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Fatigue Monitoring on an Ore Unloader

Contrôle de la fatigue d'un déchargeur de minerai

Ermüdungsüberwachung an einer Erzentladeanlage

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SUMMARY

A structural fatigue monitoring system has been installed on an ore unloader. The outputs from 96 strain-gauge channels are recorded, and loads, bending moments and principal stresses calculated in real time. The load and stress cycles are analysed by a beak-valley method and counted in matrices of mean-amplitude. Typical matrices are presented together with analogue traces for stay load. Cracks in brackets connecting the control cabin runway structure to the boom occurred in service. Strain gauges were used to determine the cause of failure and verify the adequacy of the repairs.

RESUME

Un système de contrôle de la fatigue a été installé sur un déchargeur de minerai. Les signaux provenant de 96 jauges de déformations relatives sont enregistrés et les charges, les moments de flexion ainsi que les contraintes principales sont calculées en temps réel. Les cycles de charges et de contraintes sont analysés par une méthode de comptage des valeurs extrêmes dans des matrices valeur moyenne-amplitude. Des exemples de matrices sont présentés avec les enregistrements correspondants pour la charge des haubans. Des fissures sont apparues en service dans les bras reliant la cabine de contrôle de la structure roulante aux membrures. Des jauges de déformation furent utilisées pour déterminer la cause de la rupture et contrôler la réparation.

ZUSAMMENFASSUNG

An einer Erzentladeanlage wurden Ermüdungsschäden untersucht. Messwerte von 96 Dehnmessstreifen wurden aufgenommen und damit die Belastungen, Biegemomente und Hauptspannungen in Echtzeit berechnet. Die Belastungen und Spannungsamplituden wurden mit Hilfe einer Scheitelwertmethode ermittelt und gemittelt in Matrizenform erfasst. Typische Matrizen sowie analoge Registrierkurven für stetige Belastungen werden wiedergegeben. Risse in Verbindungsgliedern zwischen Steuerkabine, Fahrbahnteil und Ladebaum traten während des Betriebes auf. Mit Dehnmessstreiffen wurde die Schadenursache abgeklärt und die Richtigkeit der veranlassten Reparaturmassnahmen bestätigt.

1. INTRODUCTION

In June 1979 a new deep water terminal was commissioned at British Steel Corporation's Hunterston site on the west coast of Scotland. Ships of up to 350,000 tonnes dwt can be accepted, and the terminal is served by two unloaders (figure 1). These are the largest of their kind in the UK, and are predominantly of welded stiffened steel box-girder construction. The horizontal main booms are 54m long with hinges at the front legs, and are supported by four stays (or ties) of hot-rolled H section.

The twin boxes which form the boom are 1600 mm deep and 970 mm wide, with an inter-connecting box girder carrying the racking pulleys at the extremity. The rails for the main trolley are located over the inner webs of the boxes, and the maximum outreach for the trolley and grab is 48m from the front leg.

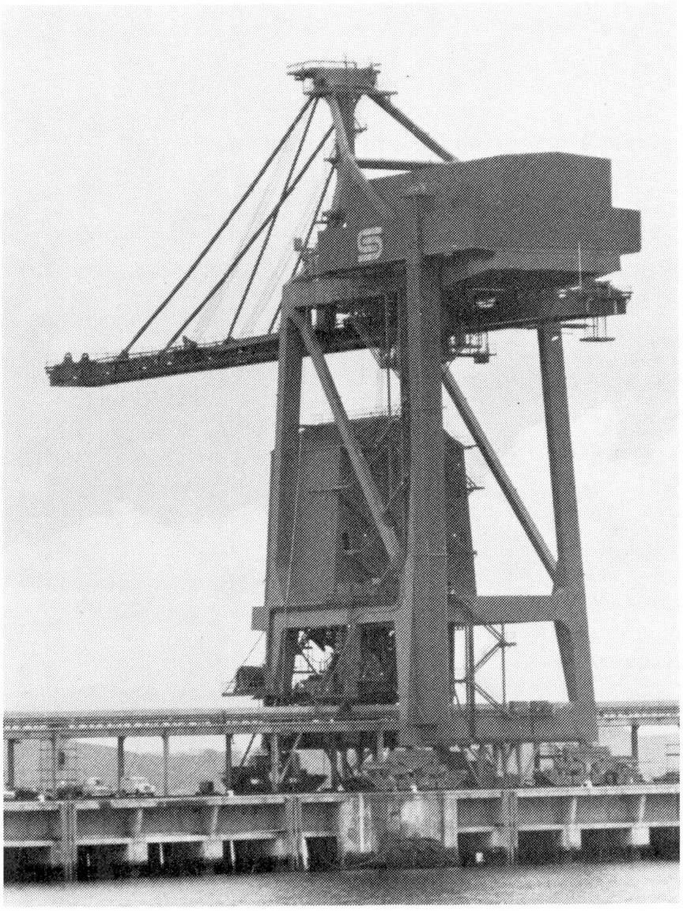


Fig. 1 Ore Unloader at Hunterston

The grab design payload when unloading iron ore is 37.7 tonnes, and for unloading coal it is 22.4 tonnes, a different design of grab being used for the two materials.

2. STATIC LOAD AND STRESS MEASUREMENT

During the construction period of the unloaders some design checks were carried out on the main structural members, and a programme of static loading tests was commissioned. Some 240 strain gauges were attached to various parts of the box girder boom structure on one unloader, together with gauges on each of the four stay members at the lower end adjacent to the hinge connection to the boom. The gauges on the boom flanges and webs were mostly of the 45° rosette type. The gauges on the stay members were arranged to measure the axial load and bending moment about the major axis. For one outer and one inner stay, additional gauges were attached to the flange edges to measure minor axis bending moment. Static measurements were made with the main trolley and grab located at a number of positions along the boom, the zero condition for the gauges being recorded with the booms in the fully raised position. A finite element analysis of the boom structure was also commissioned to enable the comparison to be made of the measured stresses and stay forces, with those predicted by linear elastic analysis.

3. FATIGUE MONITORING SYSTEM

A comprehensive microprocessor based Fault Diagnostic System (FDS) designed and built by SCOMAGG Ltd. (Motherwell) was installed at the site. Each major piece of plant is instrumented and the signals are continuously monitored. The structural monitoring system for the unloader comprises four microprocessor controlled remote outstation units interfacing directly with 96 strain gauges. These are connected via a high speed serial data link to the instation where a DEC PDP 11/34 computer provides long term data storage, report printing and programme modification facilities. The functions of the system are:-

- continuous scanning of all strain gauge channels;
- real time calculation of loads, stresses etc. and further data reduction to provide fatigue information;
- printing of fatigue data at nominated intervals or as summaries of longer periods;
- alarm monitoring on all inputs and strain-gauge failure detection;
- automatic checking on calibration and drift.

3.1 Remote Unit Functions

Each remote unit performs required calculations on the inputs from single gauges, orthogonal pairs or rosettes in any combination,the results being expressed as load, stress, or bending moment. An example is the calculation of the cyclic load in the north inner stay of the unloader from strains recorded at four points on the flanges and web of the H section member as follows:-
(see figure 2)

$$\text{Stay Axial Load} = E\left\{ (\varepsilon_9 + \varepsilon_{11})\ A_f + \frac{(\varepsilon_{10} + \varepsilon_{12})}{2}\ A_w \right\} \quad \text{KN}$$

For the orthogonal strain gauge pairs on the boom flange the longitudinal direct stress is calculated as follows:-

$$\sigma_x = E\left\{(\varepsilon_x + \nu\varepsilon_y) \div (1 - \nu^2)\right\}$$

and for the strain gauge rosettes the principal stresses and maximum shear stress are calculated from:-

$$\begin{matrix}\sigma_1 \\ \sigma_2\end{matrix} = \frac{E}{2}\left\{ \frac{\varepsilon_x + \varepsilon_y}{1 - \nu} \pm \frac{1}{(1 + \nu)} \sqrt{(\varepsilon_x - \varepsilon_y)^2 + (2\ \varepsilon_g - \varepsilon_x - \varepsilon_y)^2} \right\}$$

where ε_x, ε_g and ε_y are the measured strains at 0°, 45° and 90°

$$\tau_{max} = \frac{1}{2}\ (\sigma_1 - \sigma_2)$$

Sample and hold hardware is incorporated to ensure that all strains are read simultaneously. Detection of peaks and troughs in the values resulting from calculation of for example a varying stress, is followed by calculation of positive or negative going amplitude and mean stress values which are in turn stored as a count in a two-dimensional matrix assigned for the purpose. A matrix element is incremented each time a stress half cycle is completed, eventually producing an amplitude/mean count distribution.

The remote units are programmed to recognise and report on alarm conditions when the input from any gauge exceeds 750 $\mu\varepsilon$. In this event, simultaneous strains from all 96 gauges are recorded and printed. Peak strains occurring in the period of the alarm are recorded and printed on termination when strain in the channel in question has fallen below the alarm threshold. An excessively high (> 1500 με) input persisting beyond a specific minimum time is taken to indicate a defective strain-gauge. At regular intervals, the remote boxes perform a self-checking procedure and print the output of each channel in the de-exited condition and then with a shunt calibration resistor connected. The outputs from four channels connected to standard reference strain signals are also reported.

3.2 Structural Monitoring Function of the Instation Computer

Count matrix parameters and operating instructions held in the memory in the remote units are altered by instructions transmitted from the instation computer. Amplitude and mean ranges and scale values for up to ten matrix types may be defined and specific matrix types allocated to store the results of particular calculations. Minimum amplitude thresholds may also be specified and the remote units instructed to consider only positive going, only negative going, or alternate positive/negative going half cycles when monitoring the results of calculations. Reporting intervals may be selected within the range 1 to 51 hours.

Printing of matrices at the end of each report period can be enabled or disabled, or they can be printed on demand if required. A summary containing all data collected since the previous reset of the summary file may be printed on request.

4. DYNAMIC ANALOGUE RECORDS

To check that the gauges were functioning and also show the signal characteristics, some dynamic records were made during operation. The gauges on the four stays were recorded in turn. The gauges on the stays are positioned as in figure 2. In the case of the south boom stays, two more were added to measure lateral bending stresses. A typical record for the north boom inner stay is

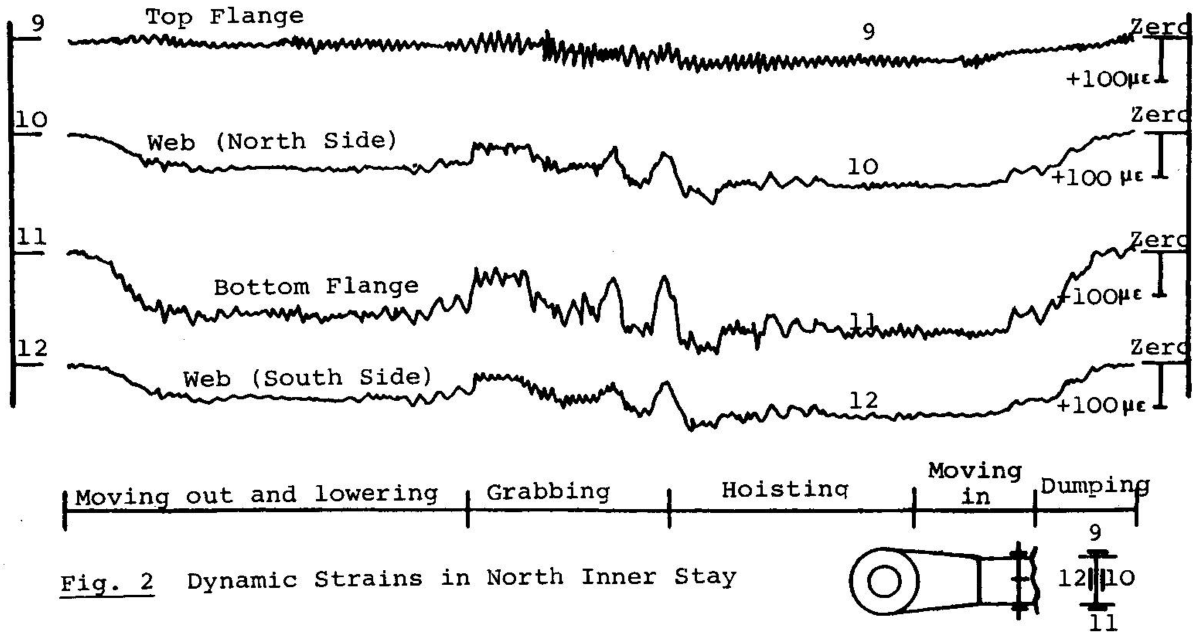


Fig. 2 Dynamic Strains in North Inner Stay

shown in figure 2. The cycle commences when the empty grab moves out along the boom, during which time the stay load steadily increases. The grab is lowered into the hold, and finally comes into contact with the ore in the ship. Two or three loading cycles occur as the grab bites into the ore and collects the payload. Hoisting then begins and the load in the stays remains fairly steady. As the grab and trolley move inwards to the hopper to deposit the payload, the stay load gradually reduces.

There are oscillations of small amplitude superimposed on the live load cycles, which are due to natural frequency vibrations of the booms and stays themselves.

The strain-gauged sections are 1 m from the hinge pin, and therefore bending strains can be due to vertical vibrations of the stays themselves. Some friction in the hinges was observed, however, in measurements taken during raising and lowering of the booms which gave stay flange stresses of ±10 N/mm^2 approximately. It is interesting to note that for gauge 9, the axial load strain is cancelled by the bending (compressive) strain most of the time.

On the south boom stays, the lateral B.M. gauges indicated the presence of an almost continuous oscillation at 2 Hz, the rate of

Tonnage Unloaded = 27,000 t

Mean (KN)	75	150	225	300	375	450	525	600	675	750	825	900
600 – 400	0	0	0	0	0	0	0	0	1	2	0	0
400 – 200	1726	2146	592	86	13	4	4	1	1	1	1	0
200 – 0	43020	16992	1925	315	58	8	2	0	0	0	0	0
0 – -200	18585	4524	152	8	1	2	1	3	0	0	0	0
-200 – -400	0	0	0	30	1	0	0	1	3	0	5	1
-400 – -600	26	1	0	0	0	0	0	0	0	0	0	1

Amplitude (KN)

TABLE 1 South Outer Stay Load

Tonnage Unloaded = 27,000 t

Mean (KN-m)	10	20	30	40	50	60	70	80	90	100	110	120
20 – 10	0	0	1	0	0	0	0	0	0	0	0	0
10 – 0	41674	16796	2110	495	71	16	4	0	0	0	0	0
0 – -10	13730	7872	1805	570	103	32	3	2	1	0	2	0
-10 – -20	1	0	0	1	0	0	0	0	0	0	0	0

Amplitude (KN-m)

TABLE 2 South Outer Stay Lateral B.M.

Tonnage Unloaded = 27,000 t

Mean (N/mm^2)	5	10	15	20	25	30	35	40	45	50	55	60
40 – 20	33	236	52	14	1	0	0	1	3	3	0	0
20 – 0	304	6047	987	93	15	3	0	0	0	0	0	0
0 – -20	21	791	170	6	0	0	1	0	0	0	0	0

Amplitude (N/mm^2)

TABLE 3 Boom Top Flange Longitudinal Stress (σ_x) (South Inner Stay)

Tonnage Unloaded = 109,000 t

Mean (N/mm^2)	5	10	15	20	25	30	35	40	45	50	55	60
60 – 40	258	1260	1112	594	239	55	20	15	0	5	0	0
40 – 20	16355	95740	41233	17600	6674	2562	850	237	25	13	0	0
20 – 0	13870	72862	9244	1447	203	4	0	0	0	0	0	0

Amplitude (N/mm^2)

TABLE 4 Boom Top Flange Principal Stress (σ_1) (North Inner Stay)

Tonnage Unloaded = 109,000 t

Mean (N/mm^2)	5	10	15	20	25	30	35	40	45	50	55	60
20 – 0	144	807	356	29	0	0	0	0	0	0	0	0
0 – -20	9568	56911	33811	11328	3736	237	2	0	0	0	0	0
-20 – -40	100	943	443	129	17	3	0	0	0	0	0	0

Amplitude (N/mm^2)

TABLE 5 Boom Top Flange Principal Stress (σ_2) (North Inner Stay)

Tonnage Unloaded = 109,000 t

Mean (N/mm^2)	5	10	15	20	25	30	35	40	45	50	55	60
20 – 0	540	13093	144	0	0	7	0	0	0	0	0	0
0 – -20	354	1417	69	14	0	0	0	0	0	0	0	0

Amplitude (N/mm^2)

TABLE 6 Boom Top Flange Maximum Shear Stress (τ_{max}) (North Inner Stay) decay being very slow. This arose particularly during longitudinal travel of the unloader. When unloading coal and some types of ore, the frequent use of longitudinal travel was necessary to assist in getting the grab into the sides and corners of the hold to extract material which did not flow to the middle.

5. LOAD AND STRESS MONITORING

Typical matrices from the SCOMAGG Structural Monitoring Unit are given in Tables 1 and 2 for stay axial load and lateral B.M. The strain-gauges were zeroed with the boom in the horizontal position so that all the loads and stresses due to deadweight were balanced out. Relaxation of these stresses occurs relatively infrequently- when the booms are raised to allow a ship to berth and sometimes when the unloader is moved from one hold of the ship to another.

Table 3 relates to longitudinal stress in the boom flange (σ_x) as derived from a gauge-pair, while Tables 4 to 6 are the principal stresses σ_1 and σ_2, and the maximum shear stress, τ_{max}, derived from a rosette of gauges on the top flange of the boom.

There are fewer recorded cycles for σ_2 and τ_{max} because many of the cycles are of smaller amplitude than the counting bands. Similarly a large number of stress cycles are of amplitude too small to be significant for fatigue considerations, and are thus ignored. The general levels of stress amplitude measured by the strain-gauges have been found to be small, with the exception of some very localised high stresses adjacent to brackets.

6. SUPPORT BRACKET FATIGUE CRACKING

After the unloaders had been in service for 15 months, extensive cracking of the angle brackets and web/flange junction of the transverse beams which supported the control cabin runway beam structure occurred. The angle brackets were connected to the outer web of the boom by two vertical fillet welds, and the transverse beams were joined to the angle by 3 HSFG bolts as shown in figure 3. Nearly all the brackets were cracked down the fillet radius at the root of the angle, and the cracks in the beams were at the web/lower flange junction, starting at the joint and running about 10-15 cm and then curving upwards into the web.
Both unloaders were equally affected.
Since neither unloader could be operated in this condition, immediate action was taken to repair the structure, and after discussions with the designers about the cause of the failure the joint and transverse beams were modified as shown in fig. 4a. The angles were replaced by a pair of plates with full strength butt welds to the boom web. In addition, diagonal angle braces were inserted in the positions indicated in fig. 4b. These repairs were completed within 2 weeks, and during this time one transverse beam and one diagonal brace were strain-gauged (see figs 4a and 4c) with the objective of verifying the effectiveness of the repairs and discovering the cause of cracking.

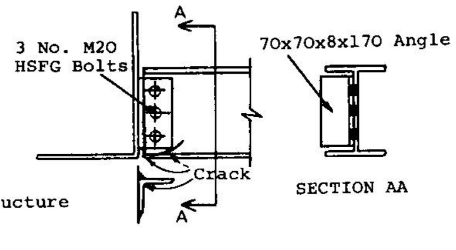
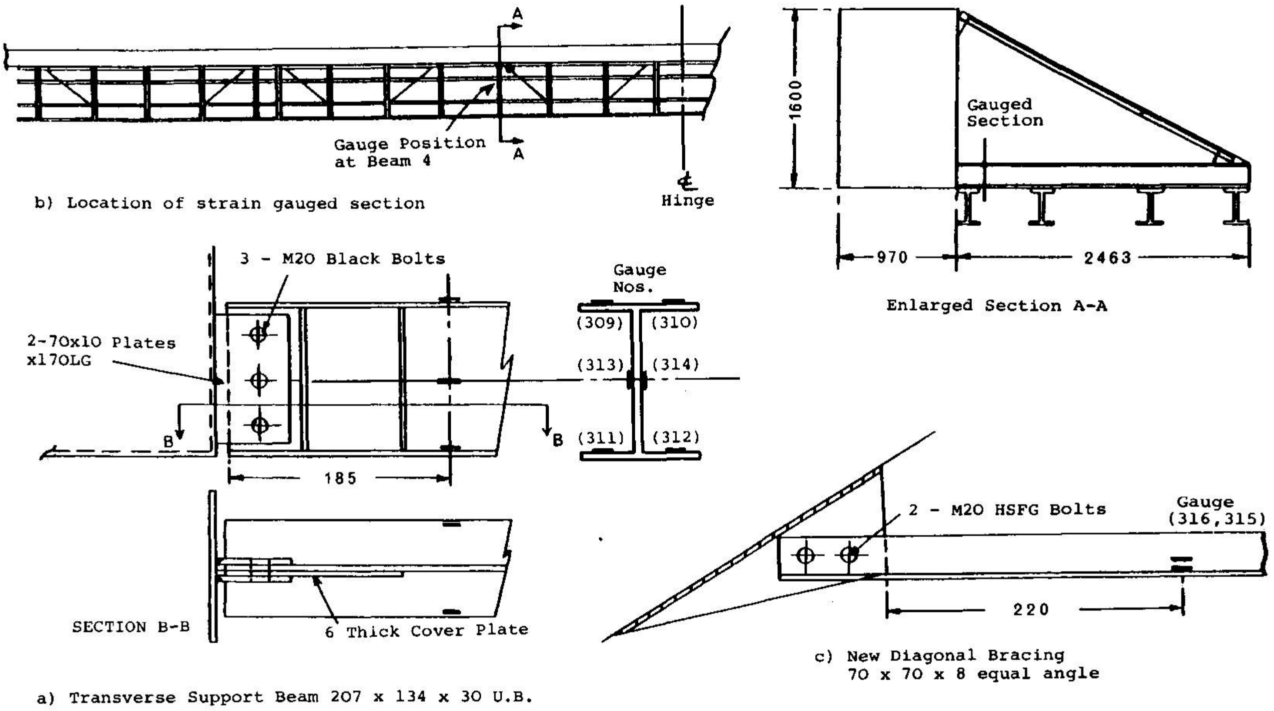


Fig. 3 Details of Original Joint Structure



b) Location of strain gauged section

a) Transverse Support Beam 207 x 134 x 30 U.B.

c) New Diagonal Bracing 70 x 70 x 8 equal angle

Fig. 4 Details of Repaired Joint Structure and Strain Gauges.

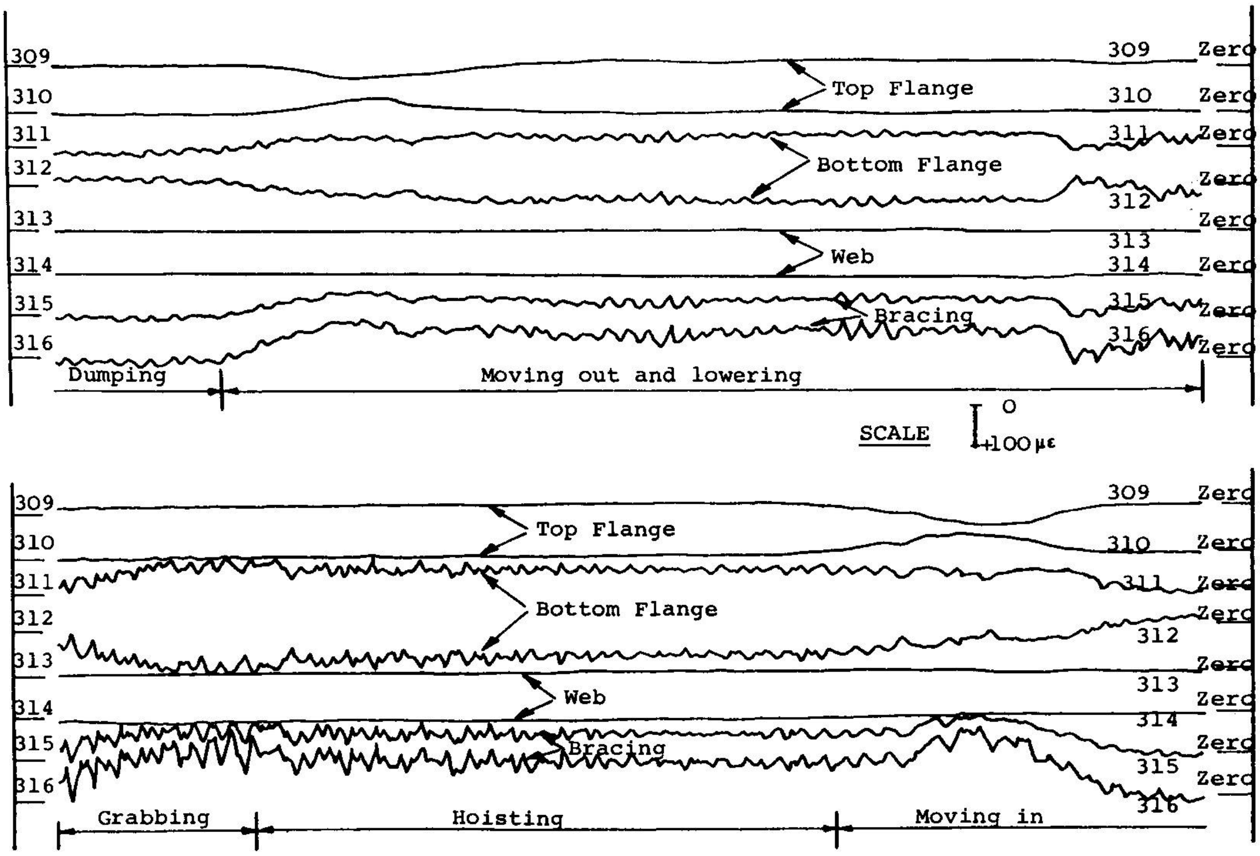


Fig. 5 Dynamic Strains in Repaired Joint Structure.

Dynamic analogue records for the 8 strain gauges were made during movement of the control cabin along the runway beams, raising and lowering of the booms, and typical operational unloading cycles. A typical recording of an operational cycle is shown in fig. 5. From these records the stress distributions in the transverse beam were plotted at key points of the cycles, and from these the major and minor axis bending moments at the gauge section were calculated together with the axial load and the torsion (from the flange warping stresses). Because of the presence of one runway beam between the gauged section and the connection to the boom web, some assumptions had to be made in order to arrive at the loads and stresses at the welded joint. The high torsional stiffness of the closed box section of the boom, and the relative flexibility of the 4 runway beams indicated that deflections of the combined structure at any point would be primarily vertical, and twisting of the box was therefore ignored. Thus each runway beam would deflect vertically by a similar amount and impose equal loads to the transverse beam. About the minor axis it was assumed that the forces in the diagonal bracing members gave rise to lateral bending, and because of the simple bolted connections between the runway and transverse beams the conservative assumption was made that there was no restraint afforded by the runway beams. Because of the lack of any flange connections at the joint to the boom web, torsional restraint was assumed to be zero, the torsion indicated at the gauge section being assumed to be carried by differential bending of the runway beams. Axial load in the transverse beam was taken straight through the joint. On the basis of these assumptions the stresses in the two vertical butt welds at the connection were calculated at the top and bottom ends, and the stress cycles for one complete operational cycle were plotted. The cycle at the worst point (bottom end) is plotted in figure 6, and calculations based on rainflow analysis for a Class F welded detail using BS 5400 Pt 10 indicates an adequate service life. The B.M. distribution in the boom (the main cause of secondary stresses in the runway structure), showed that for the fully loaded grab at the gauged section, the boom B.M. was at least as large at any other section during the rest of the operational cycle. Figs. 7 and 8 show the boom B.M. distributions for the loaded grab at the working position and at the gauged section. It was considered that the transverse beam on which stress measurements were made was typical of those at other positions and that joints at other sections would also be satisfactory. No further cracking has been observed and the unloaders have been in continual operation.

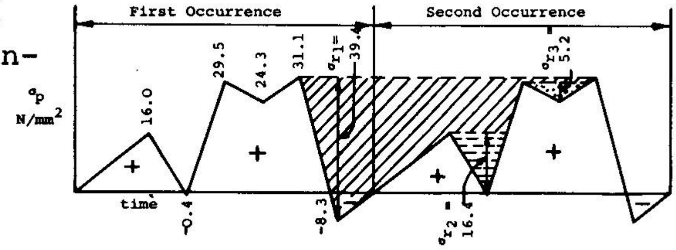


Fig. 6 Stress Cycles in Welded Joint.

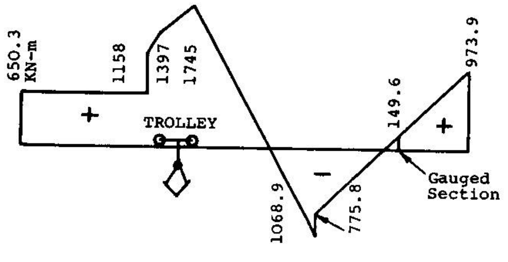


Fig. 7 Boom B.M. for Trolley in Working Position

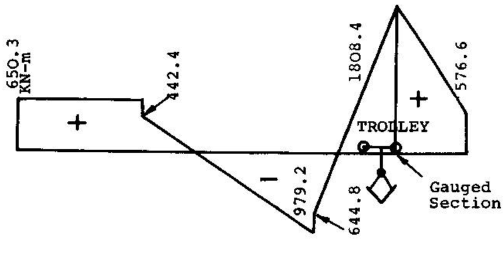


Fig. 8 Boom B.M. for Trolley passing Gauged Section