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 commis-
sioned 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)

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

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:-

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

where $\varepsilon_x, \varepsilon_g$ 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 trans-
mitted 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
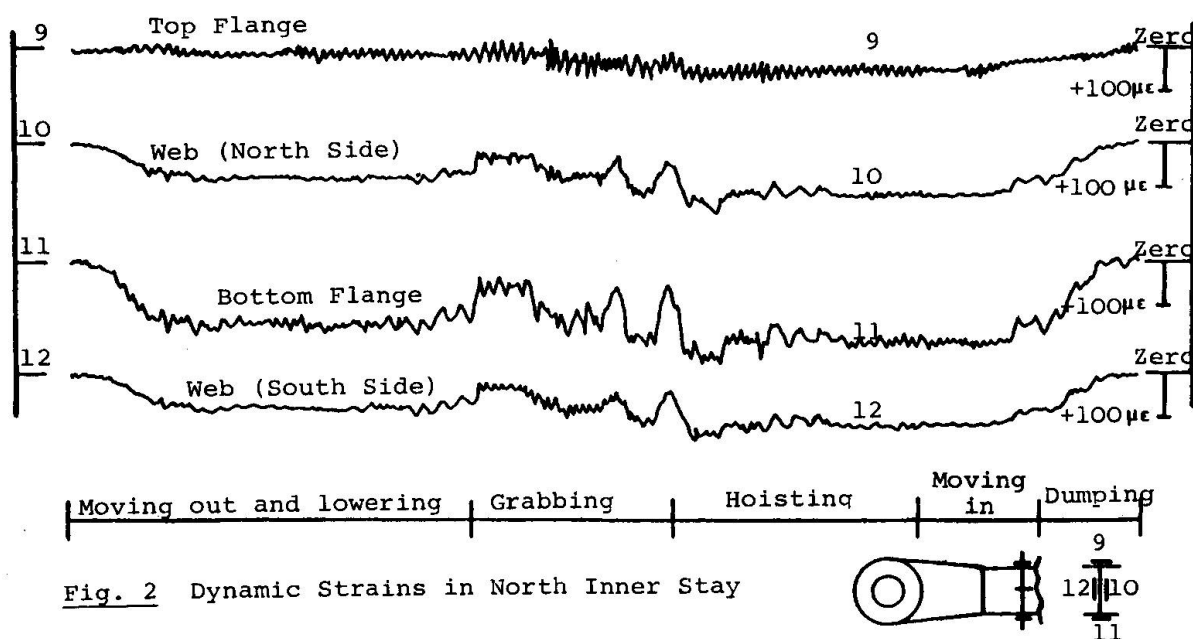stresses. A typical record for the north boom inner stay is

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/mm² 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

Mean (KN) — 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

Mean (KN-m) — 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.

Mean (N/mm²) — Tonnage Unloaded = 27,000 t

Mean (N/mm²)	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/mm²)

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

Mean (N/mm²) — Tonnage Unloaded = 109,000 t

Mean (N/mm²)	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/mm²)

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

Mean (N/mm²) — Tonnage Unloaded = 109,000 t

Mean (N/mm²)	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/mm²)

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

Mean (N/mm²) — Tonnage Unloaded = 109,000 t

Mean (N/mm²)	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/mm²)

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.
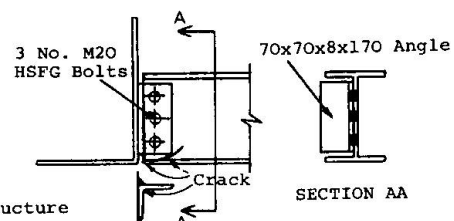

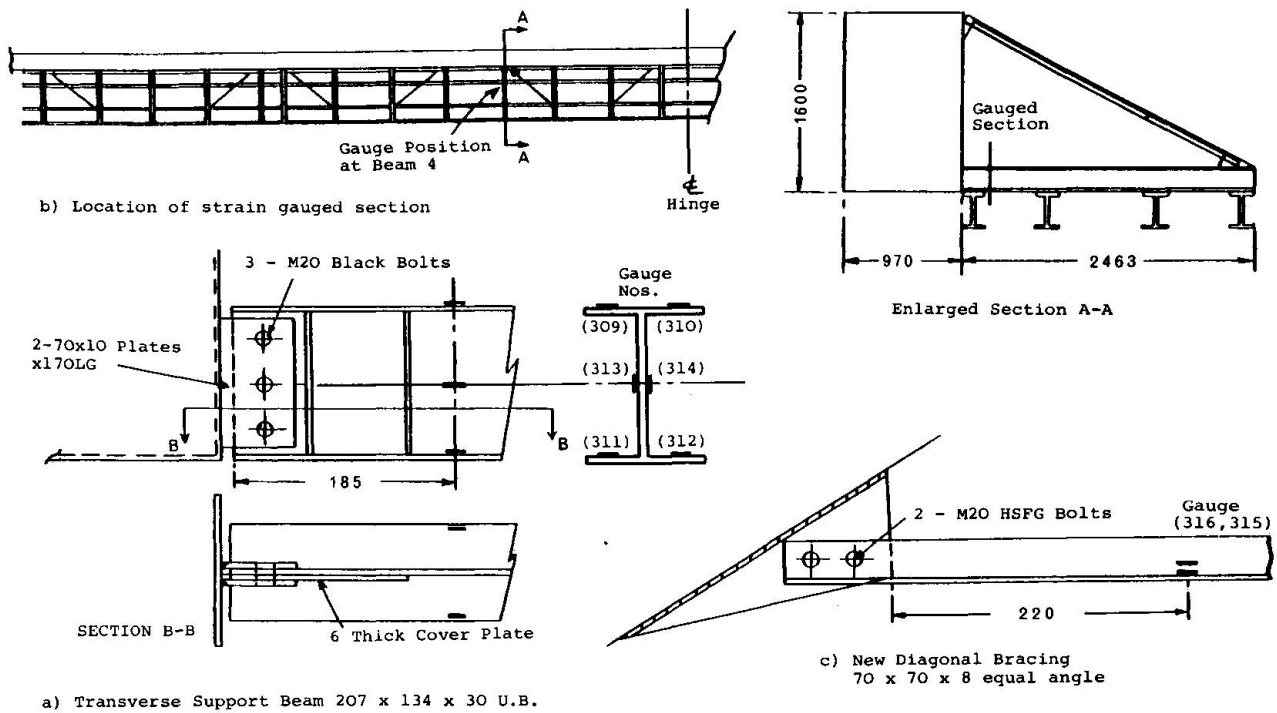Fig. 3 Details of Original Joint Structure

b) Location of strain gauged section

Enlarged Section A-A

3 - M20 Black Bolts

2-70x10 Plates
x170LG

Gauge
Nos.

(309) (310)

(313) (314)

(311) (312)

185

SECTION B-B

6 Thick Cover Plate

2 - M20 HSFG Bolts

Gauge
(316,315)

220

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

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

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

309   309   Zero
310   Top Flange   310   Zero
311   311   Zero
312   Bottom Flange   Zero
313   312   Zero
314   Web   313
                                            314   Zero
315   Bracing   315   Zero
316   316   Zero
Dumping   Moving out and lowering

SCALE   0
         +100 με

309   309   Zero
310   Top Flange   310   Zero
311   311   Zero
312   Bottom Flange   Zero
313   312
314   Web   313   Zero
315   Bracing   314
316   315   Zero
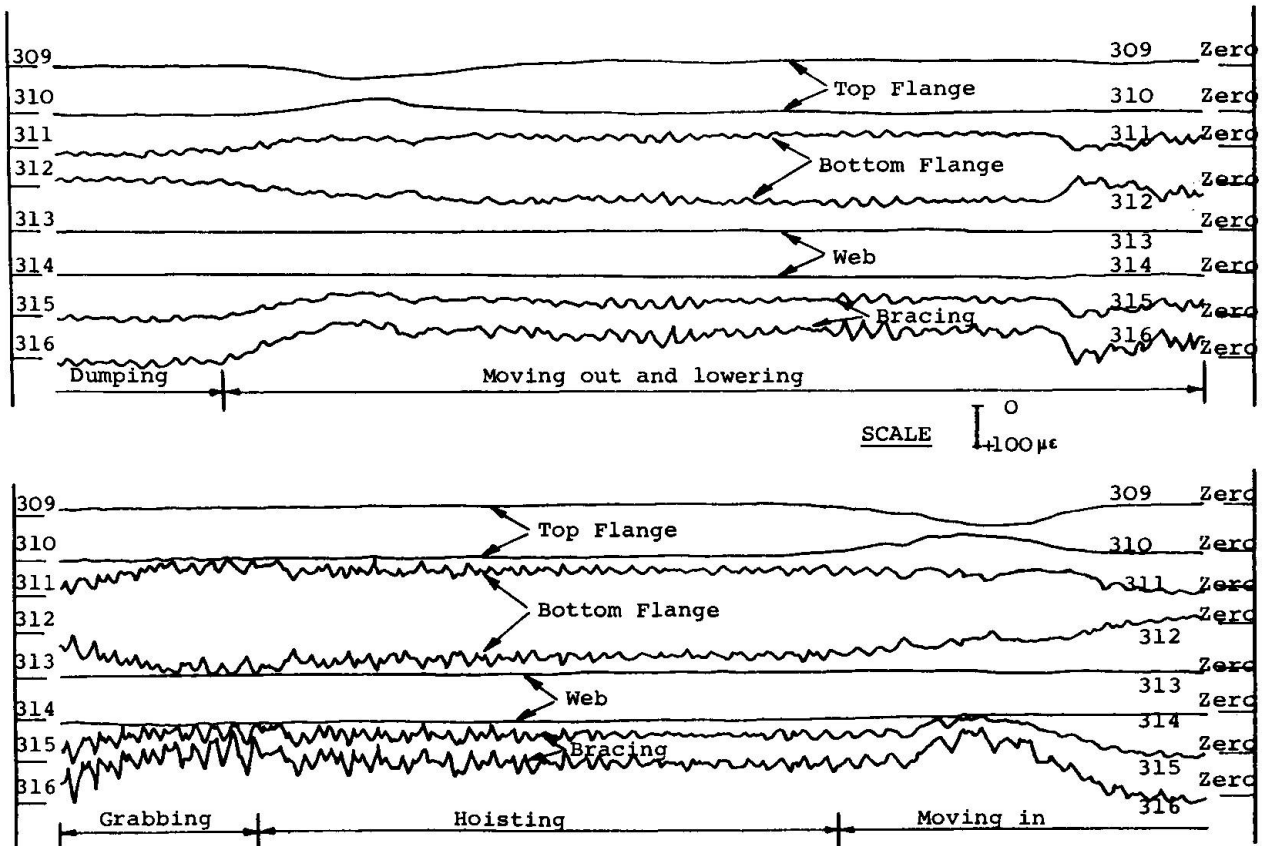Grabbing   Hoisting   Moving in   316

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 calcul-
ated 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 run-
way beams. Axial load in the
transverse beam was taken
straight through the joint.
On the basis of these assump-
tions the stresses in the two
vertical butt welds at the
connection were calculated at

Fig. 6 Stress Cycles in Welded Joint.

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 struc-
ture), showed that for the fully loaded grab at the gauged sec-
tion, 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 posi-
tion and at the gauged section. It was considered that the trans-
verse 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
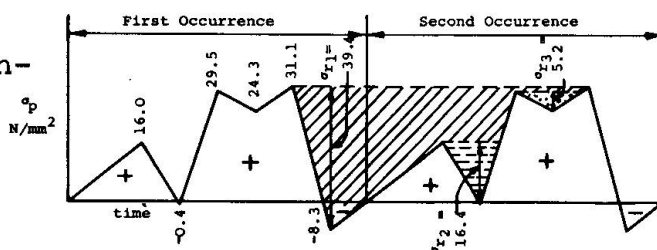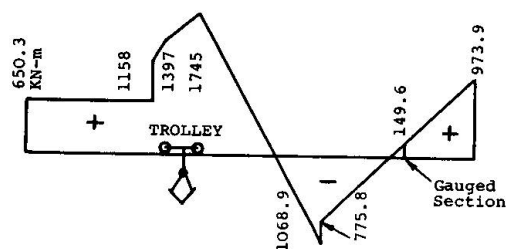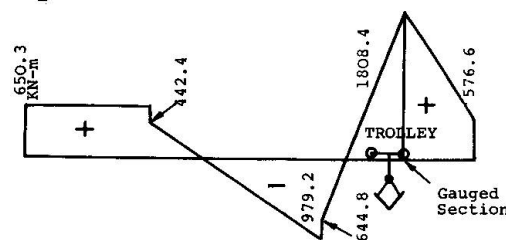the unloaders have been in continual operation.

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

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