Effect of Joint Restraint on Lamellar Tearing Susceptibility in Steel Plates

A relationship between joint restraint and the minimum ductility in short transverse direction required to avoid lamellar tearing is sought on the basis of small and large scale restraint tests

BY L. MALIK AND B. A. GRAVILLE

ABSTRACT. Although a vast number of researches on the subject of lamellar tearing have been reported in the literature, as yet there is no quantitative method available for estimating the minimum through-thickness ductility required of the steel in order to avoid lamellar tearing in production joints.

In the program described here, percent reduction in area was used as an indication of the through thickness ductility, and the concept of restraint intensity was used to characterize the joint severity. Small scale restraint tests in a rigid restraint cracking machine and large scale H-type restraint tests were then employed to seek the desired correlation.

Since the joint restraint is a geometrical parameter and is independent of the precise welding procedure, it may be calculated for any joint. Thus, the results presented here are expected to give an *a priori* indication of the optimum steel quality required.

Introduction

Lamellar tearing has been recognized as a significant fabrication problem in the last decade or so. Several investigations have helped to define the principal cause and the mechanism of lamellar tearing. There is general agreement in the literature that lamellar tearing occurs in high restraint joints when a steel plate having inadequate through-thickness ductility is required to accommodate fairly large welding strains in the through-thickness direction such as in T-joints, cruciform joints, etc. Poor ductility is usually due to the presence of elongated inclusions.

It is apparent, therefore, that the prevention of lamellar tearing could be effected by reducing the number of elongated inclusions in the steel plate and/or by reducing the magnitude of the through-thickness welding strains. Most research on lamellar tearing has been related to steel quality, and effect of inclusions, deoxidation practice, etc., on through-thickness ductility—the relation between the latter and lamellar tearing being generally accepted.

This has resulted in improvements in steelmaking practice. Consequently, steels with excellent through-thickness ductility, as assessed by small scale mechanical tests, are becoming increasingly available. The mechanical test most often employed is the short transverse tensile test, and consensus in the literature seems to be that % reduction in area (% RA in ST or Z direction) is the most sensitive indicator of the through-thickness ductility, and hence of the lamellar tearing susceptibility of the steel.

A fabricator, however, is often faced with the problem of deciding what quality of plate, as indicated by % RA in ST direction, is necessary for a particular application, and whether to purchase premium steel or not. Various weldability tests developed so far have been of limited use only since, besides being time-consuming, they determine lamellar tearing susceptibility on a relative basis only. Thus, the Z direction window test[1,2] divides steels in two categories, depending on whether or not they showed lamellar tears in this test.

In practice, lamellar tearing may still be encountered if joint severity is greater than that simulated by the test. Equally possible, is a situation where unnecessarily high quality steel is demanded to pass the Z direction window test even though the actual joint to be welded is of lower severity. In the recently developed Lehigh lamellar tearing test,[3] tearing susceptibility is determined in a quantitative manner by a parameter called "the critical weld restraint level." This, in fact, is an externally applied load in the through-thickness direction of the susceptible steel plate, and it cannot be related to any characteristic of the joint to be welded.

Since it has been a general experience that for a given steel lamellar tearing is more likely in joints that are loosely termed high restraint (such as node-connections in offshore structures, nozzle-shell joints in pressure vessels, etc.), one possible approach is to quantify the term restraint as a means of assessing the joint severity. A correlation could then be sought between a certain index of the steel susceptibility, such as % RA in the ST direction, on one hand and a critical joint restraint on the other, such that the probability of lamellar tearing occurring in joints with restraints less than the critical value would be very

L. MALIK is with Dominion Bridge Co., Ltd., Ottawa, and B. A. GRAVILLE is with the Canadian Welding Development Institute, Toronto, Canada.

low. This was the aim of the work reported here.

Restraint of a Joint

The quantitative parameter chosen to characterize the joint severity in this program is the "transverse intensity of restraint" concept as developed by Satoh and co-workers.[4] This parameter determines the magnitude of the gross reaction stress (or force) that is developed under conditions of hindered contraction; it can be defined as "the force required per unit length of the weld to cause a unit elastic displacement across the root gap." For a simple butt joint, shown in Fig. 1, the restraint 'K' is given by the equation:

$$K = \frac{E \cdot h}{l} \quad (1)$$

where E is the Young's Modulus. It can also be shown from geometrical considerations and from Hooke's law that the transverse reaction stress σ developed after the deposition and complete cooling of a single pass weld in the butt joint is:

$$\sigma = \frac{K \cdot S_T}{h} \quad (2)$$

where S_T is the transverse free shrinkage that would have occurred if the plates were free to move.

If the reaction stress exceeds the elastic limit of the weldment region, yielding will occur and the reaction stress/restraint curve is no longer linear—Fig. 2. The slope of the linear portion of this curve for a single pass weld S_T/h assuming 3-D heat flow conditions is a function of the physical properties of the steel only, and is shown to be 0.045.[4]

The main feature to be noticed in the above two equations is that the transverse reaction stress σ developed at a fixed joint restraint is dependent on the transverse free shrinkage S_T and hence on the precise welding procedure (heat input, etc.) employed. Furthermore, the transverse free shrinkage S_T may be estimated theoretically only for single pass welds. For multipass welds, the transverse free shrinkage and hence the transverse reaction stress that would be developed cannot be predicted. In contrast, the joint restraint is purely a geometrical factor independent of groove shape, weld procedure, etc., and may be calculated, estimated or measured.

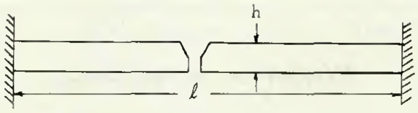


Fig. 1—A restrained butt joint

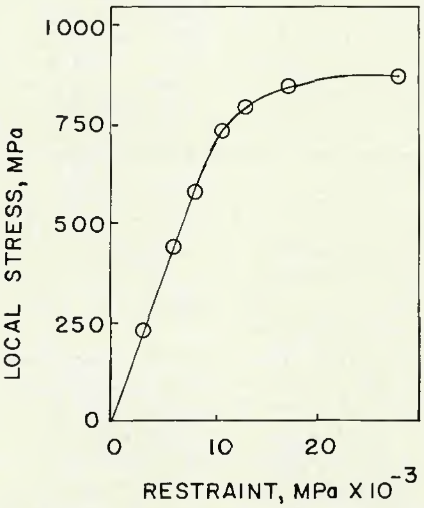


Fig. 2—Non-linearity in reaction stress vs restraint plot at high restraints for single pass weld (from Satoh, et al.[5]*)*

Experimental Procedures and Results

Materials

The chemical analyses of the steels investigated are given in Table 1. Oxygen and sulphur analyses are included since these two elements primarily determine the volume fraction of inclusions in steels. Steels B, C, D, F and G were from experimental heats wherein sulphur content was the main variable. Steels H and J, also laboratory melted heats, were aimed to be Si and Si-Al killed respectively. However, steel H also contains 0.02% Al, and, therefore, cannot be considered to be aluminum-free. All the remaining steels (A, L, N, P and R) were of commercial origin, and some had a history of lamellar tearing in practice.

A limited amount of scanning electron microscopy was done to indicate the nature of the predominant inclusions in some of the steels. The results are summarized in Table 2.

Prior to their sectioning for various tests, all plates were ultrasonically tested using conventional procedures. While steels C, D, G, H, J, N and R were indicated to be entirely defect-free, steels A, B, L and P had several defect indications, and steel F had a lamination at center-thickness in various locations.

In the sectioning of plates for various tests, an attempt was made to keep the defective areas away from the weldment region.

Mechanical Testing

The yield strength, tensile strength and % elongation in a 51 mm (2 in.) gauge length of each steel (except A) was determined using two full thickness flat tensile specimens, and results are shown in Table 3. Of greater relevance from the point of view of lamellar tearing, however, are, the % RA values in the through-thickness direction. These values were determined by welding extensions onto the surfaces of the steel plates, and then extracting and testing at least four number 12 Hounsfield tensile specimens. The average % RA value of each steel as

Table 1—Chemical Composition of the Steels Investigated, Wt-%

Steel	Plate thickness, mm[a]	C	Mn	Si	P	S	Al	Oxygen, ppm
A	25.4	0.11-0.18	1.38-1.51	0.35-0.43	0.017	0.016-0.045	N.A.	N.A.
B	12.7	0.18	1.09	0.40	0.011	0.060	0.10	100
C	12.7	0.19	1.04	0.25	0.013	0.023	0.04	60
D	12.7	0.21	1.01	0.30	0.012	0.017	0.04	80
F	12.7	0.21	1.12	0.29	0.013	0.008	0.05	90
G	12.7	0.24	1.06	0.28	0.012	0.011	0.035	50-90
H	12.7	0.23	0.99	0.28	0.017	0.024	0.02	150
J	12.7	0.22	0.98	0.32	0.017	0.025	0.07	140
L	19.1	0.14	1.38	0.33	0.026	0.017	0.02	30-500 (Avg. = 200)
N	12.7	0.13	0.77	0.01	0.013	0.016	0.05	60-150
P	50.8	0.22	1.13	0.15	0.013	0.021	0.05	50
R	25.4	0.27	1.23	0.26	0.015	0.023	0.03	150

[a] 1 in. = 25.4 mm.

well as the minimum value measured for each steel are also reported in Table 3.

An attempt was made to assess the lamellar tearing susceptibility of steel plates by direct tension testing of welded cruciform joints. The welding and sectioning of these cruciforms is shown schematically in Fig. 3.

Eight cruciforms were tested for each steel, and these comprised four variations. Two of these variations resulted from the load arm being of the same steel as the test plate or of a high strength steel, the latter being always 12.7 mm (½ in.) thick. The remaining two resulted from keeping test plate arms intact or shaving them off. The location of fracture as well as the load to fracture was noted for each test.

Table 2—Nature of Inclusions in the Steels Investigated

Steel	Nature of inclusions as detected in SEM
A	(Si, Al, Mn) Oxides; MnS
B	MnS
C	MnS
F	Was not possible to detect significant inclusions
H	Platelike inclusions containing (Ca, Al, Si); some Al_2O_3 and MnS inclusions as well.
J	Elongated and round MnS; Al_2O_3
L	Predominantly round (Mn, Si) oxides
N	Isolated and hard to locate inclusions; mostly Al_2O_3; sometimes MnS
P	Mostly MnS and MnO inclusions; sometimes Al_2O_3

Small Scale Restraint Tests

It has been suggested in the Japanese literature on weld cracking[6] that, for joints under external restraint, the intensity of restraint can be used to predict the initiation of cracks irrespective of the stress and strain history at the point of cracking. It was, therefore, first necessary to determine whether the conventional restraint also affects lamellar tearing and hence to establish whether for a given steel there is a critical restraint (K_{cr}) below which lamellar tearing would not be expected to occur. To perform these tests under carefully controlled conditions of restraint, a "rigid restraint cracking" (RRC) machine was used. This type of machine was originally developed in Japan, and has been described in the literature.

The joint configuration chosen for these tests was a T-butt joint, schematically shown in Fig. 4A. In such a joint, the transverse reaction stress and the reaction strains predominantly act in the through-thickness direction of the plates, and thus are expected to cause lamellar tearing in the test plate. Figure 4B is a schematic illustration of the experimental set-up.

A piece of the test steel approximately 300 × 51 mm (12 × 2 in.) was welded to one of the load arms, and a 45 deg single bevel preparation with 12.7 mm (½ in.) root face was flame cut on the other load arm. A constant root opening of approximately 1 mm (0.04 in.) was used in all tests. A support table with a smooth surface was botled on to the load arms with 12.7 mm (½ in.) diameter machined rolls in between. This arrangement prevented angular distortion, kept the load arms flat and allowed them to contract or expand in the transverse direction only.

During a test the distance between two gauge points was monitored by the LVDT's which could actuate the motor to maintain constant gauge length while the weld region contracted. The restraint would then be given by $K = Eh/l$ where l is the gauge length and h is the thickness of the load arms. The restraint was changed by changing l. The welding conditions were: electrodes—E7018, 4.5 mm ϕ (from an oven at 120 C or 248 F); current—240 amperes (A); voltage—21 volts (V); travel speed—approx. 2 mm/sec (4.7 ipm); number of passes—5 (to give an approx. weld throat = 20 mm or 0.79 in.).

After cooling for about 20 hours (h), the weld was removed and five sections of the test plate near the weld were cut, polished and etched. After measuring the throat of the welds, the sections were examined in an optical microscope for lamellar tears. By conducting tests at various restraint levels, it became possible to establish for each steel a critical restraint value below which lamellar tearing was not observed.

Some typical results are shown in Fig. 5, where the final weld metal reaction stress (force/weld throat × weld length) is plotted against the restraint for steels C and F, respectively. Further, from Fig. 5 it can be established that for steel C, the critical restraint for lamellar tearing, K_{cr} (C), in small scale restraint tests was approximately 14,100 MPa*, and that for steel F such a value cannot be determined because at high restaints, weld metal cracking sets in before lamellar tearing. Photographs in Fig. 6 indicate the nature of some of the cracks observed.

*$MPa \times 10^6 = Pa$, and $Pa \div 6.894757 \times 10^3 = psi$.

Table 3—Mechanical Properties of Steels Investigated

Steel	Thickness, mm[a]	Longitudinal direction: Yield strength, MPa (ksi)	Longitudinal direction: Ultimate strength, MPa (ksi)	Longitudinal direction: Elongation, %	Through-thickness direction: Ultimate strength, MPa (ksi)	Through-thickness: Reduction in area, % Average	Through-thickness: Reduction in area, % Minimum
A	25.4	388 (56.3)	552 (80.0)	—	—	—	—
B	12.7	316 (45.8)	485 (70.4)	37.5	468 (67.8)	9.7	9.7
C	12.7	324 (47.0)	499 (72.4)	36.5	536 (77.8)	17.2	14.6
D	12.7	322 (46.7)	509 (73.8)	36.3	513 (74.4)	38.4	28.0
F	12.7	357 (51.8)	546 (79.2)	36.3	585 (84.9)	58.5	58.5
G	12.7	329 (47.7)	516 (74.9)	36.3	536 (77.8)	46.7	34.0
H	12.7	328 (47.6)	525 (76.1)	32.5	561 (81.4)	17.6	10.0
J	12.7	334 (48.4)	507 (73.5)	31.0	560 (81.2)	24.2	18.0
L	19.1	347 (50.3)	509 (73.8)	47.0	497 (72.1)	10.3	4.4
N	12.7	252 (36.6)	404 (58.6)	50.0	414 (60.0)	27.4	23.2
P	50.8	—	493 (71.5)	38.0	533 (77.3)	46.0	38.0
R	25.4	—	630 (91.2)	—	640 (92.8)	13.6	10.9

[a] 1 in. = 25.4 mm.

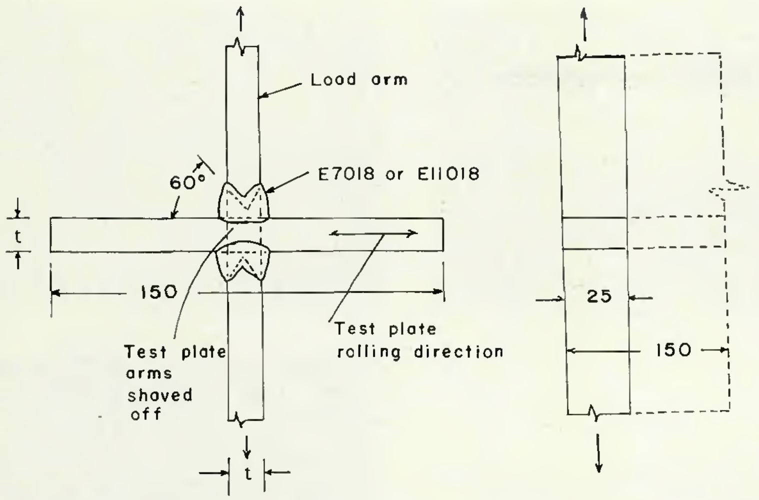


Fig. 3—Scheme for welding, sectioning and testing of cruciform joints. All dimensions in mm

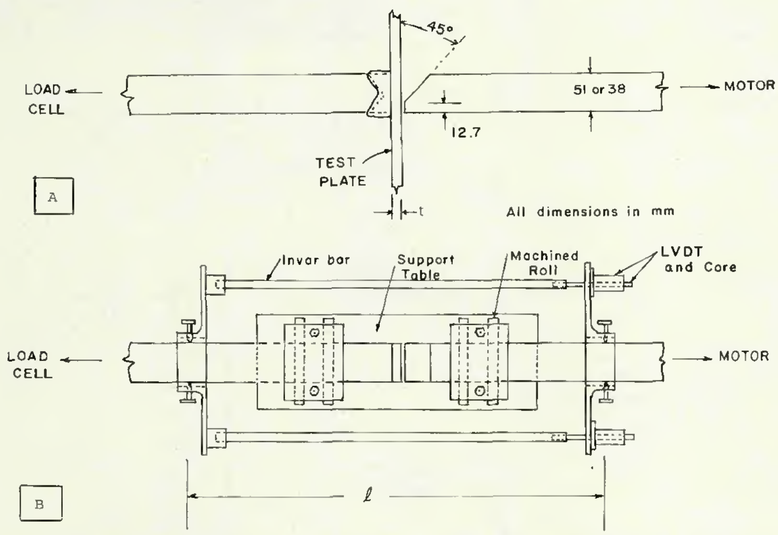


Fig. 4—Small scale restraint testing: A (top)—joint configuration for T-butt test welds; B (bottom)—schematic illustration of the experimental set-up for small scale tests

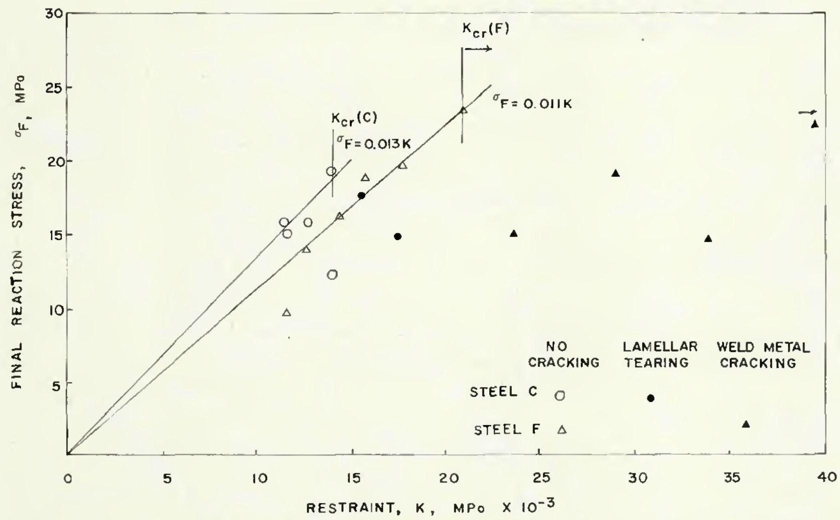


Fig. 5—Plot of final reaction stress vs. restraint in small scale restraint tests for steels C and F

H-Type (Large Scale) Restraint Tests

The small scale restraint tests proved that the approach of using the restraint concept to study lamellar tearing susceptibility was basically sound. However, it was also realized that 51 mm (2 in.) long welds deposited under laboratory conditions did not adequately represent production joints.

To simulate a more realistic welding situation, large scale restraint tests were conducted. H-type restraint specimens were employed for this purpose, and their configuration is shown in Fig. 7. The slits and the groove were prepared by flame cutting, and then the test plate (approx. 600 × 300 mm or 2 × 1 ft) was welded to the restraining plate on one side so that the root gap on the other side for the test weld was approximately 0.7 to 2 mm (0.03 to 0.08 in.). The length of weld L_c was approximately 600 mm (1 ft) in all tests.

The restraint for H-type restraint test is given very approximately by:

$$K_{app.} = \frac{E \cdot h}{B(1 + L_c/2L_s)} \qquad (3)$$

where E is the Young's Modulus and h, B, L_c and L_s are various dimensions shown in Fig. 7. The restraint for various tests was varied by changing the dimensions B, h or the ratio $L_c/2L_s$. The welding procedure employed was the same as for the small scale restraint tests on the RRC machine.

Measurements of the reaction stresses and weld contraction were made using a simple mechanical extensometer between drilled holes. Measurements were made in one direction only and stress values are regarded as approximate only.

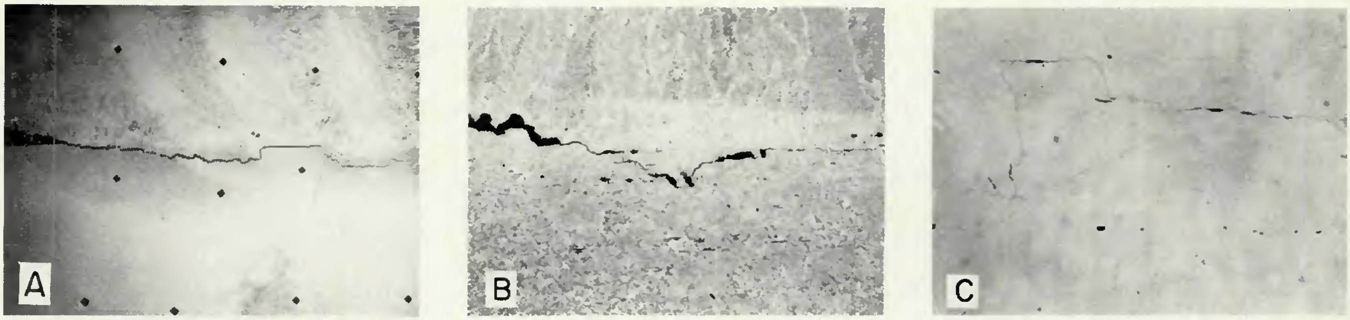
Figure 8 shows the results of measurements and calculations for one particular large scale test.

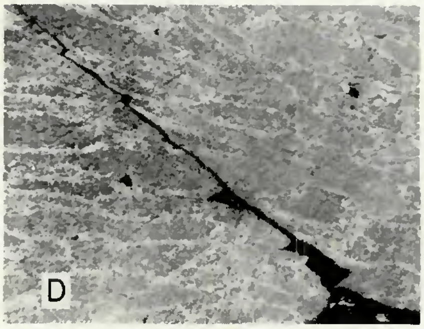
Metallography was again used for examining for lamellar tears. When detected, the tears were almost always in section obtained from the extreme ends of the test weld. Some of the lamellar tears observed in large scale tests are shown in Fig. 9. Fifteen large scale tests were done to establish the critical restraint for lamellar tearing in four steels.

Discussion

Reaction Stress Calculations

Small Scale Restraint Tests. The reaction stress depends on the restraint in the form $\sigma = mK$ where m is a constant; "m" has a value about 0.045 for single pass welds but could be different for multipass welds. Figure 5 shows reaction stress against restraint where lines are drawn from the origin





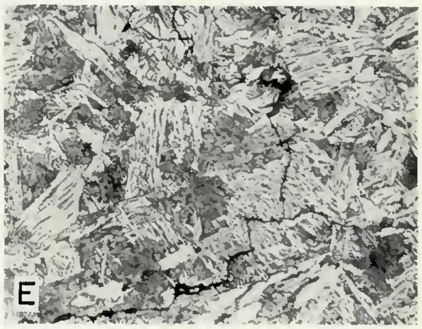


Fig. 6—Nature of cracks observed in small scale restraint tests; A—gross lamellar tear in B steel; B—fine root lamellar tear in J steel; C—extremely fine root lamellar tear in D steel; D—weld metal root crack, test plate F steel; E—non-lamellar heat affected zone crack in N steel. A—×5; Band D—×100; C and D—×500 (A reduced 43% and others 50% on reproduction)

through points that represent uncracked tests for steels C and F.

The values of m are slightly greater than 0.01. When all data was considered, however, there was considerable scatter but the value of m was always between 0.010 and 0.015. The exact value of m is expected to depend on the precise welding procedure but the values obtained appear to be reasonable.[7]

Large Scale Restraint Tests. The results plotted in Fig. 8 make it clear that the actual stress distribution was highly herterogenous, both as to their nature and their magnitude. On both top and bottom surfaces, the stresses become increasingly compressive in going from the free edges towards the slits, indicating bending of the side-arms in the plane of the plate. Between the slits the tensile stress is more or less constant for the middle half of the weld length and becomes more tensile as one proceeds towards either of the slits. This trend was more predominant on the top surfaces of all tests and less so on the bottom. On the other hand, the contraction measured across the weld was a maximum at the center of the weld and decreased towards the ends.

While the top surface stresses are tensile, the bottom surface ones are, contrary to expectation, compressive. This heterogeneity is confirmed by the fact that on each of the top and bottom surfaces, the average calculated compressive stress on the side-arms was almost always in close agreement with the average calculated tensile reaction stress in the region between the two slits.

This observation indicates a large

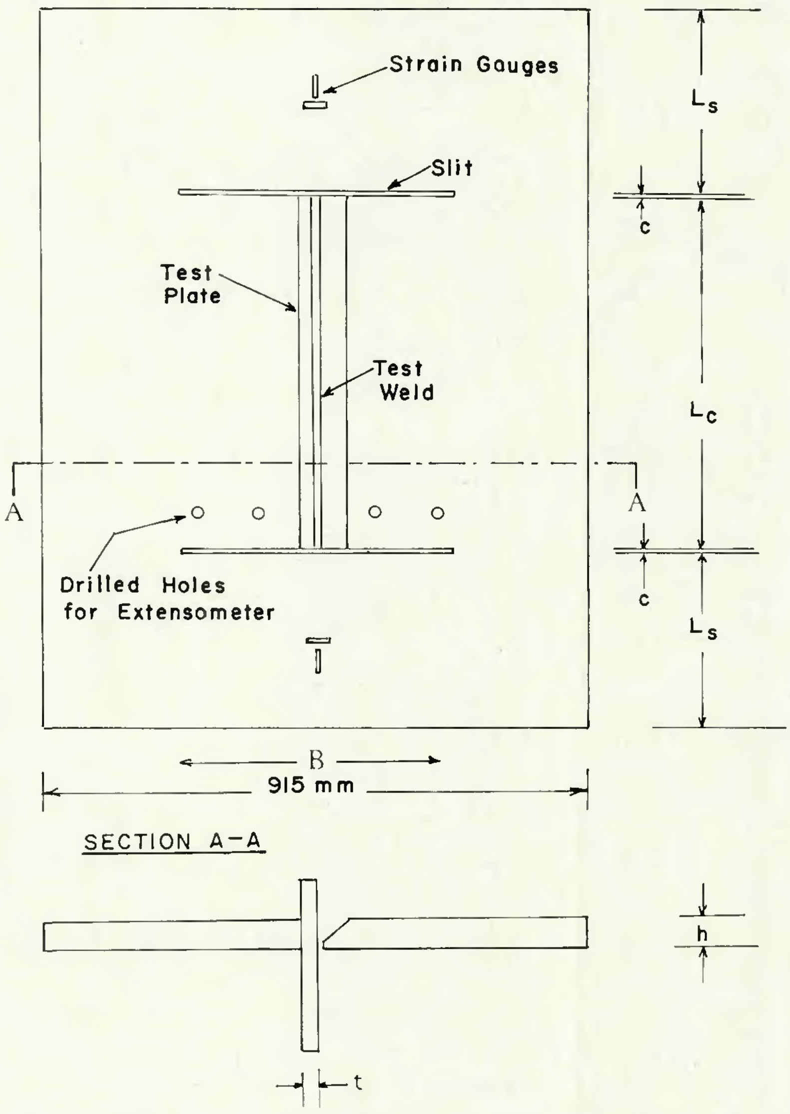


Fig. 7—Configuration of large scale H-type restraint tests

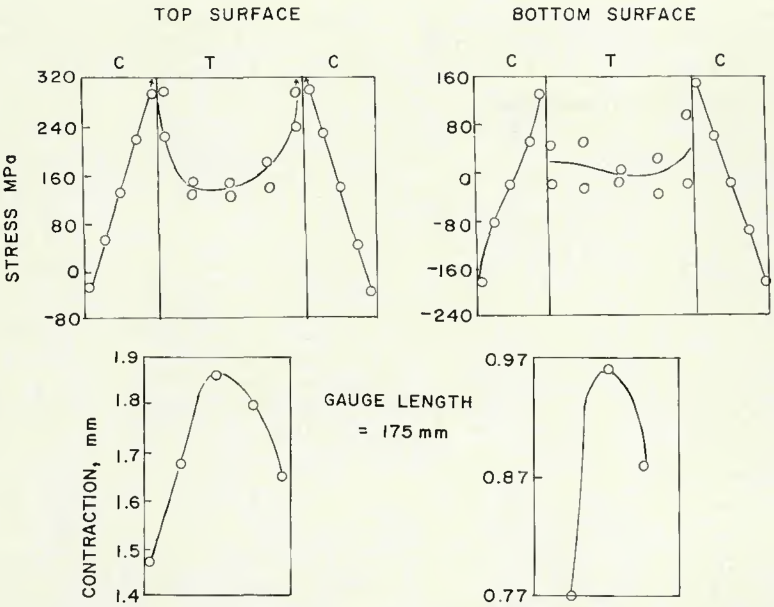


Fig. 8—Stress distribution and shrinkage measurements on top and bottom surfaces of a large scale H-type restraint test, steel N, $K_{app.}$ = 13,350 MPa

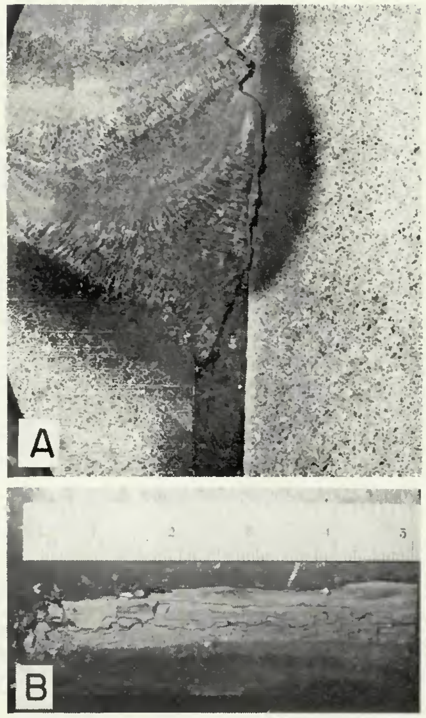


Fig. 9—Tears observed in large scale restraint tests: A—gross lamellar tear in R steel; B—complete separation due to lamellar tearing in L steel. A—×5 (reduced 35% on reproduction)

degree of rotation about the weld axis and is confirmed in Fig. 10. The data for this figure were calculated from strain gauge readings affixed on the side-arms so that variations in stress could be followed as the welding progressed.

It is seen in Fig. 10 that, at two widely different restraint levels, the weld metal reaction stresses on both the top and the bottom surfaces after the 1st pass are tensile in character. However, from the 2nd pass onwards, the bottom surface weld metal reaction stress progressively decreases, eventually becoming compressive in all tests. This is no doubt due to the single bevel shape of the groove so that the width of the weld at the top is much larger than that at the root, thereby causing maximum weld contraction at its top. This is also reflected in contraction measurements reported in Fig. 8 where the measured contraction in a constant gauge length is much greater on the top surface than that on the bottom one.

Calculated Restraint in Large Scale Restraint Test

Equation (2) can be rearranged and written as

$$K_{cal.} = \frac{\sigma h}{S_T} = \frac{\sigma h}{\frac{\Delta l + l}{E}} \qquad (4)$$

where σ is the transverse reaction stress, Δl is the constant contraction across the weld in a gauge length "l," and E is the Young's Modulus.

Calculated restraint above is directly proportional to the transverse reaction stress and inversely proportional to the shrinkage across the weld. Thus, it follows from the previous discussion that the actual restraint along the weld is not uniform, but will vary in a

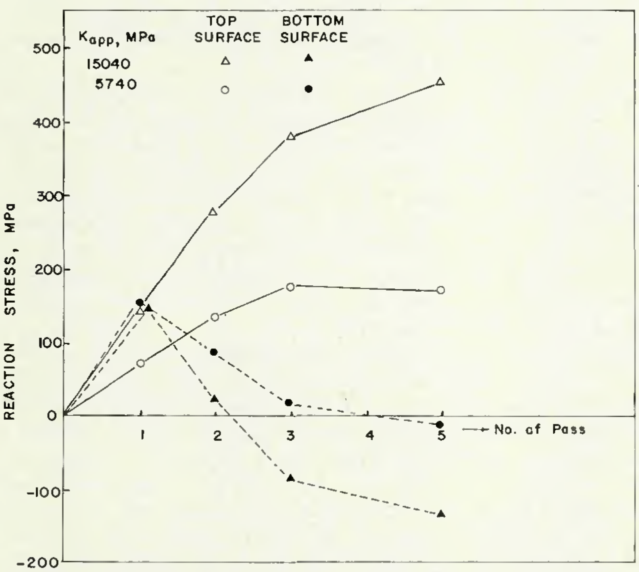


Fig. 10—Progressive development of reaction stress with welding on top and bottom surfaces in two large scale H-type restraint tests

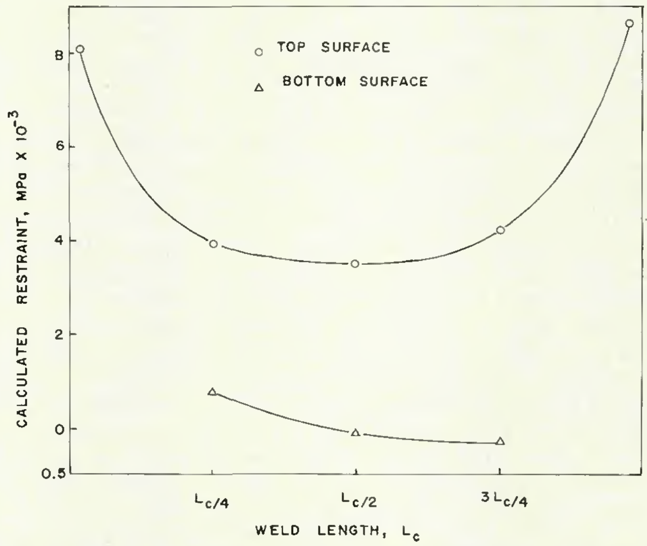


Fig. 11—Distribution of calculated restraint—equation (4)—from the data in Fig. 8

manner similar to that of the reaction stress—Fig. 11.

Further, the maximum calculated restraint near the slit (8,626 MPa) is substantially less than the approximate value (13,350 MPa) based on the simple formula of eq (3). A more accurate formula has been presented by Satoh, et *al.*:[5]

$$K = \frac{Eh}{B(1 + L_c/2L_s) + B'} \tag{5}$$

$$\text{where } B' = \frac{4L_c(\epsilon + \zeta)^2}{\pi^3}\left[\frac{\epsilon + \zeta}{\epsilon - \zeta}\sum_{m=1}^{\infty}\frac{1}{m^3}\sin^2\frac{m\pi\zeta}{\epsilon + \zeta} + \right.$$

$$\left.\sum_{m=1}^{\infty}\frac{1}{m^3}\sin^2\frac{m\pi}{\epsilon + \zeta} + \frac{1}{\epsilon}\sum_{m=1}^{\infty}\frac{1}{m^3}\sin\frac{m\pi}{\epsilon + \zeta}\sin\frac{m\pi}{\epsilon + \zeta}\right] \quad \text{and } \epsilon = \frac{2L_s}{L_c}, \quad \zeta = \frac{L_c + 2C}{L_c}$$

In the present work, $\epsilon = 1$ or 0.5, and $\zeta = 1.04 \simeq 1.0$ giving $B' = 2.17$ $L_c = 1294$ mm when $\epsilon = 1$ and $B' = 2.27$ $L_c = 1355$ mm when $\epsilon = 0.5$.

In Fig. 12, average calculated restraint on the top surface—eq (4)—and theoretical Restraint based on eq (5) are plotted against the approximate restraint based on the simple eq (3), and fairly good agreement is seen between calculations based on eqs (4) and (5).

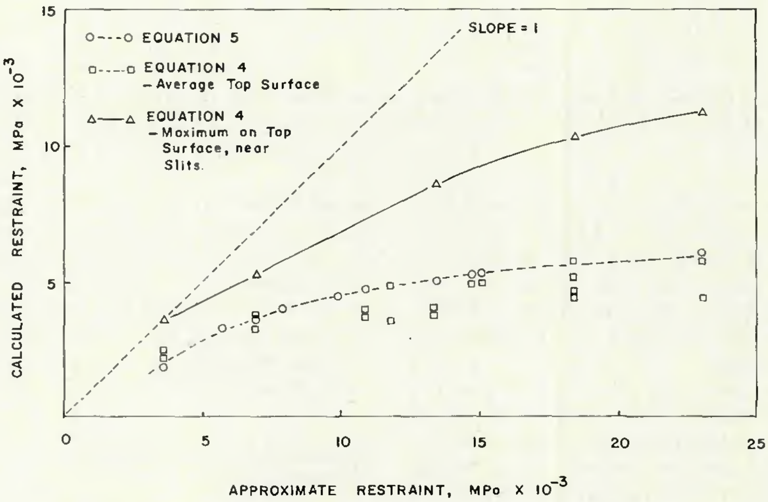


Fig. 12—Comparison of calculated and approximate values of restraint for large scale H-type restraint tests

Critical Restraint for Lamellar Tearing

Small Scale Restraint Tests. The results of crack detection on sections are plotted in Fig. 13 where ordinate is the % reduction in area of the steel, and abscissa is the restraint based on equation (1), so that results from each steel lie on a horizontal line.

It is evident from the plot that, as the % reduction in area of a steel increases, the external restraint required to cause lamellar tearing also increases. Steels A, B and R, which showed gross lamellar tears, have their % reduction in area (% RA) values less than 15%. Sections from tests done on steels C, H and J, with % RA in the range 17 to 24, showed fine lamellar tears at the root only which had to be observed microscopically.

In steel N (% RA — 27.4), no lamellar tears were detected but conventional heat-affected zone cracking occurred at higher restraints. When % RA was greater than 35% (steel D, G, P and F), lamellar tears were rarely seen, because above a restraint level of about 24,000 MPa, weld metal cracking occurred. Steel D with % RA = 38.4 provided a minor exception in that a lamellar tear was observed in the test done at a restraint of 21,000 MPa. This lamellar tear was, however, hair thin and could be observed at a magnification of 500 only—Fig. 6 (C).

There was a lot of scatter in the reaction stress vs. external restraint data. Despite this, it is possible, in Fig. 13, to establish a number or a narrow range of the external restraint below which lamellar tearing is unlikely to occur for a particular steel. This perhaps indicates that there exists a critical strain criterion which bears a direct relationship to the external restraint imposed, and is satisfied in local regions of strain concentration.

The % RA of various steels is shown in Fig. 14 plotted against their critical restraint for lamellar tearing. A line separating the lamellar tearing—no lamellar tearing zones can be drawn—which for % RA < 17.5 is close to a straight line, and above 17.5% RA may be a continuation of the same straight line or may deviate towards the restraints axis.

It can be concluded from the above discussion that there exists a critical restraint above which lamellar tearing may be expected in small scale restraint tests, especially when % RA is less than 17. Also, steels may be divided into three broad categories as regards their susceptibilities to lamellar tearing:

1. With % RA less than 13-14 where gross lamellar tears are observed.
2. With 38 > % RA > 13 where fine root lamellar tears are seen.
3. With % RA > 38 where lamellar tearing is improbable in the small scale RRC tests.

Large Scale H-Type Restraint Tests. Since the critical restraint for lamellar tearing in RRC tests is based on small 51 mm (2 in.) long welds, it need not be valid for real life weld joints. It was therefore the purpose of large scale tests with 600 mm (2 ft) long welds to simulate a real weld, and redetermine the critical restraint values for four of the steels.

The results of the microscopic examination of sections from each test are shown in Fig. 14, where % reduction in area is the ordinate, and the abscissa is the maximum calculated restraint on the top surface. This value for the restraint was chosen because, as mentioned earlier, the lamellar tears were always found near the slits, and here, the calculated restraint also had its highest value.

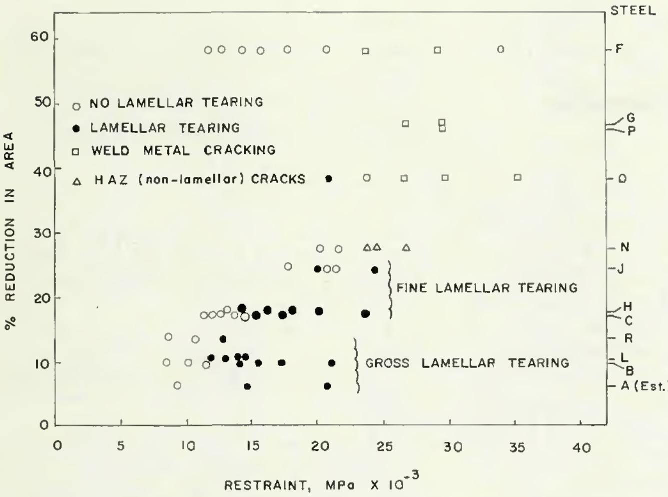


Fig. 13—Summary of crack detection in the small scale restraint tests on a %RA in ST direction vs. restraint plot

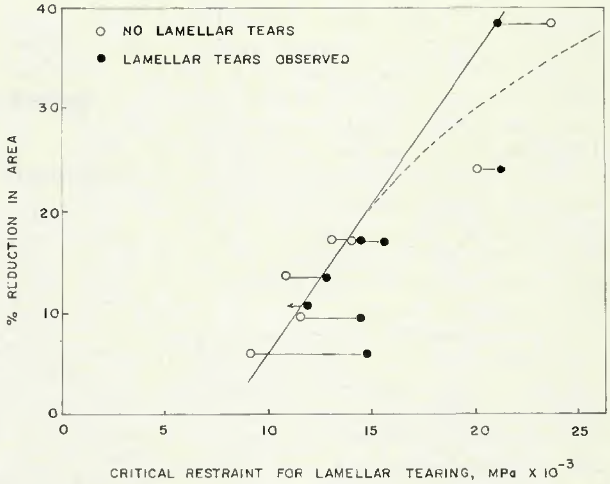


Fig. 14—Critical restraint for lamellar tearing in small scale restraint tests

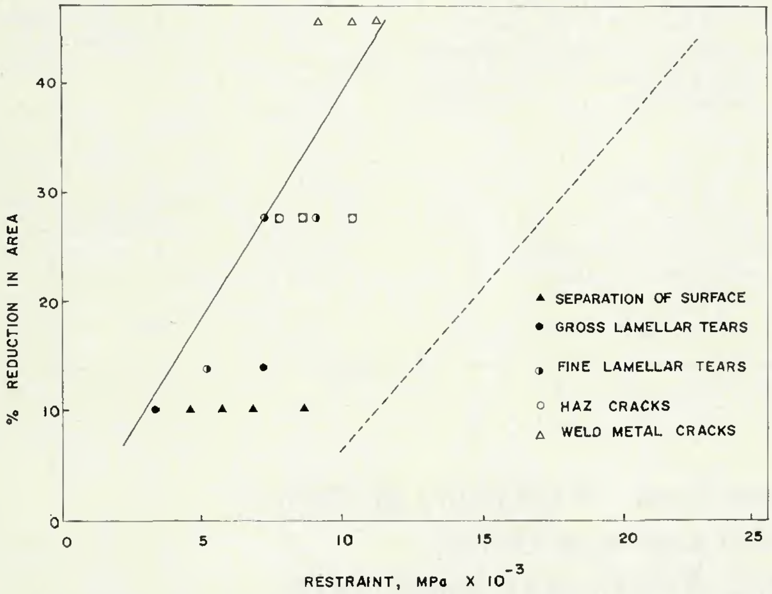


Fig. 15—Summary of crack detection in the large scale restraint tests on a %RA in ST direction vs. maximum calculated restraint (on top surface) plot

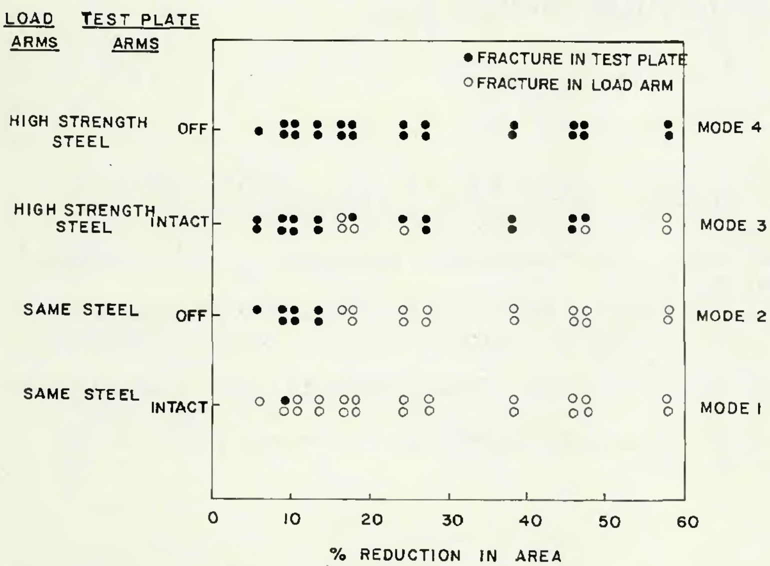


Fig. 16—Location of fracture in cruciform tests

No lamellar tearing was observed in P steel (46 % RA) even at the highest restraint at which the test was done. In contrast, L steel (% RA = 10.3) showed gross lamellar tears in all tests. In fact, complete separation took place in all tests, except the one at the lowest restraint.

Again, it is clear that as % RA value of a steel increases, so does the restraint required to cause lamellar tearing. Also, as % RA value increases, the nature of lamellar tears changes from gross to fine root tears. Similar conclusions were drawn from the small scale RRC tests.

A critical restraint line from the large tests separating no lamellar tearing—lamellar tearing zones is shown in Fig. 15 together with the line from the small tests (Fig. 14). The two lines are almost parallel, but the one based on large scale tests is far to the left of the one based on small scale tests, i.e., the critical restraint for lamellar tearing is lower in large scale tests than in small scale tests, thereby confirming the realistic simulation of production weld joints by the large scale tests.

The solid line in Fig. 15 can give an indication of the minimum required % reduction in area of a steel if lamellar tearing is to be avoided in a certain joint where restraint can be estimated. It should be pointed out that this relationship is conservative, since sound production welding practice would not permit severe conditions such as single bevel partial welds with root gaps.

Cruciform Tests

Since cruciform tension tests are relatively cheap and quick to perform, requiring only a welding facility and a tensile machine, it was decided to correlate their results to the % RA in various steels.

The easiest result to record is the location of fracture in various modes (strength of load-arms, presence or absence of test plate arms), and the results are shown in Fig. 16. Here it is seen that, in the most favorable mode for the test plate (same steel load arms, test plate arms intact), the fracture almost always occurred in the load-arm, thereby making it impossible to distinguish between susceptible and non-susceptible steels.

In a more severe mode (same steel load arms but test plate arms removed) a distinction can be made between steels with % RA less than or equal to 13.6% where fracture occurs in the test plate and those with % RA greater than about 17% where fracture occurred in load arms. In the mode of next higher severity (high strength steel, load arms and test plate arms intact), the fracture in test plate is seen to be quite frequent, even in steels with % RA values as high as 46. In the fourth, the most severe mode (high strength steel load arms and test plate arms shaved off), the fracture understandably always occurs in the test plate.

It is clear, therefore, that the second mode provides the most useful information, i.e., if fracture occurs in the test plate, then the % RA is expected to be less than approximately 14. This is also the limit below which gross lamellar tears were observed in the restraint tests, and above which fine lamellar tears were observed.

Conclusions

1. Small and large restraint tests showed that for a given steel plate a critical restraint existed below which lamellar tearing did not occur. The critical restraint increased with increasing through thickness ductility as measured by % reduction of area. From the large scale tests a relationship between maximum joint restraint and the minimum % RA to avoid lamellar tearing was determined.

2. Average restraint calculated on the top surface of large scale restraint tests agreed reasonably well with theory.

3. The cruciform tests in mode II (same steel load arms–test plate arms removed) can distinguish between steels showing gross and fine lamellar tears respectively in the restraint tests.

Acknowledgments

The authors wish to thank Esther Mar for helpful discussions and Kim Geike for experimental assistance. The research program was financially supported by the National Research Council of Canada, and thanks are due to Dominion Bridge Company, Limited for permission to publish this paper.

References

1. Farrar, J. C. M., and Dolby, R. E., "An Investigation into Lamellar Tearing," *Metal Construction and British Welding Journal*, 1, (1969) 2, p. 32.

2. Kanazawa, S., Yamato, K., Takeshi, Y., Inoue, T., Takeda, T., and Hashimoto, K., "On the Assessment of the Lamellar Tearing Susceptibility of Steel Plate," IIW Doc. IX-840-73.

3. Oates, R. P., and Stout, R. D., "A Quantitative Weldability Test for Susceptability to Lamellar Tearing," *Welding Journal* 52 (11) Nov. 1973, Research Suppl., 481-s to 491-s.

4. Satoh, K., and Matsui, S., "Reaction Stress and Weld Cracking under Hindered Contraction," IIW Doc. IX-574-68.

5. Satoh, K., Ueda, Y., and Matsui, S., "1972-1973 Literature Survey on Welding Stresses and Strains in Japan," IIW Doc. X-699-73.

6. Fujita, Y., Takeshi, Y. and Nomoto, T., "Studies on Restraint Intensity of Weld Cracking Specimens," IIW Doc. IX-627-69.

7. Mar, E., and Graville, B. A., "The Effects of Welding Procedure on Contraction and Reaction Stress in Multipass Welds," paper submitted for publication in Welding Research International.