Trend in Manufacture of Critical Welded Structures in Earthmoving Machines

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Abstract

The paper highlights the importance of welded structures in Earthmoving Machinery and the considerations involved in the design of welded joints in these structures with particular reference to the practice followed at Bharat Earth Movers Limited, which is illustrated by 2 specific case studies.

Introduction

A striking factor in the design and manufacture of earthmoving machines is that it has to take into consideration the peculiar field conditions which are encountered either due to excessive over loading or due to varied soil conditions. From past experience, we find that the majority of field complaints on the structural assemblies can be attributed to weld fatigue. Attempt is made to develop these structures economically and to withstand millions of stress reversals overload which lead to serious weld fatigue.

It is a costly and tedious process to assess the exact stresses and loads occuring during the operation of earthmoving machines. Calculations based on the structural dynamics, soil mechanics, etc., become mostly fictitious because these are based on a series of assumptions. Hence the basic approach to the design is based on empirical calculations, formulated by past experience. The major design improvement on these structures takes place during development stage itself by subjecting them to bench tests and field trials for several thousand cycles.

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With the experience gained in earthmoving machinery development, the trend is to go in for a welding process which is capable of improving the quality of critical structural assemblies and results in reduction of manufacturing costs with the optimum use of skilled labour. Optimum design of structural members can be achieved by continuous engineering process of development and by proper utilisation of the welding process available in the country.

Design Considerations

While endeavouring the design of welded structures of earthmoving machines, a good appreciation of field data with regard to service loads occuring at critical points is a prime necessity. It has been the experience of most of the earthmoving manufacturers that the field complaints apart from the failures of drive line and hydraulic system are due to the fatigue failures of welded joints.

The fatigue failures usually occur without any type of warning and exhibit a brittle type of transgranular fracture and can be on account of the following parameters which influence fatigue strength. Metal fatigue crack initiating due to discontinuity in the metal, either metallurgical or geometrical, acting as a stress raiser—Introduction of residual stresses—changes in metallurgical and mechanical properties—discontinuities caused by weld contours and weld flaws occuring in the process of welding.

Changes in micro structures and mechanical properties do not contribute to the failure of weldment as much as geometrical defects. The geometrical defects include design flaws in the joint design, incomplete penetration, lack of fusion and slag inclusions accounted due to bad workmanship.

Adequate design allowance should be provided for misuse of the equipment such as operation of the equipment by inexperienced operators and using the equipment for operations which it is not supposed to do.

The availability of normal repair welding facilities are very much limited in the fields. The equipment user's lack of knowledge on the metallurgical and physical properties of base metals and wrong selection of weld materials and processes would be a handicap for effective rectification of the weld failures in the field. The earthmoving machinery designer owns heavy responsibility in identifying the critical areas of failure at the basic design stage so that at developmental stages these areas are closely observed and modified.

It is found that the following are the three basic design factors attributable to the fatigue strength of welded structures :

(*a*) Selection of materials ;
(*b*) Design of weld joints ;
(*c*) Processes of welding.

Materials

Critical applications demand special and specific steels. The fabricated structures of earthmoving machines are of plates, castings and forgings. A good number of members are combination of castings and plate fabrication. The basis for this selection of castings and plates may not be for cost reduction but for improvement in stiffness of the members.

Most of the plates of earthmoving machines are of low carbon high strength steels in varying thicknesses of 6 mm to 36 mm. Higher thickness plates are used occasionally on specific demands. While earthmoving machine manufacturers of advanced countries have the advantage of availability of the high strength steels having a UTS of 130 kg/mm², in India we have to be satisfied with 55 HTW, IS 961 plates. This is a serious handicap for the design of structures because a larger section thickness is required to withstand the loads resulting in increase in weight.

Another drawback faced is the non-availability of plates of large lengths and widths. The fabrication

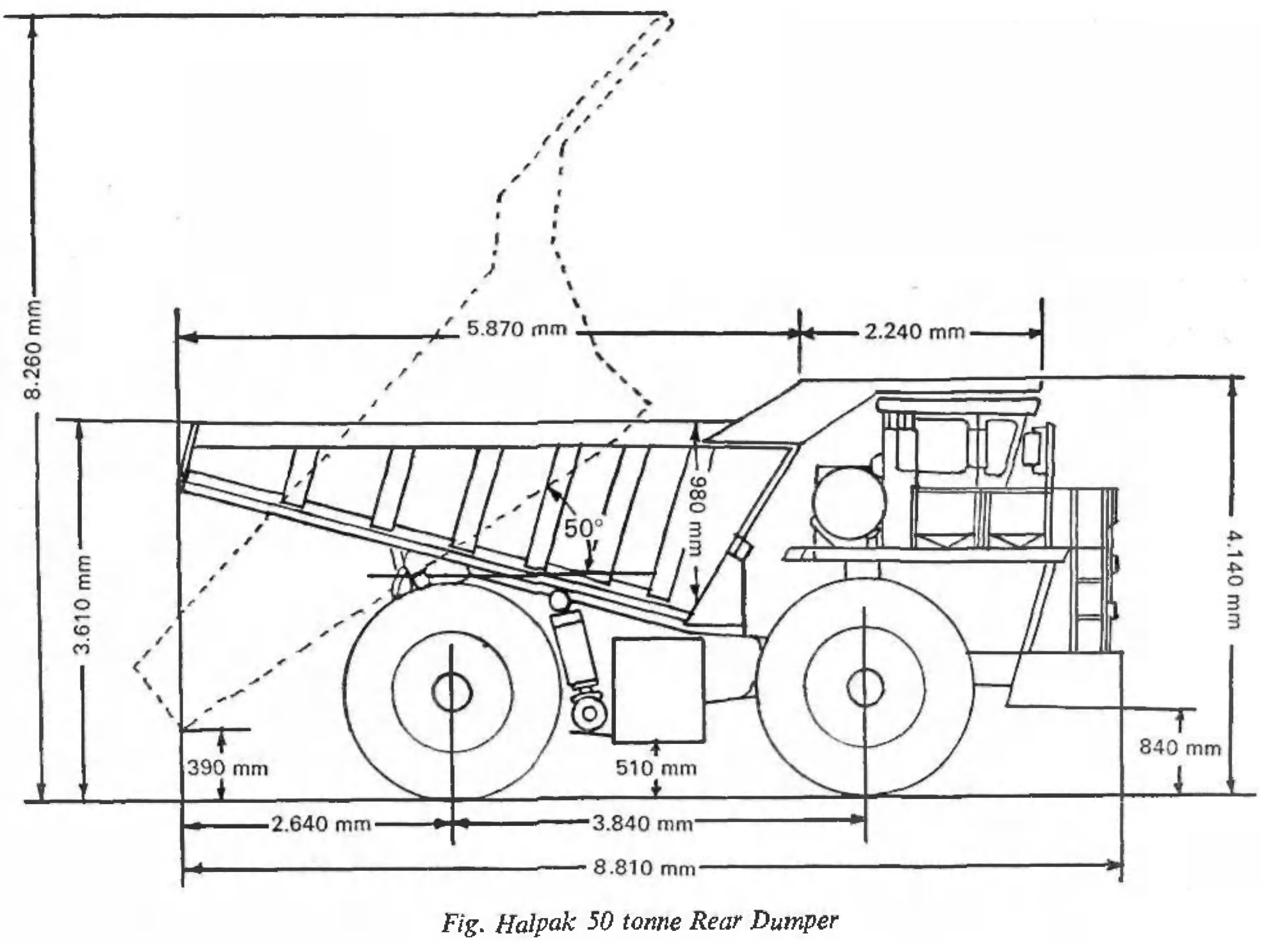

Fig. Halpak 50 tonne Rear Dumper

of large structures have to be made with a number of welded joints which not only shoot up the manufacturing cost but also add to the welding problems in weakening the structure. However, where a number of welded joints are prohibited and high strength steel upto UTS of 80 kg/mm^2 are required, such as the body plates of dumper (See Fig. 1) the plates are presently being imported from Japan, USA and Germany. This particular steel known as T_1 steel in USA (Welton 80C from Nippon Steel Corporation, Japan) is a heat treated alloy steel having high corrosion resistance combined with higher values of strength and toughness. A typical composition is given in Table-1.

Generally for T_1 steel, stress relieving is not necessary whatever the thickness and weld structure may be, unless specifically required by the codes, as for instance, where dimensional stability of machined parts is necessary. The high tensile values (80-95 kg/mm^2), the alloy composition and the heat treated state call for the observance of specified welding conditions like selection of correct electrodes, application of recommended welding heat and employment of proper welding procedures to get a sound joint which is free from discontinuities like cracks, porosities, inclusions, etc. and which withstand severe conditions as does the parent metal. *Case study-I illustrates the application of this particular* steel.

Wherever possible, the structures are made of materials of the same chemical composition and mechanical properties so that comparatively less welding problems are involved. However, in the earthmoving structural manufacture, for reasons of economy, it becomes sometimes necessary to weld together materials of differing chemical compositions and mechanical properties, as in the case of dumper body structure. This necessitates adoption of special precaution which is explained in the following case study.

CASE STUDY-I

Fabrication of Rear Dumper Body

Designed to carry pay-loads, localised or distributed, upto 50 tons and to withstand the severe impact loading during service, fatigue stresses due to cyclic operation of loading and unloading and corrosive atmosphere, the body structure is made up of quenched and tempered high tensile steel.

The fabrication of this structure can be cited as an instance where standardisation and welding expertise *have resulted in the manufacture of equipment to meet* very rigorous service conditions. Fabrication involves butt, lap, edge and fillet welding in restraint and requires utmost care and skill as cracks can occur under normal conditions.

The plates to be welded, ranging in thickness from 6 to 20 mm, are ultrasonically tested to ensure quality (that is, plates should be free from laminations, cracks and folds). Plates are sheared to size as gas cutting is generally not recommended, in order to avoid metallurgical changes and residual stresses resulting from flame cutting. When gas cutting is unavoidable, sufficient *allowance in the parent metal is given and the cut edges* are trimmed to remove the heat affected zone and the drag lines to ensure that the fatigue strength of the material is not affected.

Only electrodes with low-hydrogen coating designated by AWS-E7018, E9018 and E11018 are used for manual arc welding. These electrodes are oven dried before use, to avoid hydrogen embrittlement and under-bead cracking, as per manufacturer's recommendations, usually at 300°C for 2 hours and transferred to an intermediate oven which is kept at 120°C. The electrodes drawn out of this are used within 30 minutes.

TABLE—I

ASTM A510 GrB or Equivalent	Chemical Composition												Mechanical strength		Heat Treatment
	C	Mn	P	S	Si	Ni	Cr	Mo	v	Cu	Ti	B	Yield strength kg/mm (psi)	Tensils strength kg/mm (psi)	
USS-T1 321 BHN	0.12	0.95	0.035	0.04	0.20	0.30	0,40	0.85	0.03	0.20	0.01	0.0005	70.3	81.94	Water quenched from
(United Steel Corporation)	-0.21	-1.30	Max	Max	-0.35	-0.70	-0.65	-0.25	0.08	-0.40	-0.03	-0.005	(100,000)	(115,000-135,000)	900°c (165°P) and tempering at 620°o
Welton 80c 321 BHN	0.18	0.60	0.03	0.03	0.15		0.70	0.30		0.15		-0.0006	70	80-95	(1100°P)
(Nippon Steel Corporation)	Max	-1.20	Max	Max	-0.35	—	-1.30	-0.60	—	-0.50	—		(99,600)	(113,800-(135,100)	

A root run from a more ductile electrode AWS E9018 is made to minimise cracking and the subsequent layers are laid by high tensile electrode AWS E11018. While welding low strength steel ST 55 HTW, IS 961 as stiffeners to high strength Q&T steel, the electrode of lower strength low hydrogen E7018 is used.

While welding, sufficient care is taken such that heat input does not exceed a certain limit ; otherwise, the original tempered martensitic structure of the steel undergoes undesirable transformation in heat affected zone leading to poor notch ductility which cannot be rectified by normal stress relieving. Too low a heat input, on the other hand, will lower the ductility of the welded joint and increase the hardness of heat affected zone beyond safe values. So, plates being welded are preheated (to 100°C at normal welding current and arc voltage conditions), to a distance of about 100 mm on either side of the joint, so that the maximum energy input does not exceed the limit value for different thicknesses as given in Table II and as calculated by the formula.

Energy Input/cm = Welding current × Arc Voltage × 60/Welding speed in cm/min.
= Watt—Seconds (Joules)/cm weld

Tempil sticks are used to gauge the temperature.

While welding butt welds, the grooves are filled with a succession of stringer beads. Before laying another bead over the earlier bead it is cleaned to remove slag and scale. Weaving is avoided as it overheats the metal because of slow speed which otherwise may result in unsatisfactory welds. Air hammer peening is done to the toe passes to avoid toe cracking.

Fillet welds are made smooth correctly contoured and and well faired-in to the legs of the pieces to be joined. It is ensured that each layer of the weld has good root penetration without any undercut.

Welding sequence is given due consideration to minimise distortion of the structure and to reduce residual stresses in the weld joints.

Welding jigs and manipulators are extensively used right from the sub-assembly stage to ensure that most of the welding is done in down hand (flat position).

Stringent inspection is made at each stage followed finally by non-destructive tests like Radiography, Ultrasonic and Magnaflux tests.

Weld Joint Design

Design of weld joints is the most important factor affecting the fatigue strength of a welded structure.

Fatigue cracks occur by stress concentration. Every weld produces a change of section resulting in stress concentration. But the change of section should not lie transverse to the direction of stress.

It is well known that butt-welds are stronger than fillet welds against fatigue but it is not possible for a designer to always stick on to butt-welds. In the earth-moving structural members, the main design criterion being fatigue, an attempt is always made to see that most of the weld joints are butt-welded.

While designing a joint, the designer gives due weightage to the following aspects :

Table—2 :

Maximum recommended energy input in 1000 watt seeond (Joules/cm of weld)

Preheat or interpass temp. °c	*Plate thickness mm*				
	6	*10*	*12*	*16*	*20*
21	14.0	20.5	27.5	36.5	47.5
50	13.0	19.0	25.0	33.5	44.0
100	11.0	16.5	21.5	29.5	38.0
150	9.5	14.0	18.5	25.0	32.0
200	7.5	11.5	16.5	20.5	26.0

(*a*) Accounting for the over loads occurring in the field during its service life.

(*b*) The number of welded joints should be as minimum as possible. As already explained this is sometimes not possible because of the non-availability of larger plates. The golden rule of "Ideal welded structure is composed of as few parts as possible" cannot be followed always.

(*c*) Ensuring the welded joints to be in the region of lower stressed zones. (This is possible with data collected by past experience).

(*d*) Consider practical manufacturing problems of the plant and design the welded member accordingly. The design should also facilitate the accessibility to all the areas of welded joints.

(*e*) Cost saving aspects by recommending only required welding length/size on all welded joints and avoid additional parts on a structure which does not offer any benefits.

The fabrication of the structure as far as possible should be made utilising the present inplant capacity and with minimum additional jigs/fixtures.

Attempts are being made to ensure that the weld joint designs are standardised as far as possible, keeping the cost aspects in view. Earlier designs of joints on some of the main structural members such as Main frame and Track frames of crawler dozers and loaders and Lift arms of crawler loaders were altered to effect standardisation. These are illustrated in Fig. 2. The improved design not only caters to standardisation but also strength of joint by deep penetration.

The improved welded joints are machined by special form-tools on planing machines. This machining operation avoids any type of failure due to the heat affected zone cracks. The earlier designs of bevelled edges, though sometimes cut by gas were trimmed off by grinding the edges to remove the heat affected zone.

The new 'J' groove design feature was incorporated in view of the problem faced due to lack of penetration of the weld material in the load bearing welded structure members. It is well known that the lack of penetration of weld in a joint is a stress raiser and has considerable effect on the fatigue strength.

Weld Process

Manual metal arc welding is the most widely used welding process in our factory due to its flexibility, utility in all positions and locations and the free availability of stick electrodes for almost all types of steels However, it has the following limitations from the point of view of productivity and fatigue strength :

(*a*) It is related to the deposition efficiency and metal deposition rate.

(*b*) Electrodes used are of fixed lengths and therefore welding must be stopped after each electrode is consumed. This 'stop-start' process produces a more severe stress concentration and fatigue cracks may readily initiate from this point.

(*c*) Deslagging is required for each pass to remove the slag covering that forms on the weld. Unless utmost care is taken in cleaning the slag, some slag is likely to be included in the welded joint making room for fatigue failure.

(*d*) Smaller electrodes are to be used especially in the bevelled edges to have deep penetration to the root

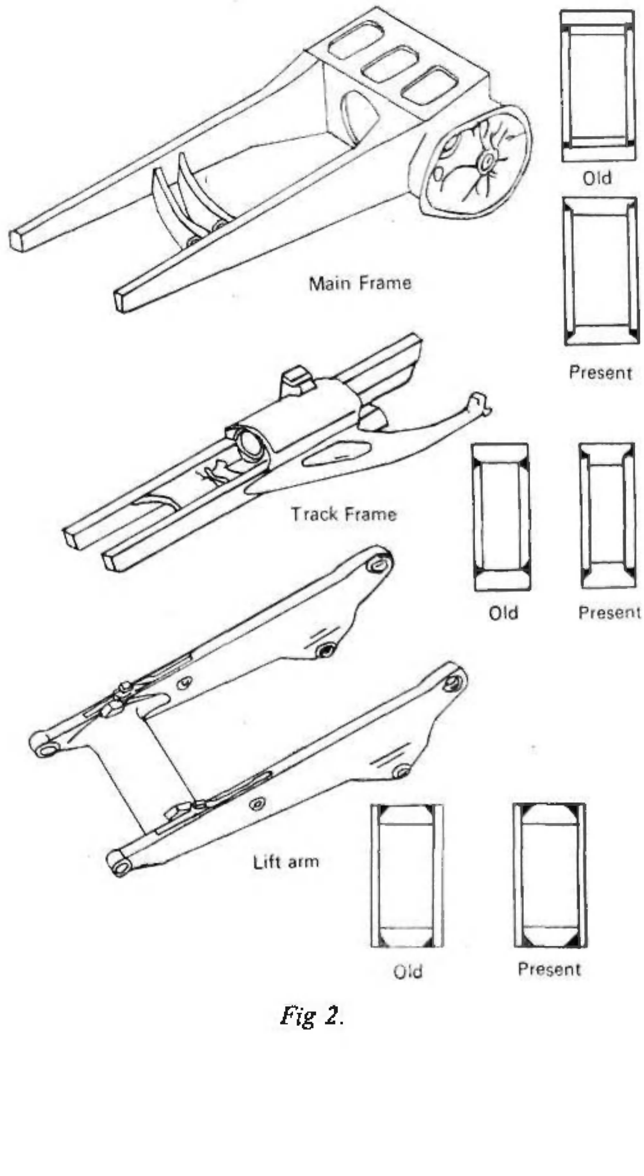

Fig 2.

of the joints. This process is not only costly but also time consuming thus affecting the productivity.

(e) The automatic process of stick electrodes is very costly.

Due to the above fact of low productivity and lesser strength against fatigue. one has to seriously think of an alternate process of welding which offers more automated and semi-automated welding and thereby improves the productivity.

Two important welding processes that are becoming popular in the fabrication of steel structures are CO_2 welding and submerged arc welding, due to their inherent advantages of improved productivity and semi-automatic nature. Earthmoving machine manufacturers of developed countries have already shifted to gas metal arc welding and submerged arc welding processes to meet almost all their welding requirements.

Gas metal arc welding with CO_2 gas as the shielding gas has the known advantages such as clear visibility of arc due to high current density and absence of slag metal reactions. Since no slag is involved, operation of slag removal and danger of slag inclusions are eliminated. In CO_2 welding process, the outstanding features are high quality welds at high speeds and the deposit rate and arc time is nearly double that of manual metal arc welding.

In CO_2 welding, the tendency is for the arc to be somewhat violent, leading to spatter problems when welding is carried out on components where appearance is of particular importance. This drawback is overshadowed by the deep penetration and fusion qualities of weld giving good properties. Presently we use this process only in a limited way.

Submerged arc welding is faster than manual metal arc welding because more current can be applied to submerged arc and because it does not involve interruption or changes in speed that are characteristic of manual metal arc welding and that impedes steady production. Other advantages of this process are elimination of weld spatter due to the arc operating under the flux cover, the need of no shielding to protect the operator and ability to work in the exposed areas with relatively high winds.

However, submerged arc welding suffers from a few limitations such as number of components of the equipment, unsuitability for metals where thickness is less than 8 mm, fear of contamination of flux and inability for all-weld positions. Practically it was also found to be not very efficient in the deep groove penetration.

Although the non-availability of large plates and involvement of complicated and intricate shaped parts are a few of the compelling factors, the soundness of the assembly due to the smoother stress flows, lesser welded joints, stiffer structure and cost reduction in a few cases can also be reasoned out for the selection of combination of castings and plates in the earthmoving machine components.

An example to illustrate the judicious combination of castings and plates in the fabrication of lift arm assembly of a crawler loader is explained as a case study-II.

CASE STUDY-II

A lift arm assembly which is hinged on the superstructure of crawler loader, holds a bucket at its front end and acts as a boom. During its operation, it has to face severe stresses and strains.

Basically, the subject lift arm assembly comprises of two arms of box section and are joined together by an elliptical box cross member near the bucket end as shown in Fig. 3a.

Developmental assembly was fabricated with ST55 HTW, IS 961 plates. The flange was 25 mm thick, the webs 20 mm thick. The cross member was of elliptical shape fabricated out of 16 mm thick plates. At the ends, plates, 16 mm thick, were welded, which in turn were welded to the arms.

All the welded joints had 12 mm$\times$45° bevelled edges gas cut and then ground to remove heat affected zones. The welding was carried out with shielded metal arc welding. After completion of fabrication and machining the lift arm assembly was assembled on the prototype loader.

Preliminary tests were carried out on the machine on the Test Track for several thousands of cycles. After the successful completion of these tests, the machine was subjected to actual field trials in a rocky and rough terrain where rigorous performance tests, were carried out. The structures which were given severe shocks intentionally, were closely observed during the endurance trials.

The weld cracks started developing after about 1000 hrs of operation at the joint of the cross member

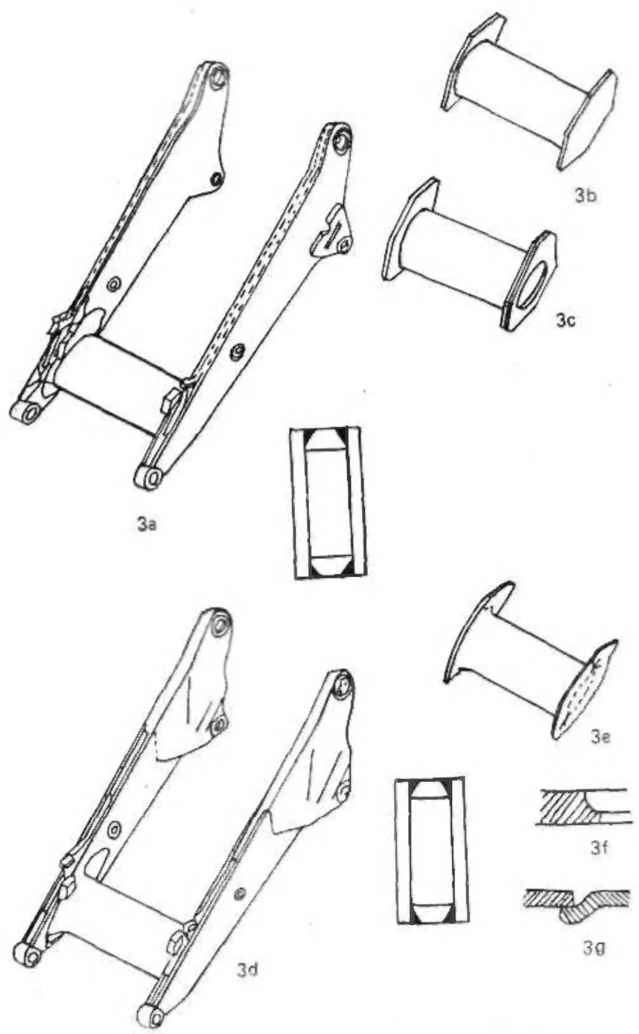

Fig 3 Left arm assembly of a crawler loader

with the arms and also at longitudinal joints of webs and flange in the regions of change of sections. The weld beads at that particular position were gouged and rewelded. But after about 500 hrs of further operation, the cracks re-appeared at the same places, this time very severely at the joint of cross member and arms.

The cross member was completely gouged and was removed from the assembly. The end plates were removed and new thicker end plates suitably flame cut inside were inserted perpendicularly half way to the cross member and were welded as shown in the Fig. 3c. This time the welding was done both inside and outside the circumference of the cross member joining the end plates. The place where the cross member was welded to the arms was completely ground and made flush to have a perfect seating of the cross member plates. The ends of the plates were also machined to correce dimensions and bevelled before they were welded to tht arms. The bevelled edges gave better penetration of weld and less possibility of defective welding occuring as compared to that of fillet, since the thickness of weld head could be given. The other places where the welding had given way were again gouged, cleaned and welded. At some places of cracks, lack of penetration of weld metal was also noticed.

As a result of the above modification, the cross member could give further weld crack-free life of more than 2000 hrs. The other longitudinal welds and circumferential welds at the bosses started revealing cracks after every 200 to 500 hrs of operation. A good number of cracks were from stop start position. The accessibility for welding at site was posing added problems.

After close study of the above premature failure and assurance of quality manufacturing, changes were made at the designer's desk to ensure reliability of the component. Thus emerged a new strong design of lift arm assembly (Fig. 3d). A judicious combination of castings and welded structures was adopted. The improvements were :

(*a*) The cross member was completely changed to a casting, material conforming to IS 2644. Gr. II machined and 'J' grooved at the ends (Fig. 3e). The casting was so shaped at the ends, that the welds were taken out of the direct load path.

(*b*) The bevelled grooves of webs were changed to 'J' grooves as there were doubts of full penetration of weld metal on a 'V' groove even after full care during welding. The new 'J' groove design is shown in Fig. 3f.

(*c*) The hinged-half of the arm was changed to a hollow casting material conforming to IS 2644 Gr. II, as the experience showed that maximum stresses were concentrated at the pivot points allowing frequent cracks. Radius at the change of section was increased to have better stress flow. The joint of this casting with the box section was smoothly made with increased welding area. 'J' grooves were inbuilt in the casting as shown in Fig. 3g.

(*d*) The total welding length was reduced by 40%.

(*e*) More care was taken during welding so that no lack of weld was observed at the stop start position.

(*f*) The bosses in the box section were given backplates to reduce the possibility of burn-through during welding.

The assembly which was put in service after endurance trials of nearly 2000 hrs, paid handsome dividends with absolutely no weld defects, with least weldments and smoother stress flow. The slight reduction in the cost of new assembly envisaged resulted in a surprise bonus in this case.

Future Trends

To keep the present phase of the trend in manufacture of welded structure, one of the handicaps we have is non-availability of quenched and tempered plates of requisite sizes.

Bharat Earth Movers with an anticipated annual production of more than 1000 equipment and with the introduction of higher capacity models with larger structures in the coming few years, is in the process of adopting new welding methods, keeping in mind productivity as the prime objective. The present method of manual metal arc welding though still popular with our welders due to their familiarity with this process, the introduction of a few equipments of CO_2 welding and submerged arc welding have improved the productivity apart from enhancing the quality of the welds. While submerged arc welding process had found its way in the early seventies and is used for fabrication of large structures such as 'C' frames of bulldozers, CO_2 welding equipment caters only to about 1% of our production welding. The acceptance of CO_2 welding equipment is still in question because of the initial problem of current setting, spatter, high heat dissipation etc. The CO_2 electrode wire for welding the high strength quenched and tempered steels for the fabrication of dumper bodies is still not available indigenously. This will also be an inhibiting factor for its smooth entry in our fabrication. Once the above problems are sorted out we do not find any reasons for the non-acceptance of CO_2 welding which outweighs the other two welding processes in quality and productivity.

Analysis of the weld fatigue on the structures can be done by simulating the loads and operating conditions in the laboratory. We are having plans to establish suitable instrumentation and other allied facilities to carry out accelerated endurance tests on the structures. Howver, at the moment, we are making use of certain facilities available with Indian Institue of Technology, Madras.

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