” This is explored in the tests reported here. It should also be pointed out that the shear reduction factor applies whether or not the cross-section has been locally reduced in some way (Salmon and Johnson, 1996). Consider, for example, an angle welded to a gusset plate by fillet welds at the heel and toe of one of the legs. The gross cross-section and the net cross-section are identical, yet it is obvious that shear lag must be considered.

If only longitudinal welds are used in the slotted tube connection, then the net cross-section should be used, i.e., gross cross-section less the end area of the two slots. If fillets welds are present where the gusset plate meets the end of the slot in the tubular member (transverse welds), then the gross cross-section of the tube should be used. In either case, the shear lag reduction factor, U, should be applied.

PREVIOUS RESEARCH

Although there are two previous studies that relate to the investigation reported here, neither of them deals with circular tubes. One was a numerical study done by Girard, Picard, and Fafard (1995). That research examined the effect of shear lag on a slotted rectangular tube welded into a gusset plate. No physical tests were undertaken in this program. The second study was that done by Korol (1996). This researcher tested 18 specimens, all of which were slotted square or rectangular tubes connected to gusset plates. Only seven of the specimens tested failed in a way that explored the shear lag phenomenon. In the other 11 tests, failure was by tearing out of a block of material (“block shear”). No analysis was included in this study, but the work of Girard et al. was used to provide a prediction for one test specimen. The Girard et al. model did not give a particularly good prediction for this case. Korol observed that restrictions on the numerical model of Girard et al. limit its usefulness.

Considering the lack of experimental evidence, it is appropriate to explore whether shear lag actually exists in a slotted tube connection and, if so, report on the suitability of the AISC HSS Specification rules for this type of connection. Both an experimental program and numerical modeling were undertaken to examine the tensile capacity of round tubular members that are slotted and then connected by welding to gusset plates.

TEST PROGRAM

The objective of the testing program was to examine the ductility and the capacity of the slotted tubular tension

Table 1.										
Specimen	Tube Size dia. × wall thick-ness mm	Trans-verse Weld	Fillet Weld length × leg size mm	Shear Lag Factor U	Test Results		AISC LRFD Calculated Loads			Ultimate Load Numerical Analysis kN
					$P_{U\ TEST}$ kN	Δ_{max} mm	Yield Load $\phi_t = 1.0$ kN	Ultimate Load $\phi_t = 1.0$ kN	Ultimate Load ϕ_t, $U = 1.0$ kN	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
S 1–1	102×6.4	no	170×6	0.81	830	34	743	642	792	827
S 2–1	102×6.4	yes	170×6	0.81	869	135	743	688	849	856
S 2–2	102×6.4	yes	170×6	0.81	849	137	743	688	849	856
S 2–3	102×6.4	yes	170×6	0.81	875	142	743	688	849	856
S 3–1	102×4.8	yes	150×5	0.78	645	99	519	487	624	629
S 3–2	102×4.8	yes	150×5	0.78	634	102	519	487	624	629
S 3–3	102×4.8	yes	150×5	0.78	631	76	519	487	624	629
S 4–1	219×8.0	yes	345×10	0.80	2160	128	1729	1713	2141	2168
S 5–1	219×8.0	yes	275×10	0.75	2157	54	1729	1606	2141	2110

members. This was done using the series of tests outlined in Table 1.

The HSS sections used are those produced in Canada. They were hot-rolled and were Grade 350W steel. The specified yield strength for this steel is 350 MPa and for HSS the ultimate tensile strength must fall in the range 450 MPa to 620 MPa. All calculations necessary for the specimens in this program were made using measured dimensions and material properties (Cheng, Kulak, and Khoo, 1998).

As shown in Table 1, the sections used were HSS 102×4.8, HSS 102×6.4 and HSS 219×8.0. The first of these is not available in US practice, but the latter two sections correspond to HSS 4×0.25 and HSS 8.625×0.313, respectively, in US customary units (AISC, 1997). The static yield and ultimate strengths were, respectively, 375 MPa and 451 MPa for the HSS 102×4.8, 339 and 449 MPa for the HSS 102×6.4, and 348 MPa and 431 MPa for the HSS 219×8.0. The final elongation (50 mm gage length) ranged from 31 to 38 percent.

The shear lag factor calculated according to Equation 2 ranges from 0.75 to 0.81 for these specimens. All the specimens except S 1-1 had a fillet weld across the junction of the tube slot with the gusset plate in addition to four longitudinal fillet welds.

The specimens were loaded axially using a clevis fixture that was accommodated in the testing machine. The length of the tube between gusset plates ranged from 330 mm to 350 mm. Measurements of loads, deformations and strains were made as a specimen was loaded. Loading was carried out at a slow rate and in the inelastic range loading was stopped at intervals so as to ensure no dynamic effect. Further details of the tests can be found elsewhere (Cheng et al., 1998).

Seven of the nine specimens failed at the mid-length of the member after extensive necking had taken place. Figure 3 shows a typical specimen in this category (S 4-1). The two exceptions were S 1-1 and S 5-1. In these cases, failure occurred in the tube where it entered the gusset plate, that is, at the stressed end of the slot. Figure 4 shows the fracture of S 1-1. In all the tests there was extensive deformation prior to fracture, even for the two tests in which fracture occurred at the junction of the slot and the gusset plate. When fracture was at the mid-length, the failure surfaces were of a "cup-cone" configuration, which is typical of a ductile tensile fracture.

An example of the load vs. deformation curve (S 4-1) is presented in Figure 5, and the test results of all the specimens are summarized in Table 1. Calculated values in the table were obtained using measured dimensions and material properties (Cheng et al., 1998). The net cross-sectional area was used for strength calculation of Specimen S 1-1 since only longitudinal welds were present. In all other cases, the gross cross-sectional area was used.

The capacity of a tension member according to the AISC LRFD Specification (AISC, 1993) is given in Section D1. The limit states are yielding in the gross cross-section and fracture in the net section. Thus, the capacity according to the LRFD Specification is the lesser of

$$P_n = \phi_t F_y A_g \tag{4}$$

and

$$P_n = \phi_t F_u A_e \tag{5}$$

The value of the resistance factor, ϕ_t, is to be taken as 0.90 in Equation 4 and as 0.75 in Equation 5. The lower value used for Equation 5 is in recognition that failure is by fracture. As discussed earlier, the reduction factor, U, must be included in the calculation of A_e in Equation 5.

The calculated capacity of the members according to Equations 4 and 5, but using $\phi_t = 1.0$, is shown in columns 8 and 9 of Table 1. The value of the resistance factor is set at unity in order that the design equations can be compared directly with the test results. Equation 5 governs for all specimens, whether or not the resistance factors are included in the calculation.

The test load recorded in this program is the ultimate (fracture) load. Thus, it is the predictions shown in column 9 that should be compared with the test values, column 6. It can be seen that the AISC predictor equation (Equation 5, but with $\phi_t = 1.0$) significantly underestimates the actual fracture load. The mean value of the ratio, AISC predicted ultimate load to test ultimate load is 0.78 and the standard deviation is 0.02. It is observed that this under-prediction is about equal to the HSS Specification shear lag factor for these specimens. If the shear lag factor is set at unity, then the predicted ultimate loads are those shown in column 10 of Table 1. When the predicted-to-test ratio is examined now, the mean value is 0.98 and the standard deviation is 0.01.

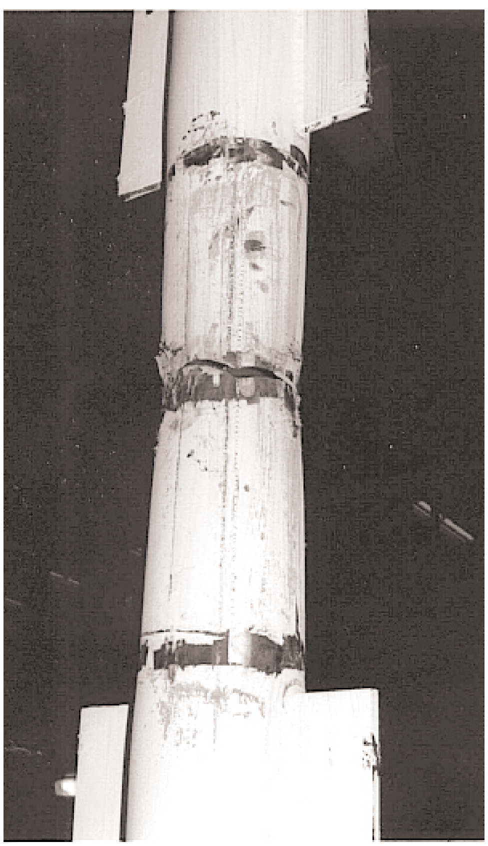


Fig. 3. Fracture of specimen S 4-1 at mid-length.

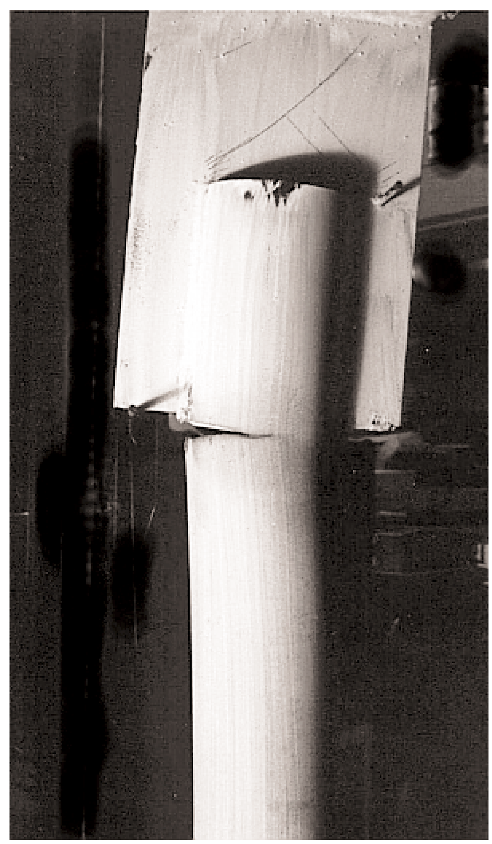


Fig. 4. Fracture at slotted end of specimen S 1-1.

On the basis of this comparison, it can be concluded that there was negligible shear lag in these test specimens. This is discussed further below, however.

The information in Table 1 shows that the ductility of specimens that fractured at the slotted end (S 1-1 and S 5-1) is significantly less than those that fractured at their mid-length (the remainder).

The effect of shear lag should not necessarily be dismissed. Figure 6 shows measured strains at the slotted end of Specimen S 4-1 for a load that is about 60 percent of the fracture load (the figure also shows strains obtained from a numerical analysis; this will be discussed later). According to Figure 6, the strain in the region of the tube that is in contact with the gusset plate is about double the lowest strain. This reflects the fact that there is shear lag in the system-not all of the cross-section is at the same strain as the member enters the gusset plate. Thus, when the weld length is short relative to the member size the large stresses at this location (i.e., shear lag) may result in fracture at the leading end of the slot-tube junction rather than at the mid-length of the tube. This is what was observed in Specimen S 5-1. The stress concentration at this location is also elevated when there is no transverse weld: S 1-1 fractured at the slotted end and at a reduced ductility as compared to the specimens with the weld end return. However, even with the stress concentration, the majority of the test specimens fractured at a location other than the slot-tube junction. This can be attributed to the stiffening effect provided by the gusset plate. The tube is restrained from contracting circumferentially by the gusset plate, whereas at mid-length the tube is free to contract. This effect is explored further in the numerical analysis.

NUMERICAL ANALYSIS

In order to study the behavior of the connections, elasto-plastic numerical analyses were carried out using the finite element program ABAQUS (Hibbitt, Karlsson, and Sorensen, 1994). In the analyses, the materials are assumed to behave according to the incremental, isotropic-hardening plasticity model and connection failure is assumed to occur when the equivalent plastic strain in any part of the connection reaches a critical value. This critical value was determined from the tensile coupon tests, but in order to model and predict the connection failure adequately the material properties beyond the initiation of necking had to be established. The details of how this was done are available elsewhere (Cheng et al., 1998). In all of the analyses, failure was assumed to occur in either the gusset plate or in the tube, but not in the weld.

The numerical analyses provided a good prediction of the behavior of the connection. The results are shown in Column 11 of Table 1, and the predictions are always within 2 percent of the physical test values. In each case, the numerical analyses also correctly predicted the location of fracture, and it also predicted the reduced ductility for both S 1-1 and S 5-1 that was observed in the tests. Although the analysis was not able to predict the deformation at fracture as accurately, it was still able to provide a reasonable prediction of the connection ductility. Figures 5 and 7 illustrate the good agreement between the actual load vs. deformation response and the numerical solution for Specimens S 4-1 and S 5-1, respectively, except for the deformation at fracture.

The strain distribution shown in Figure 6 and the normal (longitudinal) stress distribution shown in Figure 8 confirm the expectation that there is a significant stress concentration at the slotted end, right under the gusset plate. The high stresses reflect two features: the fact that the true stress vs. strain material response is used and the confining (von Mises) effect at the junction of the tube and the gusset plate. As illustrated in Figure 8, a considerable increase in the stress concentration occurs when the weld length is reduced from 345 mm for S 4-1 to 275 mm for S 5-1, which are

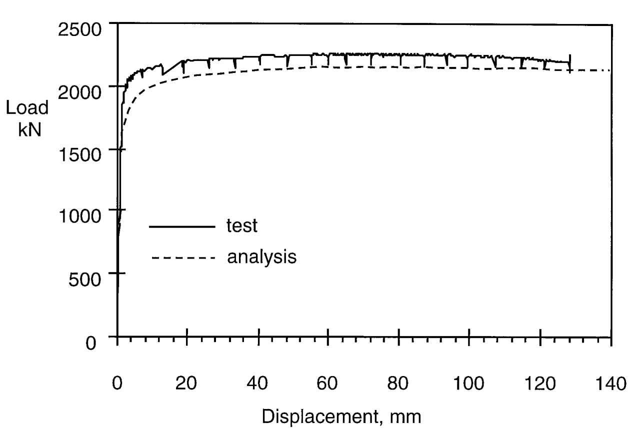


Fig. 5. Load vs. displacement specimen S 4-1.

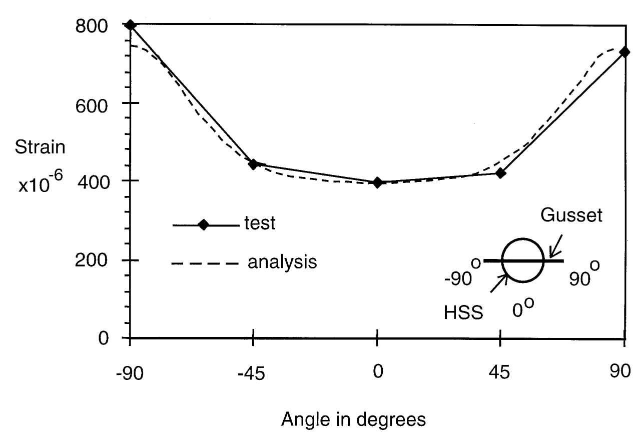


Fig. 6. Strain Distribution in S 4-1 at 500 kN, slotted end.

identical specimens otherwise. The stress concentration also increases significantly when there is no transverse weld. Because of these higher stress concentrations, S 1-1 and S 5-1 have a lower ductility and failed at the slotted end.

Notwithstanding these observations regarding the stress concentration (shear lag) in the slotted tube-to-gusset plate connections, in all of the physical tests the connections have achieved, or came close to, the ultimate capacity based on the gross area (except, net area for S 1-1). Furthermore, in all test specimens except S 1-1 and S 5-1, necking and fracture occurred at the mid-length of the tube. This indicates that the effect of shear lag on the ultimate strength of the tube is not significant. Because of the shape of the circular tube and the constraint provided by the gusset plate, the tube is restrained from contracting circumferentially and, as a result, tension hoop stress is developed in the tube at its junction with the gusset plate. This increases the effective stiffness of the tube at the slotted end as compared to the mid-length, where the tube is free to contract. As a result, the tube at the slotted end location is capable of carrying a higher load than at its mid-length for the same level of the equivalent plastic strain. Consequently, fracture occurs at the mid-length of the tube because of the higher average plastic strain. Of course, if the stress concentration is too high, the slotted end could fracture before the mid-length maximum load carrying capacity is reached.

CONCLUSIONS AND RECOMMENDATIONS

The numerical analyses were able to predict the ultimate load and location of the fracture. In addition, they provided a reasonable estimate of the ductility of these slotted tubular members. The analyses and the physical tests showed that the slotted end of the tube is stiffened significantly as the result of the constraint provided by the gusset plate. In most of the physical tests, fracture occurred in the main portion of the tube and not in the connection region. However, use of a short weld length or the absence of transverse welds across the thickness of the gusset plate weld may increase the stress concentration sufficiently that fracture will take place where the tube enters the gusset plate. In such a case, ductility will be reduced. Nevertheless, in all the configurations investigated the slotted round tubular members exhibited considerable ductility, regardless of the location of fracture.

Based on the tests and the numerical analyses reported herein, it is concluded that shear lag does not significantly affect the ultimate strength of slotted round tubular sections that are welded to a gusset plate. The shear lag expression given in Section 2.1(b) of the AISC *Specification for the Design of Steel Hollow Structural Sections* does not accurately represent the behavior of a slotted tube-to-gusset plate connection. It is recommended that these connections be designed with no reduction for shear lag as long as the weld length is at least 1.3 times the tube diameter. The reasons for this limitation reflect the ranges of the weld length tested in the program and the reality that the block shear failure mode is likely to govern when the weld length is less than this limitation. It is also recommended that a transverse weld be used across the thickness of the gusset plate at the location where the slot contacts the gusset plate (this may not be possible if the connection is made in the field because it would demand close tolerances). Use of a transverse weld increases the ductility of the slotted member significantly without incurring much extra cost.

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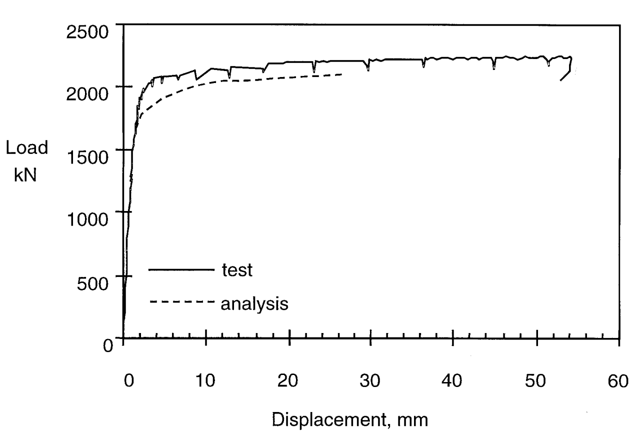

Fig. 7. Load vs. displacement specimen S 5-1.

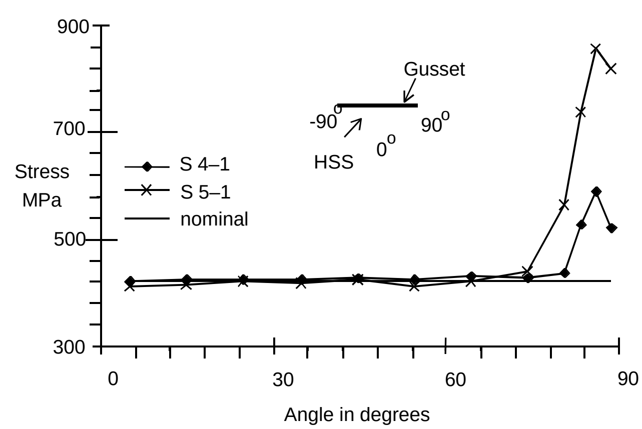

Fig. 8. Normal stress around tube at slotted end, load 2100 kN.

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