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EXAMINATION OF FAILED END PIECE FROM A BAILEY BRIDGE PANEL

by

W. P. CAMPBELL

PHYSICAL METALLURGY DIVISION

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Mines Branch Investigation Report IR 64-34

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by

W. P. Campbell*

SUMMARY OF RESULTS

The two side channels of the end piece in a Bailey bridge panel failed by brittle fractures which were iniated at edges, ends, or cracks in the craters, of fillet welds. The presence of heat-affected zones having predominantly martensitic microstructures, particularly in combination with cracks, is concluded to have increased the tendency for the initiation of brittle fractures. Such defects resulted from the use of inadequate welding procedures during fabrication of the end piece. The steel in the channels had compositions and mechanical properties similar to the steel in the end piece which was examined previously(1), and was intended to conform to the B.S. 968-1941 specification. The steel did not have good weldability, and lacked adequate notch-ductility for service at low temperatures. The failure of this end piece was similar to that of the end piece examined previously(1).

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INTRODUCTION

In a letter dated December 10, 1963 (Ref. 31-2-66), Mr. N. E. Laycraft, Chief, Testing Laboratories, Department of Public Works, Ottawa, Ontario, requested that an examination be made to determine the cause of failure of a male end section of a Bailey bridge panel. The panel was installed in the 70 ft double single span at the south end of a three-span Bailey bridge over the Hyland River at Mile 65, Nahanni Pioneer Road, Y. T.

In December 1962, at an air temperature of -55°F, the north span of this bridge collapsed as a loaded ore truck passed over it. A fractured male end section from the bottom chord of one of the panels in the failed span was examined subsequently at the Physical Metallurgy Division. It was concluded(1) that the failure of that end section was due to brittle fractures originating at small heat-affected zone cracks which resulted from incorrect welding procedures.

The failed male end section in the south span, which did not collapse, was found during an inspection of the bridge after the collapse of the north span.

PROCEDURE

(1) The assembly was examined visually and photographs were taken of the assembly and fracture surfaces. The channels are identified as channel A and channel B respectively. It should be noted that the references to channels A and B in this report and in a previous report(1) are to different channel members.

(2) Paint was removed by means of a liquid paint remover and the assembly was examined by the fluorescent wet magnetic powder method.

(3) Chemical analyses were performed on drillings from the web of each channel.

(4) A tensile test was made on a specimen machined from the lower flange of each channel.

(5) Impact tests at several temperatures were made on 5 mm x 10 mm bars cut longitudinally from the web of each channel. The thickness of the web precluded the use of standard Charpy specimens. Each bar had a standard Charpy V-notch cut perpendicular to the surface of the web. At least two bars were broken at each temperature.

(6) Sections, removed from the locations shown in Figures 5 and 6, were examined microscopically. Two illustrative photomacrographs were taken. Sections, transverse to longitudinal crack indications on the outer surfaces of the webs of the channels, which were found by magnetic particle inspection (See Figure 2), were also examined microscopically.

(7) Hardness traverses were made across the weld deposit, heat-affected zones and into the unaffected base metal of sections A4 and B 4 (See Figures 5, 6, 7, and 8).

RESULTS AND DISCUSSION

The appearance of the fracture surfaces shows that all failures occurred without any significant plastic deformation and thus are classified as brittle fractures. The surfaces showed some chevron patterns which indicated that the fractures had initiated at or near the ends of the fillet welds joining the transverse connecting pieces to the web of each channel. These fracture surfaces were similar in appearance to those in the end piece which was examined previously(1), except that there was no evidence of pre-existing defects and the fracture paths were somewhat different.

In the end piece examined previously(1), the lower fracture started at or close to the edges of the weld crater of the outer lower fillet welds. It is evident from Figures 5 and 6 that failures could readily have started from similar locations in the second end piece, although at the starting points rather than at the termination points of welds. However, only secondary fractures were initiated at these weld starting points. In channel B, the crack did not extend more than about 3/4 in. downward into the web (See location of section B2 in Figure 5). In channel A, the crack ran at an angle until it intersected the main fracture (See Figure 6). The joining of the secondary and primary fractures, and the failure of a portion of the fillet weld which crossed the end of the connecting piece (See Figure 3), resulted in the loss of a small triangular shaped piece of metal.

It can be concluded that, on the lower side of the channels in the second end piece, the preferred primary fracture paths were along the toes of the inner fillet welds, as they crossed the end of the connecting plate. This is particularly evident in Figures 3, 4, and 8 for channel B. The exact location of the primary fracture path is less evident in channel A because of the loss of the small triangular shaped piece of metal. However, in Figure 3 it can be seen that at least a portion of the primary fracture was close to the junction of the end fillet weld with the inner surface of the web of channel A. Also, the sections A3 and A4 (See Figures 6 and 7) showed only a small remnant of the fillet weld on the part of the channel located on the left side of Figure 6. In addition, a comparison of Figures 5 and 6 illustrates the similarity of the primary lower fracture paths in both channels.

An examination of Figures 5 and 6 shows that the upper fracture paths were similar to each other. The initiating point of fracture in channel A was at or very close to the edge of the weld crater at the termination of the outer fillet weld. The upper fracture in channel B started at a crack in the weld crater at the termination of the corresponding weld. In Figure 2, it can be seen that the fillet welds, between the inner surfaces of the channel webs and the upper surface of the connecting plate, were fractured along the weld throats over a distance of about 1/2 to 3/4 in. between the upper fractures in the webs and the end of the connecting plate. Fractures also occurred through the weld deposits made around the end of the upper connecting plates; as illustrated in Figure 4. The shearing through the throats of these welds must have occurred after the brittle fractures in the channels. After the end piece was completely severed, the two portions had been held closely together by the rigidity of the span, although some longitudinal movement must have occurred subsequently. The longitudinal shear fractures in the upper, inner fillet welds (Figure 2) had been polished, and there was some evidence of battering at a few points on the fractured surfaces.

The magnetic particle examination of the end piece, after removal of paint, did not reveal any cracks associated with the welds other than those at the locations of the B1 and B2 microsections (See Figure 5). These cracks had been evident on visual examination, although the crack at the B2 location was made more prominent by the magnetic particle examination. Four cracks of lengths from 1/2 to 1 in. were found on the outer surface of channel B at about the longitudinal centre line (See Figure 2). One short crack was found extending from the flame cut slot at the longitudinal centre line of channel A. None of the cracks which intersected the flame cut slot or the fracture were found by magnetic particle examination to extend through the thickness. Sections, cut transversely to cracks in each channel, showed that the cracks were not more than about 1/32 in. in depth, and were associated with an accumulation of non-metallic inclusions. These must have occurred during the manufacture of the channels. The cracks played no part in the failure of the end piece.

The results of chemical analyses of drillings from each channel are compared in Table 1 with the requirements of two British Standards Institution specifications.

TABLE 1

Chemical Composition

	Element, Per Cent*						
	C	Mn	Si	S	P	Cr	Ni
Channel A	0.27	1.70	0.16	0.047	0.053	0.09	0.06
Channel B	0.25	1.70	0.15	0.053	0.056	0.09	0.06
BS 968-1941**	0.23 max	1.8 max	0.35 max	0.06 max	0.06 max	1.0 max	0.5 max
BS 968-1962***	0.20 max	1.50 max	0.35 max	0.05 max	0.05 max	0.50 max	-

*Internal Report MS-AC-64-267 (Mineral Sciences Division).

**War Emergency British Standard Specification for High Tensile (Fusion Welding Quality) Structural Steel for Bridges, etc., and General Building Construction, June 1941.

***Specification for High Yield Stress (Welding Quality) Structural Steel, April 1962.

The composition of both channels met the requirements of BS 968-1941 except for the carbon contents which were in excess of the maximum specified. Both the carbon and the manganese levels of the channels were considerably in excess of the limits of BS 968-1962, a more weldable grade which superseded the earlier BS 968 specification. The sulphur and phosphorous contents of the channels were slightly in excess of the limits of BS 968-1962. The compositions of the steel in the channels were similar to those in the end piece examined previously(1).

Tensile test results of steel from each channel are compared in Table 2 with the requirements of BS 968-1941.

TABLE 2

Tensile Test Results

	UTS Kpsi	YS** Kpsi	% El***
Channel A	93.6	65.0	27.5
Channel B	93.4	59.2	27.5
BS 968-1941	78.3-91.8	47.0 min	14 min

* From Internal Report PM-T-1045 (Mechanical Testing Section, Physical Metallurgy Division).

** The yield strength of steel from the channels was determined at 0.2% offset; BS 968-1941 requirements are based on the drop-of-the-beam method.

***The per cent elongation of steel from the channels was determined in a 2 in. gauge length, BS 968-1941 requirements are for an 8 in. gauge length.

The ultimate tensile strength values for both channels were slightly above the maximum specified in BS 968. A direct comparison of the yield strength and elongation values obtained for the channels cannot be made with the specification requirements, but it can be concluded that the values obtained indicate adequate tensile properties. Similar tensile values were obtained for the steel from the channels in the end piece examined previously, although the elongation values were slightly lower in the first sample. The results of impact testing of 5 mm x 10 mm Charpy V-notch bars are given in Table 3.

TABLE 3

Results* of Charpy V-notch Impact Tests

Temperature °F	Channel A		Channel B	
	Values Obtained ft-lb	Ave. ft-lb	Values Obtained ft-lb	Ave. ft-lb
140	40, 38	39	26, 40, 39	35
100	40, 36, 34	37	15, 35, 38	29
76	30, 20, 18	23	10, 36, 8	18
32	8, 12, 14	11	16, 14	15
0	1, 2	1.5	4, 12, 4	7
-55	No tests done		1, 8	4.5

These results indicate that the notch ductility of both channels is quite low at temperatures below about 32,F and is of questionable adequacy even at temperatures intermediate between 32°F and 76°F. This is also indicated by the appearance of the fracture surfaces of the impact specimens. For specimens from both channels, it was estimated that test temperatures of 76°F to 100°F, but closer to 76°F, corresponded to fractures having about the same ratio of crystalline to fibrous appearance. The temperature corresponding to a 1:1 ratio of crystalline to fibrous appearance has been used by some investigators as a guide to the suitability of steel for service where assurance against brittle fracture is desired. It should be noted that the impact testing of steel from the channels of the end piece, examined previously(1), also showed a low order of notch ductility at the lower test temperatures.

Most of the sections removed from the locations illustrated in Figures 5 and 6 were found by microscopic examination to have predominantly martensitic heat-affected zones. Heat-affected zone cracking was detected only in sections A4, B3, and B4. The microstructure and cracking were similar to that found in the end piece examined previously(1) and one of the photomicrographs shown in that report is reproduced in Figure 9 to illustrate the same features in the second end piece. The microstructure of the channels, in areas unaffected by welding, was similar to that in the first end piece shown in Figure 16 of the previous report(1).

Reference was made previously to the crack at the location of the B2 section (See Figure 5). If failure had occurred at this location, the lower fracture would have been almost identical to that found in channel B of the first end piece (See Figure 4 of the previous report(1)). Microscopic examination indicated that the crack was a brittle fracture which had been initiated at or near the start of the outer fillet weld in the martensitic heat-affected zone.

Hardness values, obtained in a traverse across section B4 (Figure 8), were 95 to 98 Rockwell B in the weld deposit, 97 Rockwell B to 21 Rockwell C in the unaffected base metal, and 34 to 50 Rockwell C in the heat-affected zone. In section A4 (Figure 7), hardness was 21 to 29 Rockwell C in the weld metal, 97 Rockwell B to 21 Rockwell C in the unaffected base metal, and 32 to 52 Rockwell C in the heat-affected zones. The higher hardness values of the weld deposit and heat-affected zone in section A4 were due to the much thinner deposit which had cooled more rapidly than the larger deposit in section B4. The maximum hardness values were obtained in the coarse-grained martensite of the heat-affected zones close to the weld fusion lines.

It is evident that the welding procedures, like those used in the fabrication of the first end piece(1), were inadequate and resulted in brittle martensitic zones and heat-affected zone cracking. The composition of the steel is such that considerable care must be taken to avoid such defects. Even if the welding procedure had been capable of eliminating heat-affected zone cracks, it cannot be concluded that brittle failure would not be initiated by brittle martensitic heat-affected zones. It is quite possible that the stress concentration at the toes of fillet welds could be sufficient to initiate brittle failures in this steel at low ambient temperatures even in the absence of brittle martensitic heat-affected zones. Weld metal defects, such as the crater crack in the upper fillet of channel B (See Figure 5) can initiate brittle fractures at low temperatures. In fact, any notch, such as provided in an irregularly made flame-cut surface, might initiate fractures in this steel under severe conditions of service.

Defects such as brittle heat-affected zones, and cracks in the heat-affected zones or weld deposits, can be avoided by using proper welding techniques. The notch effect at the toes of fillet welds can be reduced by avoiding abrupt transitions. However, even if great care is taken during welding, there will still be stress concentration at the terminations of welds. Therefore, in order to have greater assurance that brittle fractures will not occur, particularly under low temperature conditions, it would be logical to select a steel having very much better notch-ductility than the steel which was used in the channels of the two end pieces.

The non-mandatory clause in the B.S. 968:1962 specification states that by special agreement between the manufacturer and purchaser, plates may be supplied to a Charpy V-notch requirement. The requirement, for standard 10 mm x 10 mm Charpy bars cut along the principal direction of rolling and with the notch perpendicular to the plate surface of the thickest plate involved, is an average of 20 ft-lb at -5°F for three tests, with no single value less than 15 ft-lb. It is possible that an agreement might also be reached for the channel members. Allowance would have to be made for the fact that sub-size impact specimens would have to be used due to the thickness of the channel. An average value of 20 ft-lb at -5°F is somewhat reassuring in comparison to the values indicated from tests on the steel in the channels of the two end pieces. However, it is considered that this requirement is still inadequate for critical members in service at temperatures as low as -55°F. Undoubtedly, the requirement in B.S. 968:1962 is a reflection of the fact that temperatures, thought of in the U.K. as being low, are much higher than those which occur commonly in many parts of Canada.

Some improvement in notch ductility would be obtained if the channels were made from steel conforming to the CSA G40.8-1960 specification "Structural Steels With Improved Resistance to Brittle Fracture". Although the specification does not specify impact requirements, certain expected values are quoted in an Appendix. Grade C is expected to have an average Charpy V-notch value of 15 ft-lb at -25°F for standard size impact specimens and "a proportionately lower value for sub-size specimens". This would indicate an expected value of about 8 ft-lb at -25°F for 5 mm x 10 mm specimens. These values indicate an improvement in notch ductility as compared to the steel in the two end pieces, but still better notch ductility would be desirable for critical applications at low temperatures. A definite increase in the size of structural members would be required if panels were made from steel conforming to the G40.8 Grade C specification rather than the B.S. 968 specification. For steel of thickness up to and including 5/8 in., the G40.8 steel has a minimum yield strength of 40,000 psi and an ultimate strength of 65,000 to 85,000 psi. For the same thickness range, B.S. 968:1962 steel has a minimum yield stress of 51,500 psi, and an ultimate tensile strength of 71,700 to 87,400 psi. The G40.8 Grade C steel would be expected to have better weldability than the B.S. 968:1962 steel.

Consideration should be given to manufacturing the panels using channels made from steel conforming to a specification such as ASTM A441. This steel has a minimum tensile strength of 70,000 psi and a minimum yield point of 50,000 psi, in thicknesses up to and including 3/4 in. The specification limits the composition to ensure good weldability. A bulletin, supplied by The Steel Company of Canada, states that the steel made to this specification by this company would be expected to have a Charpy V-notch impact value of 15 ft-lb at a maximum temperature of -20°F. This value would be expected on samples cut from 1 inch plates and in the longitudinal direction of rolling. This suggests that even better notch ductility would be obtained on lighter members, such as channels of the size required in the Bailey bridge panel. The same company also supplies a steel, called Stelcoloy S, which conforms to ASTM specification A242. This specification has the same limits on mechanical properties as does ASTM A441, but the chemical composition is not closely controlled by the specification. However, the manufacturer states(2) that Stelcoloy S will be supplied to certain definite composition limits, and these limits indicate that the steel should have good weldability. The expected minimum Charpy V-notch impact value, on specimens cut from 1 in. plates and in the longitudinal direction of rolling, is stated(2) to be 15 ft-lb at -50°F. Again, it would be expected that even better notch ductility would be obtained on lighter members. If the channels used in Bailey bridge panels were made from steel such as ASTM A441 or Stelcoloy S, then the sections could be of the same size as those which are required with steel to the B.S. 968 specification.

It is suggested that the use, in Bailey bridge panels, of quenched and tempered high strength steels, such as exemplified by the "T-1" grade developed by the United States Steel Corporation, would be worthy of consideration. For the "T-1" grade, the minimum yield strength is 100,000 psi, the tensile strength is 115,000 to 140,000 psi, and for shapes having web thicknesses over 1/2 in., a minimum longitudinal Charpy V-notch value of 15 ft-lb at -50°F may be specified. Modified impact values may be negotiated for shapes with web thickness under 1/2 in. This type of steel may be welded satisfactorily without the necessity for arduous precautions. Due to the high strength levels, some reduction in the sizes of sections should be possible.

In the above suggestions, reference has been made to illustrative proprietary steels because the specification bodies have not yet produced specifications which are sufficiently comprehensive to indicate all the properties of such steels. It must be pointed out that other steel manufacturers, in addition to those mentioned, should be able to supply equivalent steels.

CONCLUSIONS

(1) Brittle fractures were initiated in the channels at points of stress concentration provided by the junctions, with the inner surfaces of the channel, of the two fillet welds around the ends of the lower connecting plate. Brittle fractures were also initiated in the channels by crater cracks or weld terminations of the outer fillet welds joining the upper connecting plate to the channels. The presence of predominantly martensitic microstructures, especially in conjunction with cracks, in the weld heat-affected zones, increased significantly the tendency for the initiation of brittle fractures.

(2) The failure of the second end piece was similar to that of the end piece which was examined previously.

(3) Inadequate welding procedures had been used in fabricating the end piece. As in the end piece which was examined previously, predominantly martensitic microstructures and cracking were found in weld heat-affected zones.

(4) The evidence of inadequate welding procedures in the two end pieces examined to date, suggests that brittle microstructures and cracks in weld heat-affected zones may be quite prevalent in Bailey bridge panels fabricated from steel to the BS 968:1941 specification. Much greater care than is normally taken in welding structural steels would be required to ensure that such defects are avoided.

(5) The compositions and the tensile properties of steel from the channels were similar to those obtained in the end piece examined previously and indicate that the steel was intended to conform to the BS 968:1941 specification.

(6) Impact tests showed that the steel in the channels, as in the end piece examined previously, had inferior notch ductility for a structure operating under low temperature conditions.

(7) If assurance against brittle fracture is required, Bailey bridge panels for use under winter conditions should be made from steel having substantially better weldability and notch-ductility than that of steel to the BS 968:1941 specification. In addition, reasonable precautions should be taken during welding to avoid points of stress concentration that are caused by weld crater cracks or abrupt transitions between welds and the members being joined.

REFERENCES

1. "Examination of Failed Section from a Bailey Bridge Panel" - Mines Branch Investigation Report IR 63-42 (April 19, 1963).
2. "Selection and Use of Stelco Structural Steels" - publ. by The Steel Company of Canada Limited (October, 1962).

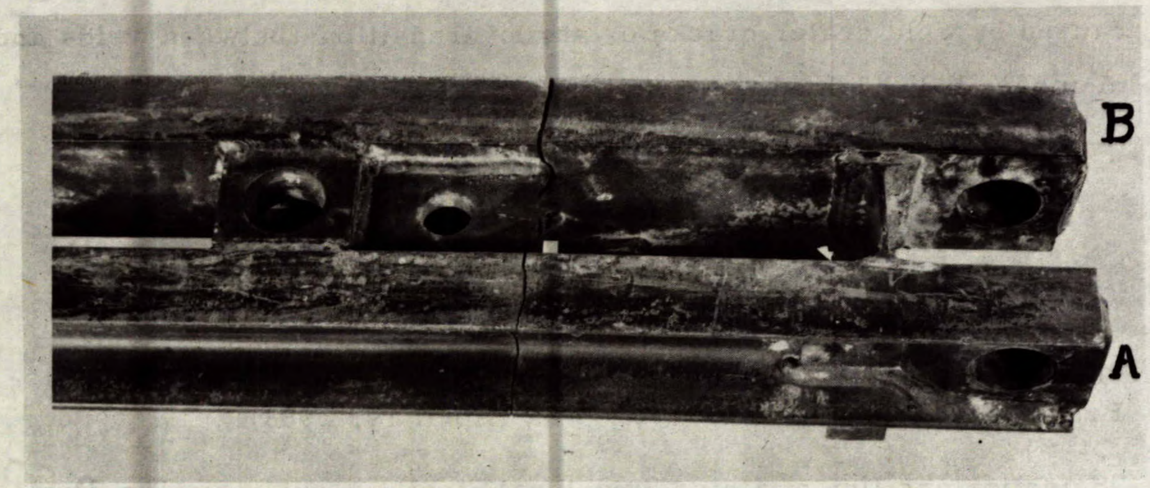

Figure 1 - View from the under side of the fractured end piece, with channel A at the bottom and channel B at the top of the picture.

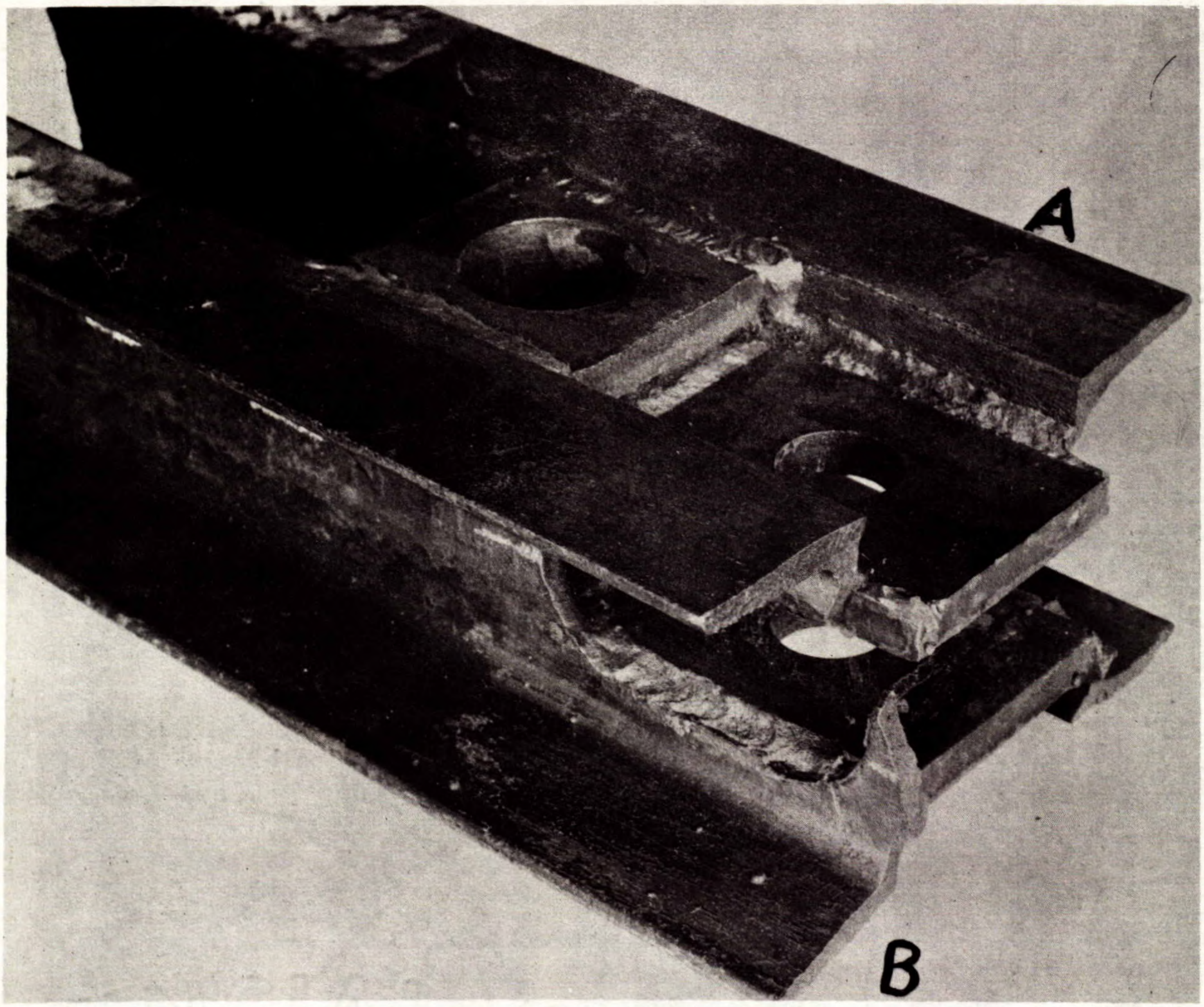

Figure 2 - View of one part of the fractured end piece. White marks indicate cracks located by magnetic particle examination. These include, in channel B, a crack running across the lower weld near its starting point and down into the web, and four short cracks on the outer surface of the web approximately along the centre line. None of these cracks played any part in the failure. About 1/2 scale.

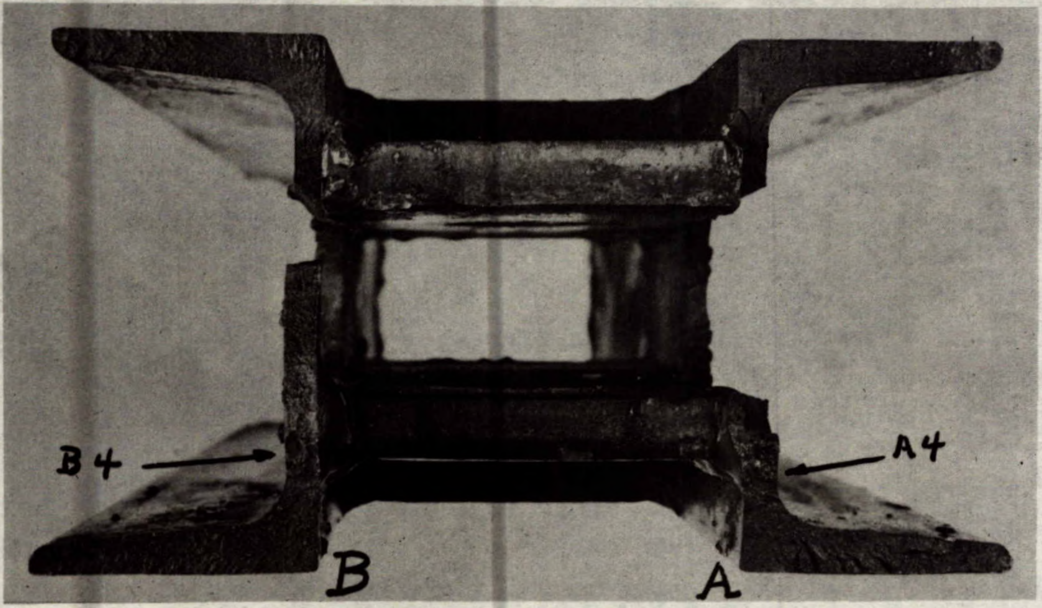

Figure 3 - View of the fractured surfaces in the two channels and showing also the locations of sections A4 and B4 which were subsequently removed for examination.
About 3/4 scale.

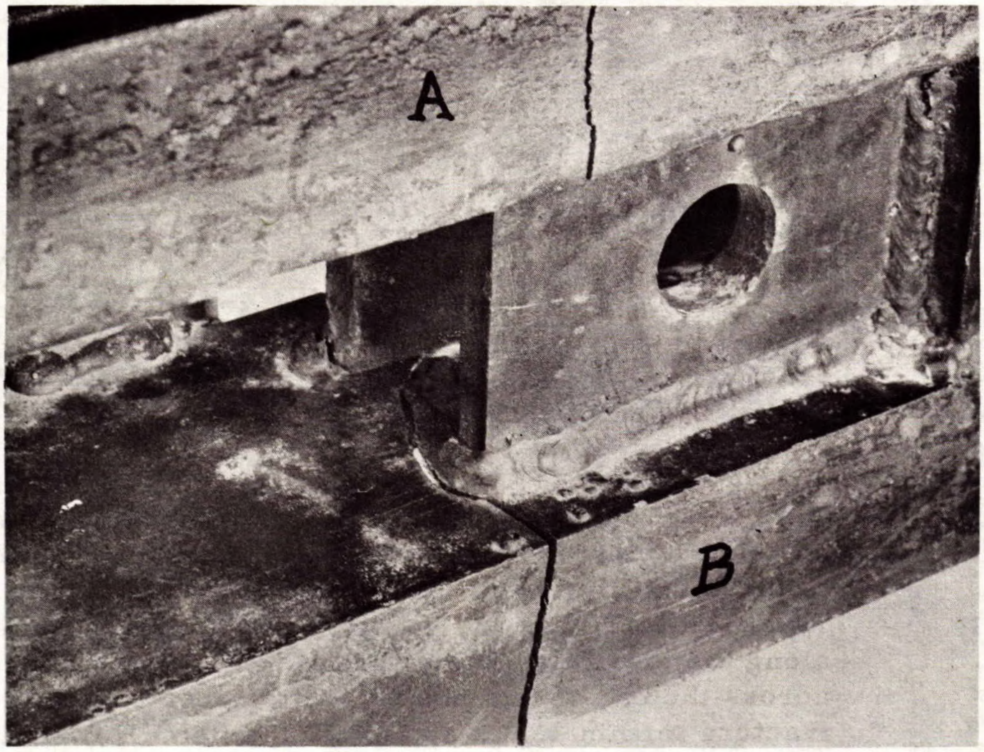

Figure 4 - Showing the lower fracture path in channel B, looking from the bottom side. Note that the fracture path follows along the toe of the fillet weld made around the end of the central connecting plate joining it to the inner surface of the channel.

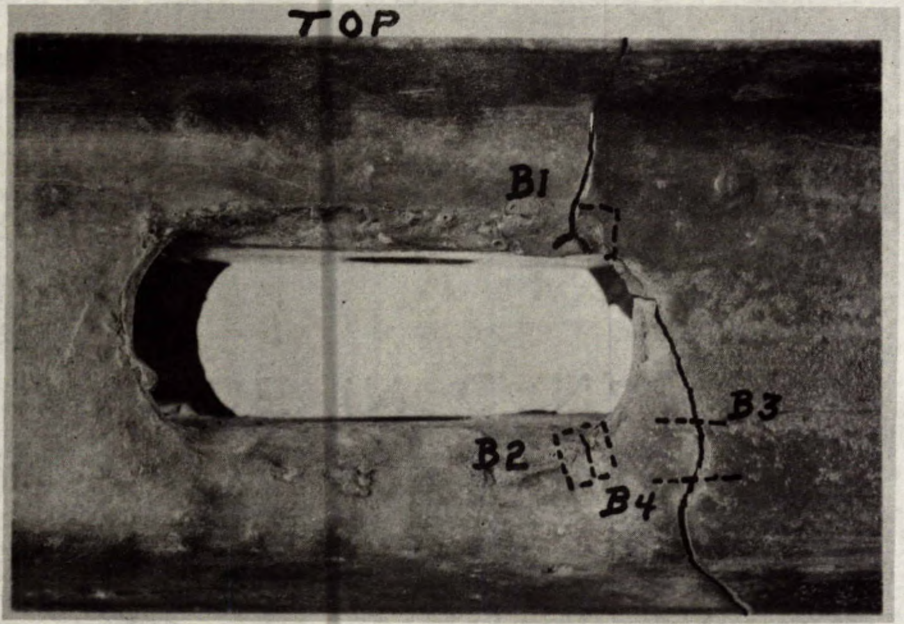

Figure 5 - Side view looking at channel B with top side of channel at top of picture. The lower fracture path is not related to the outer fillet weld joining the lower connecting plate. As shown in Figures 3, 4, and 8, the fracture runs along the toe of the inner fillet weld which was made across the end of this plate. At its upper end, this fracture terminates at a notch in the flame cut slot. Although not involved in the failure, a crack, starting close to the right hand end of the outer lower fillet weld (actually the starting end of the weld), runs across the weld and about 3/4 in. downward into the web. This crack was faintly visible on the sample as received, as a result of rust staining. It was much more evident on magnetic particle examination after removal of the paint.

The upper fracture travels through the centre of the weld crater at the end of the outer fillet weld and then travels roughly straight upward through the web and flange. A crater crack, joining with the fracture was detected by magnetic particle inspection. This crack most probably initiated the upper fracture.

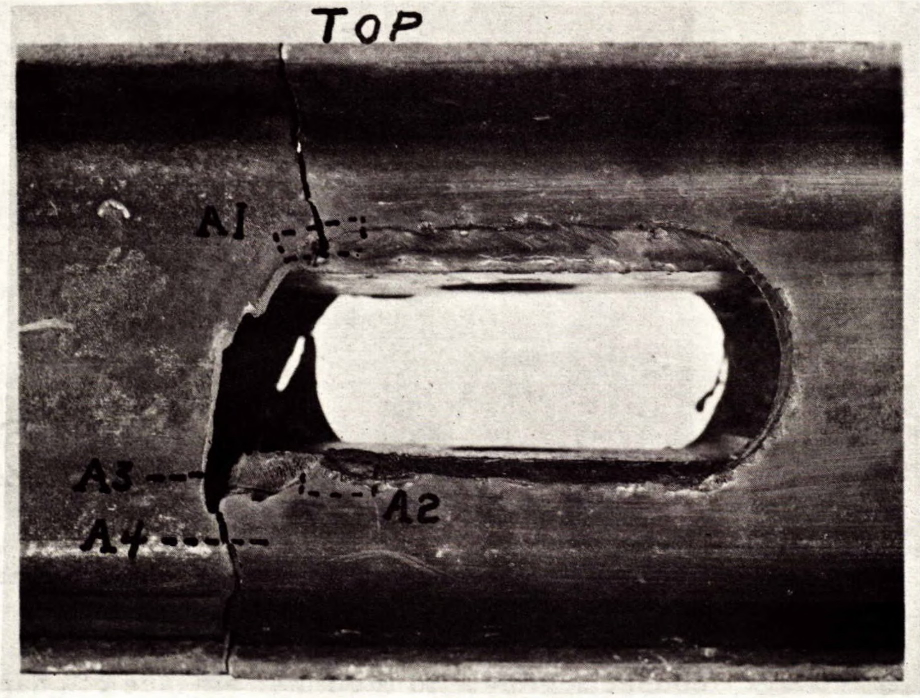

Figure 6 - Side view looking at channel A with top side of channel at top of picture. The lower fracture followed a path similar to that in channel B, but in addition a secondary fracture ran from close to the edge of the starting point of the lower weld out to the main fracture. Thus, a triangular shaped piece of metal from the web is missing. The upper fracture travels along the edge of the weld crater at the termination of the outer fillet weld and then almost straight upward through the channel web and flange.

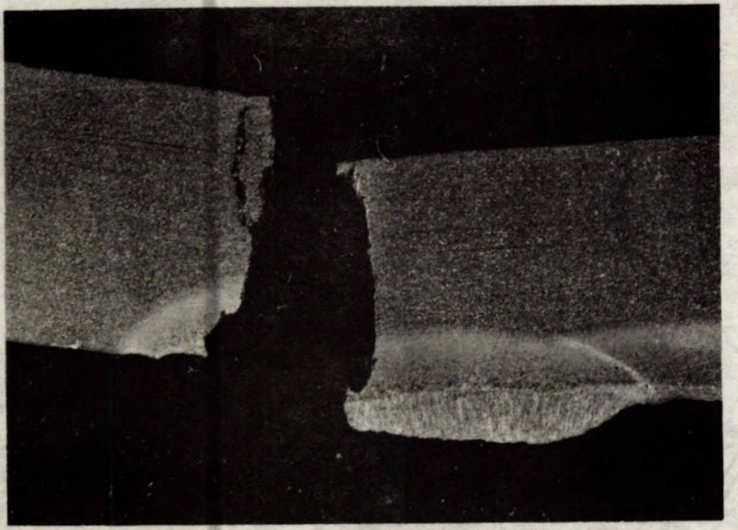

Figure 7 - Section A4 (See Figures 3 and 6) showing that the lower fracture in channel A was at or very close to the toe of the fillet weld joining the connecting plate to the inner surface of channel A. The section was taken close to the termination of this weld.
Etched 2% Nital. X6

Figure 8 - Section B4 (See Figures 3 and 5) showing path of fracture close to the toe of the fillet weld joining the connecting plate (lower left) to the inner surface of channel B.
Etched 2% Nital. X6

Figure 9 - Illustrating the predominantly martensitic microstructure close to the fusion line of most of the welds, and heat-affected zone cracks found in some of the sections. Weld metal is at top.
Etched 2% Nital. X250.

None of the samples, alone, is considered suitable for the manufacture of facing brick, the plastic properties and/or firing characteristics being unsatisfactory. The majority of the samples are of low plasticity and dilatant nature, and require the addition of a plasticizer and binder. Additions of grog or some similar material would be useful to extend the firing range and decrease the firing shrinkage.

Mixtures of clay and rock tailings, containing 30 to 50 per cent rock and plasticized with swelling bentonite, have suitable forming properties for use in the manufacture of facing brick; power requirements are about normal, the structure and appearance of the product good, and the strength adequate, although not high. Lignosulphonate plasticizers do not appear to contribute substantially to green strength or to reduce dilatancy: very small amounts may be useful for dispersing the bentonite, which should be added as a slurry with part of the pugging water.

The mixtures can be dried rapidly without cracking, and have low drying shrinkages (2 to 3 per cent).

The firing ranges of the mixtures vary from 70 to 85°F, sufficiently wide for normal tunnel-kiln control. The longer firing ranges are associated with the larger rock additions. These also result in increased mean firing temperatures, all of which are cone 02 plus, about one cone higher than normal to the industry. Increased additions of bentonite might lower firing temperatures and further improve extrusion and increase green strength - additions of more than 3 to 4 per cent would possibly introduce drying problems.

The high firing shrinkages of the mixtures, from about 6 to 9 per cent in all cases, occur almost wholly during the latter stages of firing. Great care would be required in control of temperatures and heat distribution throughout the hot zone of the kiln, to prevent excessive losses and wrecked car-settings. Certain modifications in the kiln design would probably be helpful: recirculation in the preheat zone would allow the hot zone to be extended so that the rate of temperature increase could be slowed during the critical stages; under-car firing (perhaps in conjunction with burners firing downwards from the crown) would help prevent local hot-spots; and setting patterns designed to promote uniform gas flow throughout the setting would assist in obtaining uniform temperatures over the cross-section of the setting.

KEB:dg