Image Cover Sheet

CLASSIFICATION UNCLASSIFIED	**SYSTEM NUMBER** 507222
TITLE LASER WELDING IN SHIP CONSTRUCTION	

System Number:

Patron Number:

Requester:

Notes: Paper #19 contained in Parent Sysnum #507203

DSIS Use only:

Deliver to: DK

#507222 (19)

Laser Welding in Ship Construction

By: **J Bird**, Ministry of Defence, Abbey Wood, Bristol, UK
A Furio, Naval Warfare Centre, Carderock Division, Bethesda, Maryland, USA

Introduction

The need to remain competitive in an ever increasingly competitive market is of paramount importance in the shipbuilding industry where far eastern fabricators, with significantly lower labour costs compared with those in Europe, compete aggressively. It has been stated that structural rework accounts for anything up to 25% of basic man hour fabrication costs as a result of misalignment and distortion resulting from welding and other fabrication related problems. Consequently anything that can be done to save some or all of the 25% of the currently expended rework man hours will go a long way to allowing European shipyards to remain competitive in the world market.

Large scale structural distortion and poor fit up can be effectively counteracted by use of CAD/CAM techniques. With accurate laser cutting of the individual structural steel components, a truer structure can be fabricated. This relies on individual accurately cut structural steel components being carefully positioned and firmly located for welding. However, using arc welding procedures, when considerable amounts of weld metal are used to join the individual items together, large scale restraint stresses may be generated due to weld metal contraction. The structure consequently can and usually does suffer unwanted distortion. In contrast, laser welding uses small welds, with little or no filler, and as a consequence contraction is reduced and thus the potential for large restraint stresses and the accompanying distortion.

By using accurately cut steel plate and sections, with precise alignment and great attention being paid to the positioning and location of the components to be laser welded, a structurally efficient fabrication can be manufactured exhibiting minimal distortion. The means of joining the various components, plate, sections, etc by laser welding is achieved using butt welds, stake welds and what has been called skid (1) welding.

The object of the paper is to illustrate what has been achieved using laser welding with respect to warship structures. In addition to the general use of laser welding for fabricating conventional ship structures, laser welding of lightweight stiff structures illustrates the potential for novel structural development. This may have specific applications, in the fast ferry industry (2), where designs with respect to increasing size, is outweighing the capability of aluminium to fulfil the materials role, whilst still producing a cost effective acceptable power to weight ratio vessel.

Overall it has been suggested that the use of Laser welding will result in:

1. decreased imperfection levels, due to more precise and controlled heat input;
2. increased joining rates;
3. less consumable costs, due to the reduced need for filler material;

4. more precise structural fabrication reducing design margins, allowing for inaccuracies;
5. improved reproducibility.

Laser Fabrications

1. Frame Stiffened Panels

Frame stiffened panels in naval vessels have the frames fillet welded on both sides, either continuously or intermittently, to form a rigid structure which has a lower weight compared with simple plate of equivalent stiffness. In order to produce a structurally efficient frame stiffened panel from plate segments, the plate must be flat, be accurately cut and carefully positioned for arc welding with the minimum quantity of weld metal to minimise distortion. To manufacture such a panel by laser welding requires accurate cutting of the plate, as with the arc welding, but using laser cutting under CAD/CAM control the accuracy of the cut this is readily achieved. Fit up then must be equivalent to standard panel manufacture and it must be guaranteed to a gap tolerance of 1mm. The joint can be formed using a single pass, full thickness, frame to plate laser weld, adequate to carry the design load. For thick framing, laser welding can be carried out from both sides of the frame to form a fully fused joint. Consequently the distortion do to weld contraction is not only minimised but directed in one direction as compared with the more usual fillet welds. This will clearly produce over a large structure, a significant decrease in distortion and the fit up of individual fabricated structural sections can be expected to be vastly improved, with total distortion of some 10% of that of arc welded structures being quoted.

The proposal to use welds without fillets to help transfer the load may at first seem to be counter productive as regards induced stress level and in consequence fatigue performance and overall ductility. In order to investigate the effect of replacing a two sided fillet weld with one which in essence joined only the stiffener thickness to the plate, a number of large scale tests were fabricated and tested in tensile, bending and fatigue. These included:-

a) Large scale ductility tests
b) Large scale crack arrest tests
c) Large scale buckling tests
d) Large scale fatigue tests
e) Fracture mechanics tests

a) Large scale ductility tests

It is a requirement of the classification authorities that 22% elongation be developed in constructional welds. However because of the small size of the laser welds it is very difficult to identify a tensile test which will reliably measure the ductility of a laser deposit. Consequently, in order to show that in construction adequate levels of ductility could be developed, large scale tensile tests were devised to demonstrate that such levels of ductility could be achieved.

The specimen developed for large scale ductility testing, figure 1. measured 1000mm wide by 850mm wide and 12mm thick containing a longitudinal butt weld and two transverse stiffeners. The arc welded version of the test carried out for comparison purposes was made using a four pass single-sided procedure whilst the laser panel was constructed with a single pass laser weld made at 1m/min. The panels in both cases were made from the same plate of Grade A steel.

The stress was applied to the specimens via a heavy cross pieces loaded by two large hydraulic jacks, in a rig used for wide plate testing, the elongation being measured by four extensometers with a gauge length of 1100mm. Because the extensometers were limited to 50mm travel the overall plastic strain for the panel was estimated on the basis of machine displacement and a particular gauge length , the parallel length of the panel, 940mm. The overall elongation produced significant lateral contraction, which caused buckling of the transverse frames and plate dishing between the frames. There was no evidence of damage to the longitudinal weld. In spite of the buckling of the frames, especially in the laser panel which was taken to a higher elongation, there was no signs of local tearing in the welds attaching the frames to the plating. The overall elongation was estimated as 7.5% for the arc panel and 10.5% for the laser welded panel.

The structural relevance of requiring 22% elongation from the weld is unclear. What matters is the structural response as a whole. In context, the 10.5% overall elongation achieved on the large laser welded panel tested is considered to demonstrate a more than adequate level of structural ductility and consequently to show that laser welding does possess adequate ductility for ship construction.

b) Large scale crack arrest tests

Brittle fracture has from time to time been a major problem in ship steels, as indicated in the liberty ship failures and more recent failures, a significant contribution to which has been brittle fracture. In the current laser welding trials Grade A was used as the test material. Consequently it was thought relevant to determine if fast fractures could develop and propagate in the molten zone or HAZ of the laser welds as it was known that such areas would, due to the high cooling rate, be very strong and as a result likely to be of low toughness. In order to determine how the laser welds were performing compared with currently used equivalent tests were carried out on arc welded panels.

The test sample is shown in figure 2. and with a central test section 1000mm wide by 850mm high comprising four equally sized 12mm thick plates butt welded together using arc or laser welding. The arc welds were deposited using Flux Cored Wire welds for the root and a submerged arc fill resulting in a total of 4 passes per arc weld. In contrast the laser welds were made using a single pass at 1m/min. The object of the test was to present the transverse (horizontal) weld in assembly with a fast running crack whilst the test section was subjected to a remote stress representative of what might be encountered in a ships deck. The longitudinal (vertical) weld was included with the intention of including realistic residual stresses. The load was applied to the test piece via a tapered transition piece bolted at its ends into a heavy cross member loaded as for the previously described tensile tests.

The fracture toughness of low strength ship steels and weldments are generally found to be sensitive to strain rate. A brittle crack will only initiate under static loading if the temperature is below the minimum encountered in ship structures. Because dynamic loading is difficult to apply to large test pieces crack initiation was achieved by cooling the central portion of the test piece down to -120°C before driving a small wedge device into the centre of the plate. The region remote from the crack initiation point was held at a more realistic ship design temperature, -30°C to

0°C using solid carbon dioxide in aluminium trays. The resulting temperature gradient was monitored using contact thermocouples.

In all cases running cracks were initiated in the horizontal welds of the arc and laser welded panels. For the arc welds, the remote stress at initiation was 151MPa and 178MPa. The cracks ran for a small distance in the weld, a maximum of 150mm before deviating into the plate and arresting at temperatures between -5°C and -15°C. The cracks initiated in the laser welded panels, which were subjected to remote stresses of 146mpa and 62mpa, immediately deviated into the plate material before arresting at temperatures between -15°C and -30°C. One laser welded panel was ground flush 50mm either side of the central hole in an attempt to confine the crack to the weld, side grooving was not practical, but this only resulted in the crack remaining in the weld for 6mm before deviating into the plate.

The large scale crack arrest tests provide an encouraging demonstration of the defect tolerance of laser welds in comparison with standard arc welds with crack deviation dominating. The applied nominal stress 150MPa is an extreme level and there is only a small probability of it being encountered in a ship's lifetime. Later charpy testing indicated that this Grade A steel would have qualified as Grade D steel with a minimum charpy toughness level of 27J.

c) Large scale buckling tests

These tests were an initial attempt to obtain structural information which would allow the ship designer to confidently use laser welded structures in place of more conventional arc welded structures. Three principal areas were to be assessed:

1. residual stresses due to welding
2. plating imperfection levels due to welding
3. overall structural performance

The design of the panel used for comparing the structural performance of arc and laser welded structures is shown in figure 3. After welding both panels an assessment of the structural distortion developed in the panel together with residual stress measurements determined via strain gauges positioned midbay on the plating and the frame web tables was made. This was followed by longitudinally compressing the panel until buckling failure occurred.

The comparison indicated that the laser welded panel had lower imperfection levels, lower residual compressive stress levels, but similar levels of sub-component misalignment to the arc welded structure. Thus it might be expected that the structural performance of the two panels would differ. This was highlighted by the fact that the laser welded panel behaves linearly figure 4. up to a greater portion of the structural crush load compared with the conventional panel and exhibited a more catastrophic failure mode see figure 5. Both panels failed at the same peak load with the laser welded panel showing lower post-collapse levels of strength.

It has been suggested that by modifying the structural slenderness of the plating in the laser welded panel it may be possible to constrain the failure mode of the structure to a smoother elasto-plastic failure. This will produce a lighter structure of a similar ultimate strength, with a safe failure mode, which will be of great value to the ship designer. Further work is required to assess the parametric performance of such variations in panel design but it should be possible, using current design methods adapted for laser welded structures, to design safe satisfactory laser welded structures.

d) Large scale fatigue tests

Structural fatigue testing was carried out using the sample shown in figure 6. to compare laser and arc welded panels. The details of primary concern in the ship are the transverse stiffeners and these have been incorporated on both sides of the test piece for convenience. The two laser welded panels contained two single pass fillet, one double pass fillet and one single pass butt weld. The arc welded panels were made using single pass fillets and single sided four pass butt weld. The test section measured 1100mm by 550mm wide and 12mm thick, the test section having been reduced from the original 1600mm width. All butt welds attaching the end sections to the test rig were ground flush with the plate surface to reduce stress concentration effects.

The test were undertaken in air at a frequency of 1Hz. Strain being measured by strain gauges located as shown in figure 6. The stress ranges used for the pairs of panels were 6 to 106MPa and 6 to 156MPa. The arc welds failed as might be expected with fatigue cracks spreading from the toes of the fillet welds. None of the laser welded panels failed in the test section. The more lowly stressed (100MPa) laser welded panel survived twice the number of cycles of the arc welded equivalent and the more highly stressed laser panel (150MPa) survived to five times its arc welded equivalent before the test was prematurely terminated.

In the above tests the plain transverse butt weld and the non load carrying transverse fillet weld can be classified according to the British Standard on fatigue design in welded structures as Class D and Class F respectively. The SN data for the tests are plotted in figures 7. and 8. If mean stress is used both arc weld results lie below the minus two standard deviation Class F design curve. But using maximum strain the results are more in line with the expected behaviour of Class F welds. The surprisingly short life of the arc welded panel may be due to the large length of weld tested. For the laser welds, the specimens are unbroken and the results lie above the Class D line. In the case of one of the laser welded panels the arc welded supporting fixture (Class D) failed and in consequence provides strong circumstantial confirmation that laser fillet welds can be classified as Class D or better in contrast to arc fillet welds which barely meet Class F for this type of specimen.

The most likely explanation for the superior fatigue performance of the laser welded panel is the much neater weld profile. It is known that the stress concentration effect of a transverse fillet becomes more severe as the leg length of the fillet increases.

e) Fracture mechanics toughness tests

Dynamic CTOD tests were carried out on the test plates in order to obtain a more direct link between laboratory tests and structural performance than can be achieved using charpy energy. The necessity to use dynamic CTOD tests is because most ship steels and welds are sensitive to loading rate. If static fracture mechanics testing is used, a ship steel which maybe brittle under dynamic loading may appear misleadingly ductile if slowly loaded. The dynamic CTOD test is performed on a sample of the same thickness and crack sharpness (fatigue cracked) as the structure, at a structurally relevant temperature and loading rate. Using the structurally relevant parameters, temperature, strain rate and stress level fracture mechanics will give an unambiguous answer on whether the steel or weld is suitable for use in ship construction.

In the testing described a number of sample types were used see figure 9:

1) a deep machine notch on weld centre line;
2) a deep machine notch on weld HAZ;
3) a deep machine notch in the plate;
4) a shallow notch on weld centreline;
5) a shallow notch on weld fusion line.

The result of the tests can be summed up in figure 10. for the weld centreline where the laser weld results are superior to those for single and multipass arc welds. For the weld HAZ the dynamic toughness of the laser welds figure 11. are equivalent to those for the single pass arc welds but somewhat less than for the multipass arc HAZ. The defect tolerance of the laser weld zone is greater than that of conventional arc welds and that of the laser weld HAZ is equivalent to that of the single pass arc weld. It is clear therefore that the laser welds tested have adequate toughness for use in ship structures (3). Where the fatigue crack is located in the weld the crack deviated and propagated by cleavage along the fusion boundary whereas a crack initiating in the fusion boundary continued in that plane.

2. Corrugated Core Structures

An alternative concept to frame stiffened panels is LASCOR a lightweight metal corrugated cored structure which has been under development since the late seventies. Test and evaluation is continuing in the areas of static and dynamic strength, fire, corrosion, fatigue and ease of manufacture. The concept originally developed for reduced weight and survivability, was focused on top side structures above the main strength deck where there is the highest payoff. However , there are many other applications below topside and above the ships centre of gravity where there could be advantages in weight savings such as decks, bulkheads, ramps, hatch covers, etc. Although reduced strength is not ruled out in main strength decks it would require a significant test and evaluation program to validate its use.

Originally a number of cored structures were considered to give designers options over conventional ship structures at affordable cost. Lascor does not require conventional stiffening until you get to major transverse supports and the designers by taking advantage of the self stiffening configuration can increase the usable compartment volume. This provides more usable space and uninterrupted flat surface areas for supporting marine systems which results in reduced fabrication costs over conventional plate beam construction.

Lascor sandwich panels are a type of stress-skin construction in which the face sheets resist nearly all of the applied edgewise loads (i.e. in-plane compression and tension) and flatwise bending moments and shear. The corrugated core spaces and stabilises the face sheets and transmits the shear. The concept relies on two strong, thin face sheets far enough apart to achieve a high ratio of stiffness to weight, using a strong core that provides the spacing and also provides the required shear resistance and face sheet stability. Because of its basic corrugated core configuration, the structure can be optimised on the basis of weight and/or cost by varying one or more of the design variables: core height, core pitch, core angle, core landing, core thickness, face sheet, and material height, figure 12. For example, if high stiffness is required, as with the case of vibration concerns, then more closely spaced corrugations are required. However, this necessitates increased welding time because of the increased number of corrugations which require to be welded. To reduce cost and weight, a non-symmetrical design may be generated by reducing the bottom plate thickness. It should be noted that in bending of thin plates alone, LASCOR is about 10 times stiffer than steel.

Lascor is orthotropic and thus it was necessary to develop a parametric FEM study to establish its response in to bending moments, shear forces, membrane forces and deflections. The developed theoretical equations required validation and this has been carried out using small scale tests of in-plane compression, bending and shear. The test data allows reliable equations to be developed which predict the critical buckling strength of the face sheet and core under these conditions. Based on this data the initial structural failure of the panel can occur by local buckling of either the face sheet or the core. This has been confirmed many times but what is not fully understood is what the global buckling behaviour is and how to predict its behaviour.

a) Results of Small Scale Testing

The Lascor concept is a departure from the norm and equal confidence must be developed in the reliability and performance of these structures before designers will consider using such structures as a viable alternative in ship construction. In order to develop confidence in Lascor structures it is necessary to examine the performance of the proposed structures. This can best be achieved with small scale panels the eventual transition to large structures and finally a full scale construction on the form of a ship. What the designer wishes to know is, having designed a Lascor panel for a particular purpose to meet certain strength and stiffness requirements, will the panel perform in the predicted manner? Equally important, will the laser weld stand up the imposed stresses.

The US and UK navies have developed a number of designs for laser panels with a variety of dimensions, testing them both statically and in fatigue. The static tests were carried out in order to determine the Longitudinal and Transverse Bending Strength, the Longitudinal and Transverse Shear Strength, the Flatwise Compression Strength and the Longitudinal and Transverse Edgewise Compression Strength. Additionally, a number of fatigue tests were carried out using of the above test directions.

The tests described here were carried out on laser welded panels with the dimensions shown in figure 13. Although panels have been manufactured using single, twin, triple and sinusoidal laser welds per corrugation, the results quoted here refer to panels welded only using a single linear run per corrugation.

The results of the longitudinal and transverse bend tests are shown in figure 14. plotting deflection, as measured by a displacement transducer located in the centre of the panel against load, measured directly from the testing machine. It is clear, as might be expected, that in the longitudinal direction, the maximum bending load achieved is considerably greater then in the transverse direction. The loading in both test directions increases to a maximum before falling away as bowing commences in the core adjacent to the face plate below the loading points. As bowing develops through the core, as in the case of the longitudinal bending test, the load remains high before falling as the core collapses.

For the comparison of the longitudinal and transverse shear strength tests, figure 15. there is again a considerable difference between the two test directions.

After reaching a maximum the load, in the case of the longitudinal test sample, remains high as bowing occurs in the core, before collapse of the structure takes place below the loading points, as indicated by the fall off load. The load thereafter rises again as the structure becomes rigid due to the local interaction of the buckling and bowing modes of failure.

The collapse of the flatwise compression test sample was characterised by two peaks in the load deflection curve, figure 16. The load initially rises as the panel resists the imposed deflection before falling off as the core succumbs to failure by buckling. Following the initial failure mode there is a further increase in load as the realigned core continues to resist the increased deflection before the load ultimately falls again with the final buckling of the vertical core members Clearly deformation of the panel in the through thickness direction has the potential for absorbing a considerable amount of energy as the core collapses. This could be beneficial in some circumstances, such as blast loading.

Longitudinal and Transverse Edgewise compression tests also show considerable variation in performance, figure 17. Once again the results for the load carrying capacity of the longitudinal sample is much greater than that for the transverse sample The small flat portion of the transverse curve is the result of the early buckling which is not evident in the longitudinal sample.

The final failure in all the static tests was by core buckling. In no case did any of the laser welds fail even though in some extreme cases the surface plates showed signs of ductile tearing. The modes of collapse varied somewhat but generally followed the forms shown in figure 18.

In addition to the static loads tests some fatigue testing has been carried out using similar loading regimes. Here, it was assumed that there was equivalence between a "longitudinal welded attachment loaded parallel to the weld," (British Standard Classification C (BS5400 Part10, 1980 Steel, Concrete and Composite Bridges, Code of Practice for Fatigue)) and the Lascor samples tested in longitudinal compression. It was also assumed that the Lascor transverse bend, longitudinal edgewise compression and the transverse edgewise compression fatigue tests were equivalent to a "longitudinal welded attachment loaded transverse to the weld" (BS5400 Classification F). The results for these tests, figure 19., indicate that the various requirements are attainable. It has also been shown that, as might be expected, multiple welded panels perform better than panels with single linear welds and that panels using sinusoidal laser welds to attach the face plates to the core exhibit the best performance.

b) Service Requirements

1. Fire.

In general Lascor type structures have an advantage when it comes to fire, as compared with steel plate beam structures which require insulation, in that the open volume acts as an insulation barrier in the transmission of heat from one side to the other. This barrier contributes to a significant temperature differential when Lascor panels are subjected to ASTM E-119 slow temperature rise versus time type fire tests. The E-119 criteria requires that the temperature on the non-fire side remains below 232°C (the accepted temperature for the ignition temperature of common consumable materials) for the first 30 minutes. For the E-119 fire tests a bare 51mm thick Lascor panel took twice as long to reach 232°C as the flat plate equivalent, eight times as long if the voids are filled with foam (polyisocyanate) and will never reach 232°C in a 60 minute E-119 test with 25.4 mm of standard insulation on one side; no foam filled voids.

2. Noise

Lascor panels are effective in reducing the transmission of high frequency sound but less effective in attenuating low frequency sounds.

3. Corrosion

Lascor was never intended to be submerged in water as is the case of a hull structure, but rather used topside (exposed weather) and internal structure above and below the main strength deck. When Lascor is manufactured from a suitable stainless steel there is no corrosion problem. However, when it is made from carbon steel corrosion protection of the inner core must be considered because of the inaccessible void. For deckhouse structures and other applications exposed to the weather corrosion protection is advisable. For internal non-weather applications corrosion protection may not be required. For cases where corrosion protection is required the use of lightweight close celled foam (polyisocyanate) could potentially solve the problem. This foam can be sprayed into the inner core after fabrication and expands to a given volume filling up the entire void volume. From preliminary corrosion testing this foam has shown considerable promise in eliminating internal corrosion. It completely seals all the hidden volume within the core and it does not absorb water. It also shows promise in providing an effective fire barrier and in some cases may even reduce the amount of fire insulation required.

3. Applications

There are a number of examples in service where corrugated core panels have been used:

a. Close in weapons system enclosure, 8' x 8' x 21', on a destroyer comprising a weather exposed deckhouse made up of a magazine, repair compartment and gun control room. Lascor deckhouse resulted in a 25% reduction in weight.

b. A large avionics workshop complex and stowage platform on board a carrier the former measuring 60' 45' x 10' and the latter 12' x 60'.

c. Deck edge elevator hanger bay door on a carrier. It is reported that there is a decrease in the required maintenance for the machinery which operates the door as a result of a 50% decrease in weight of the door. This door has been exposed to aircraft, forklift, truck traffic and wave slap loads without incident.

d. Large 36' x 12' x 3" antenna platforms on a Navy combattant resulting in a 33% weight saving and adequate structural stiffness.

e. Currently a number of 42' x 22' Lascor hatch covers, which will experience severe static and dynamic loads from stowage and movement of vehicles (tanks, trucks, forklifts, etc.) are being fabricated for the sealift ship programme. It is proposed to fabricate future deckhouses in US Naval and Coast Guard vessels.

f. Primary structural applications are also being considered including flight decks, strength decks, athwart ship watertight subdivision and longitudinal bulkheads.

g. The UK Navy have recently constructed a Lascor 8' x 8' carrier flight deck panel which is about to undergo rigorous testing including buckling. Further tests of this type of structure for both UK and US authorities are planned.

4. Lessons learned

1. No flame straightening of Lascor structure required.
2. Straight orderly routing of marine systems can be achieved.
3. Thermal insulation requirement reduced in Lascor structures due to air space between face sheets.
4. Requirement for structural painting and coating reduced as less surface area exposed.
5. Flatness of Lascor panels minimises deck tiling difficulties associated with conventional decking.
6. Installation of equipment and machinery foundations less complicated.
7. Fire blocking ability of Lascor structures is of great value.

5. Summary

Tests on laser welded ship structural samples has shown that their performance in respect to strength, toughness, fracture mechanics and fatigue is equivalent or superior to similar conventional arc welded structures. Some further work needs to be undertaken to investigate the buckling behaviour of laser welded structures. It is believed that with the appropriate design changes, modifying the structural slenderness of the plating, it will be possible to constrain the failure mode to a smoother elasto - plastic failure.

Laser welded Lascor corrugated core structures have demonstrated acceptable performance via a variety of strength and fatigue tests. Significant weight reductions have been achieved in the structures that have been designed for use in existing classes of warship. The reported performance of these structures to date is very encouraging. Further benefits will accrue from the use of Lascor structures with respect to fire, insulation, flatness, ease of painting and coating etc.

References

1. Brooke S J	High Power Laser Welding of T Joints in Ship Production. Transactions of North East Coast Institution of Engineers and Shipbuilders. Vol. 104, No 3, June 1988.
2. Furio A J Bird J	Lightweight Metallic Corrugated Core Structures an Option for the Future. Proceedings of the Fast Ferry Conference, Singapore 25th - 27th February 1997.
3. Sumpter J D G	Fracture Toughness of Laser Welds in Ship Steel. Advanced Performance Materials 3, 393-405 (1996). Editor F H Froes, Kluwer Academic Publihers.

LARGE DUCTILITY TEST PANEL DIMENSIONS

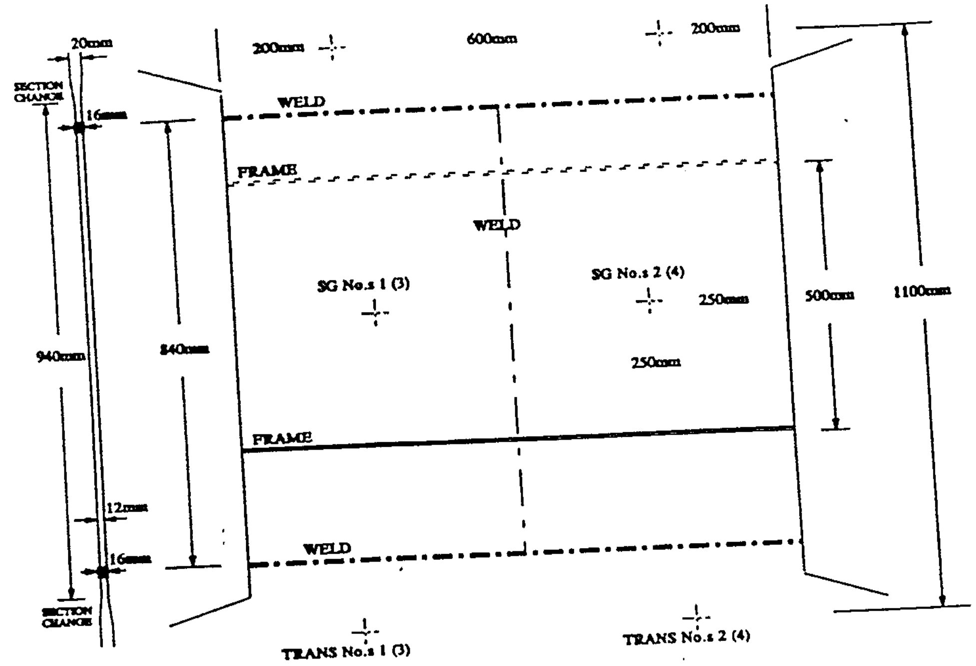

Figure 1.

DIMENSIONS of WIDE PLATE CRACK ARREST TEST

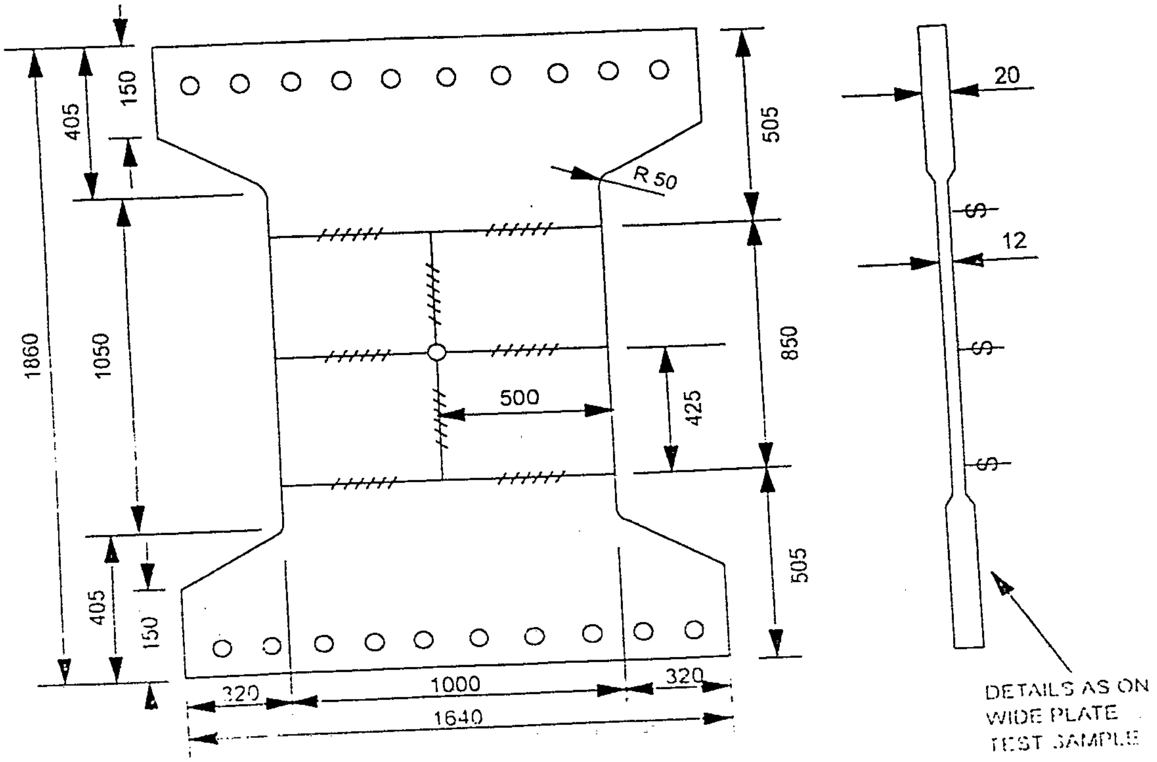

Figure 2.

PLAN VIEW of STRUCTURAL PANEL

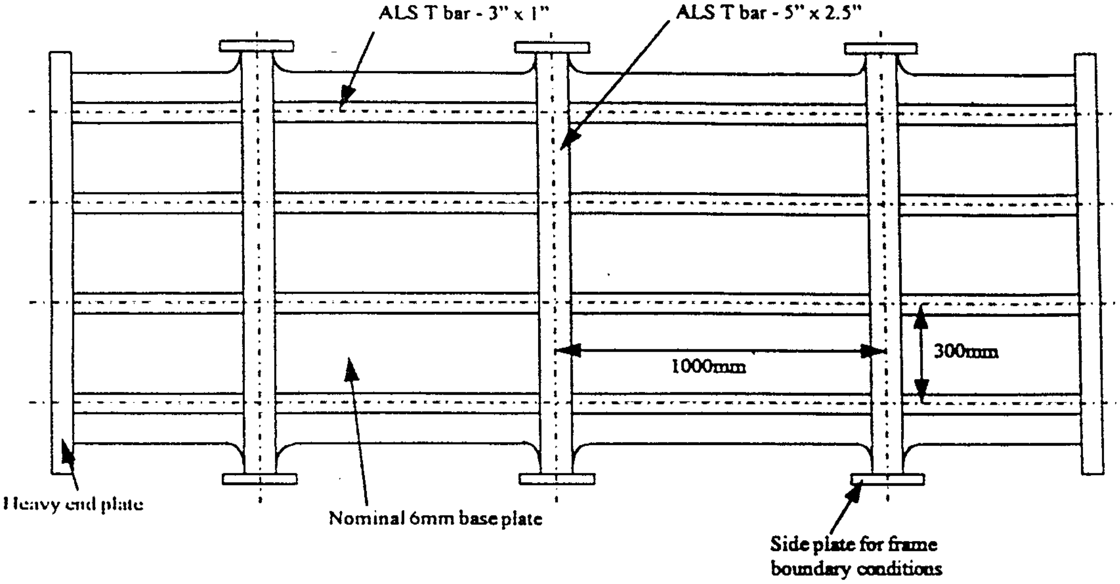

Figure 3.

LASER WELDED PANEL LOAD DEFLECTION CURVE

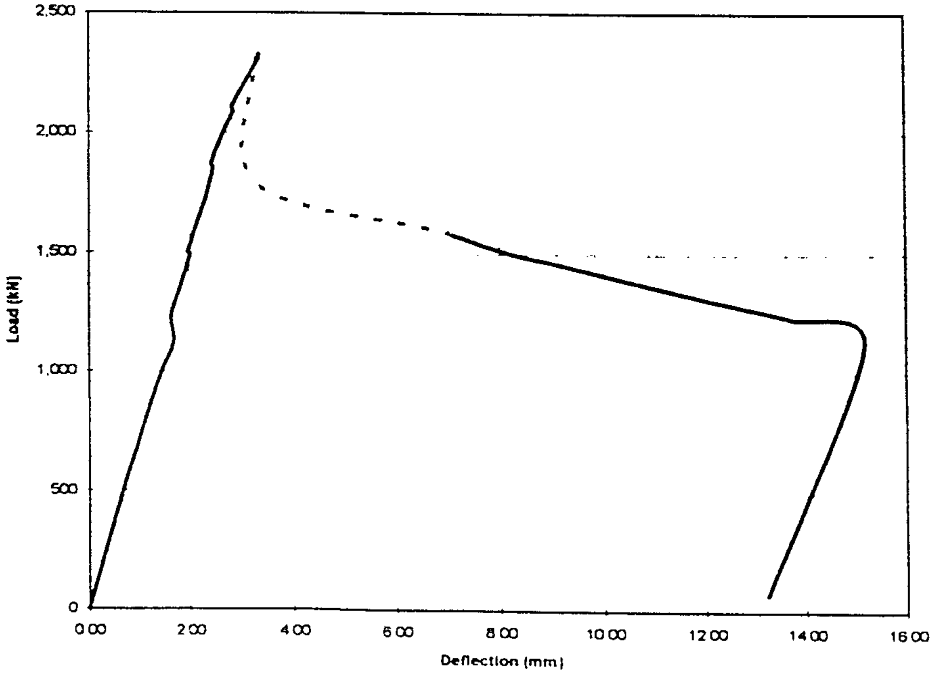

Figure 4.

ARC WELDED PANEL LOAD DEFLECTION CURVE

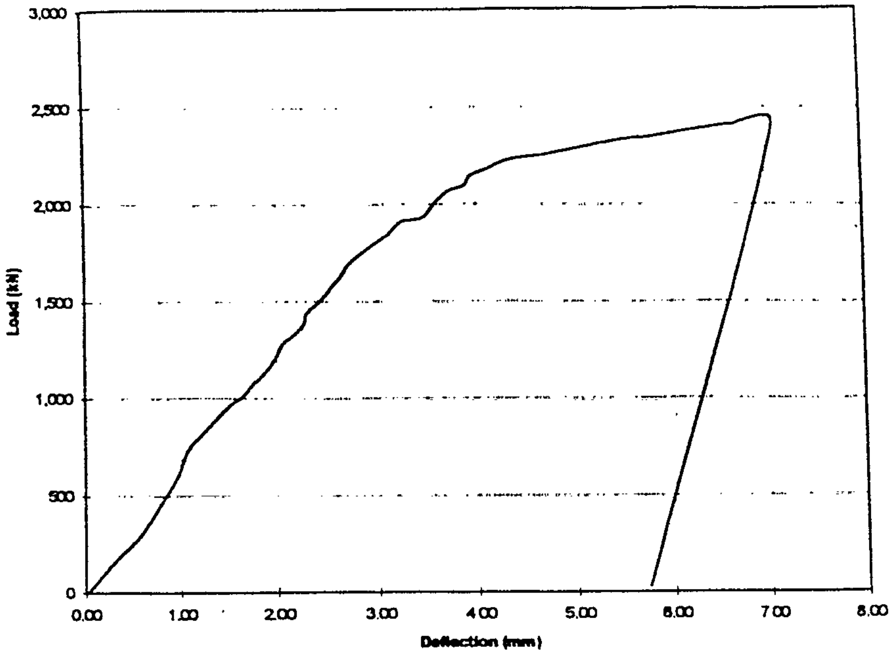

Figure 5.

FATIGUE TEST PANEL DIMENSIONS

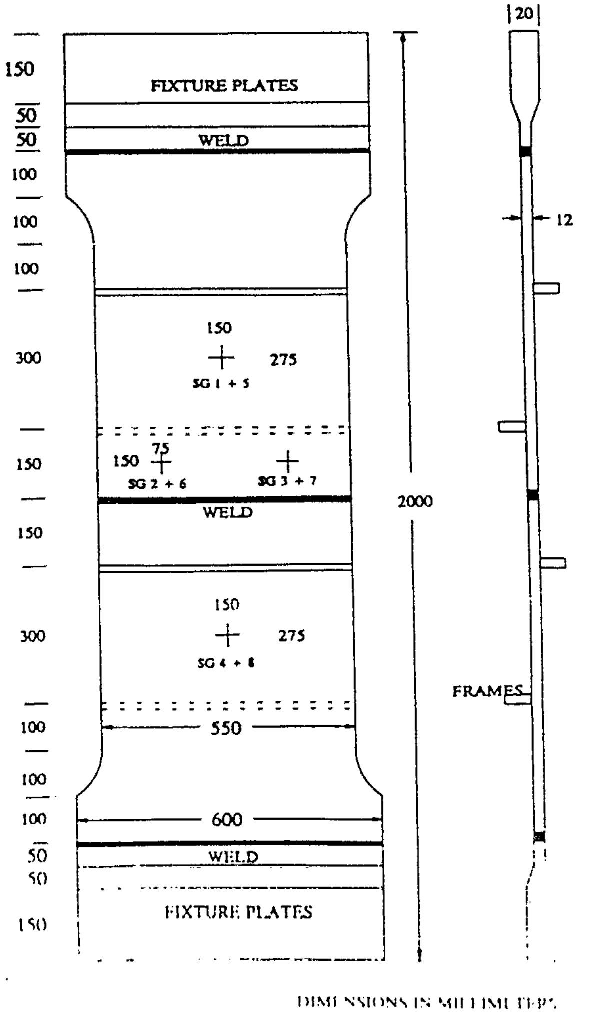

Figure 6.

MEAN CURVE CATAGORIES for FILLET and BUTT WELDS

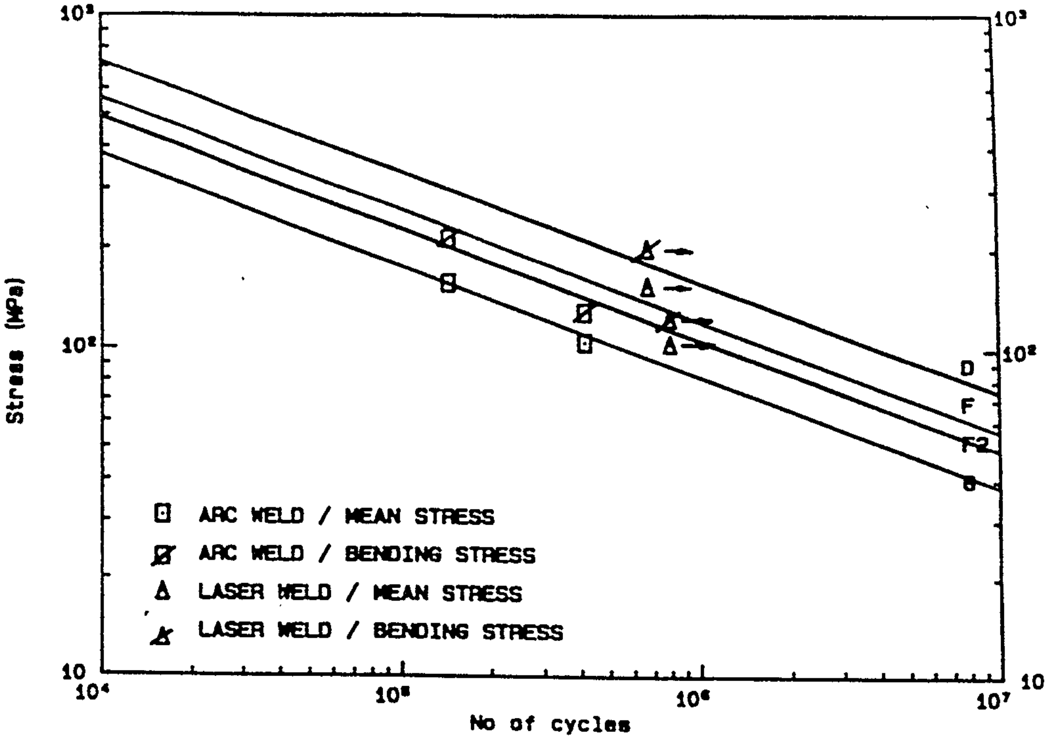

Figure 7.

-2sd CURVE CATAGORIES for FILLET and BUTT WELDS

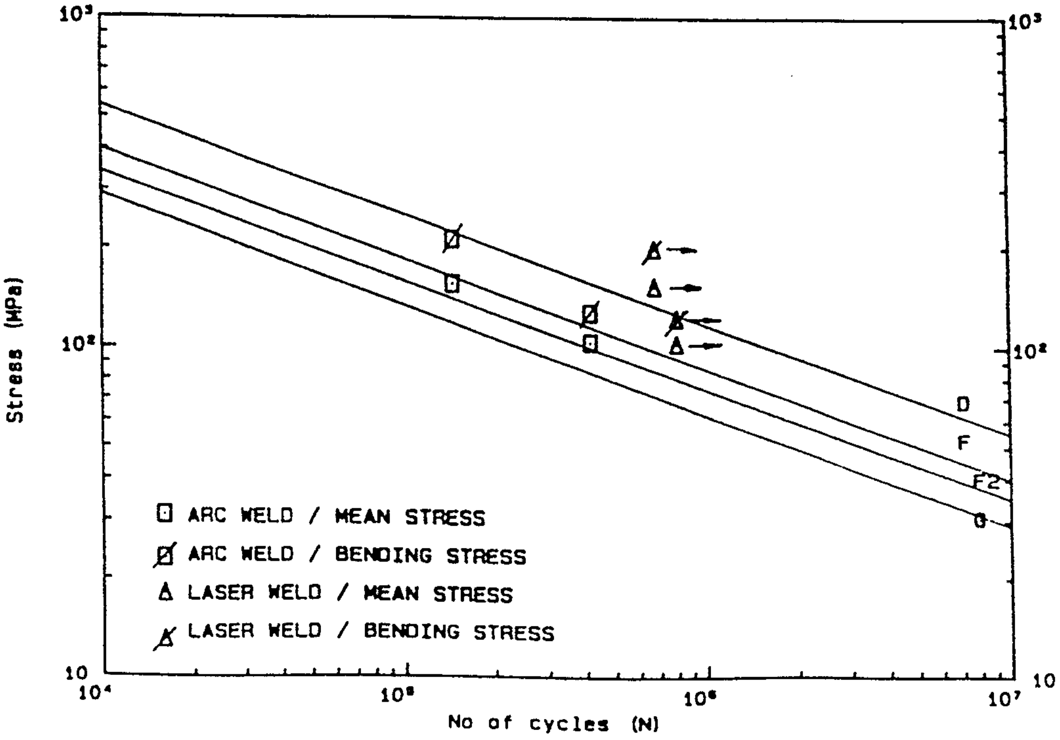

Figure 8.

FRACTURE MECHANICS SPECIMEN DESIGNS

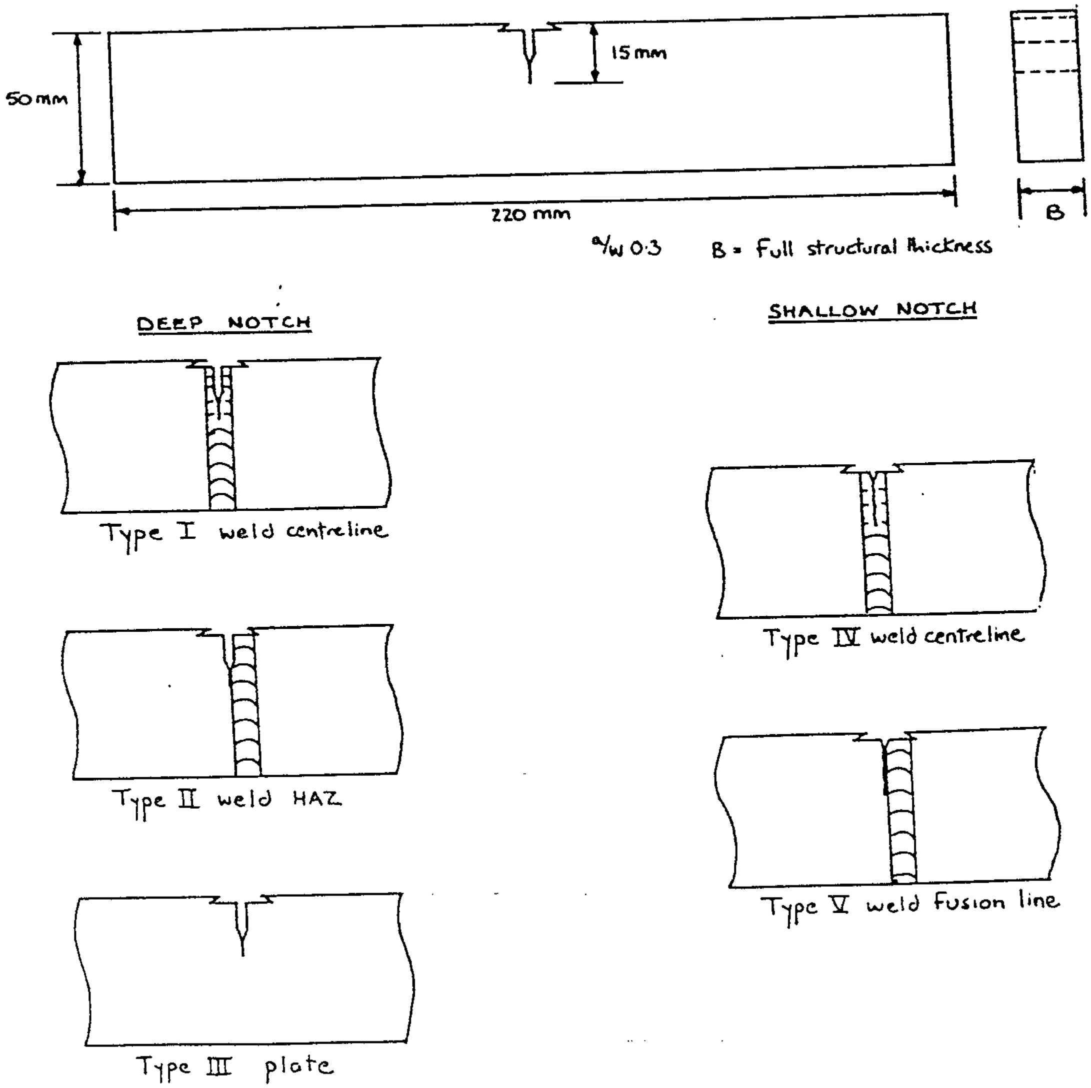

Figure 9.

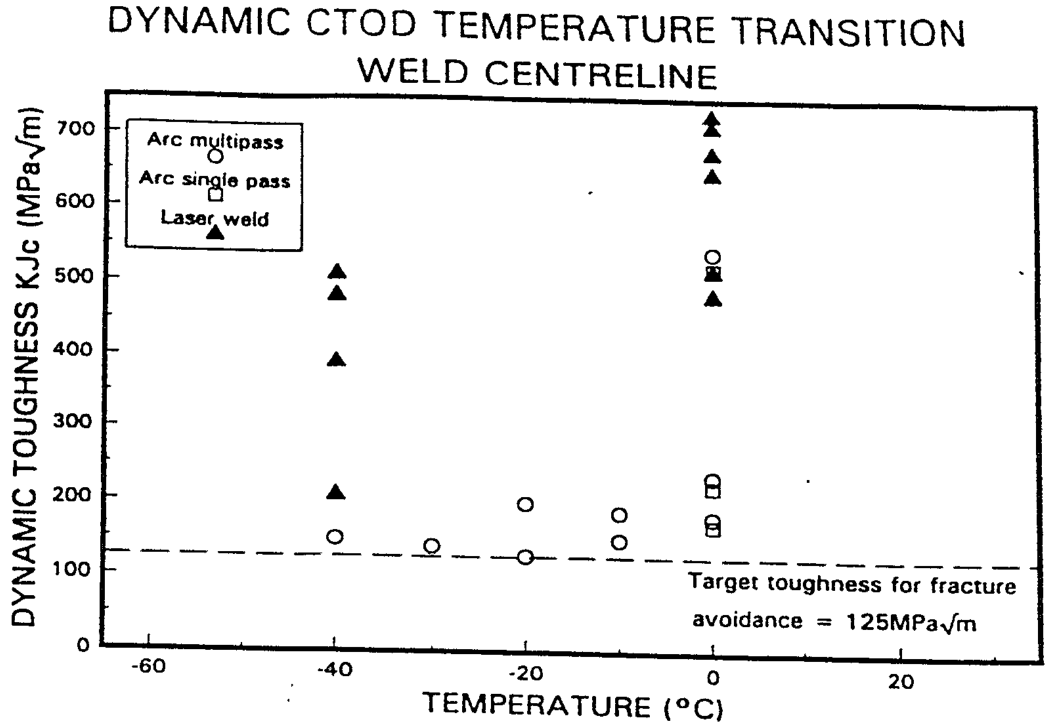

Figure 10.

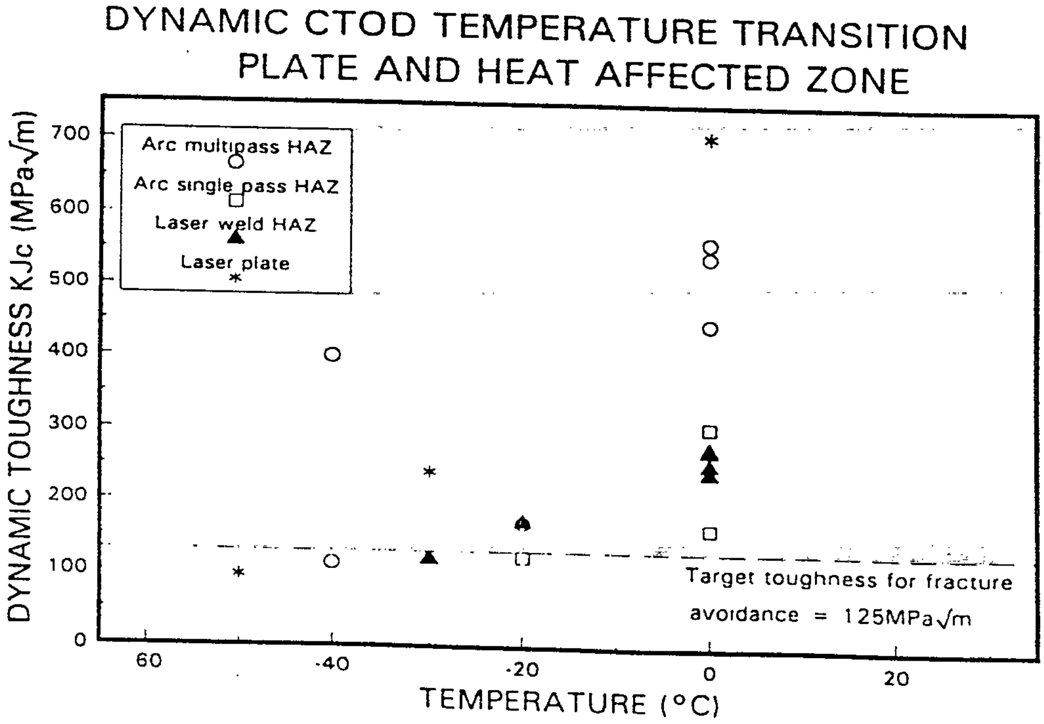

Figure 11.

CORRUGATED CORE SCANTLINGS

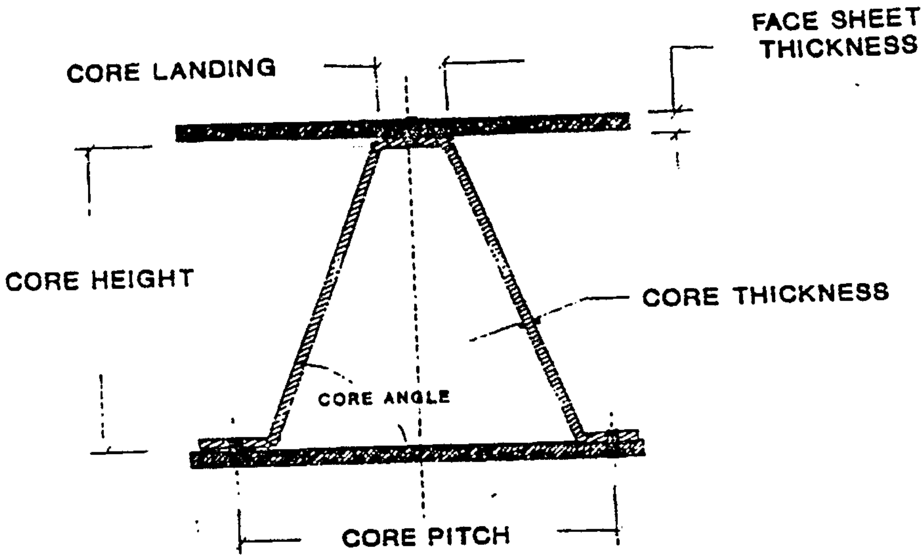

Figure 12.

TEST PANEL CONFIGURATION

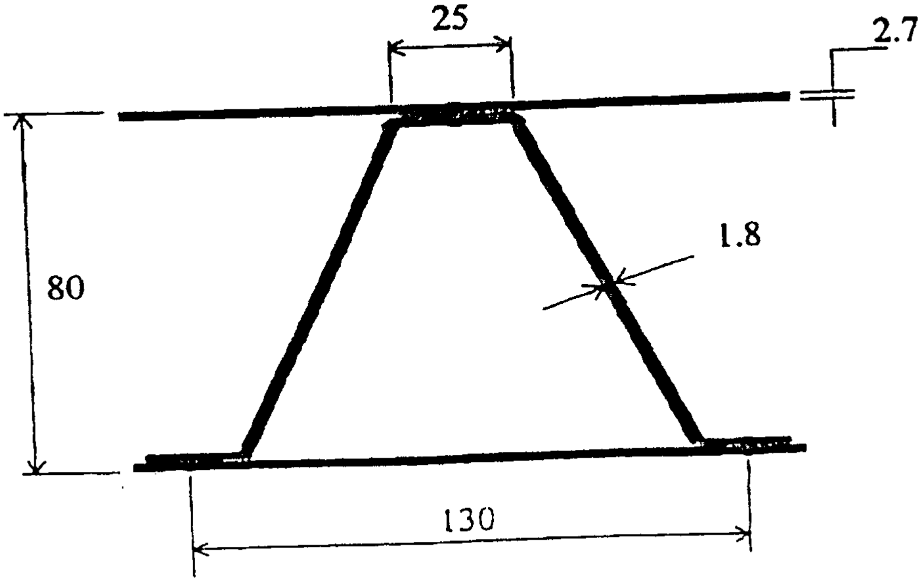

Figure 13.

BENDING STRENGTH

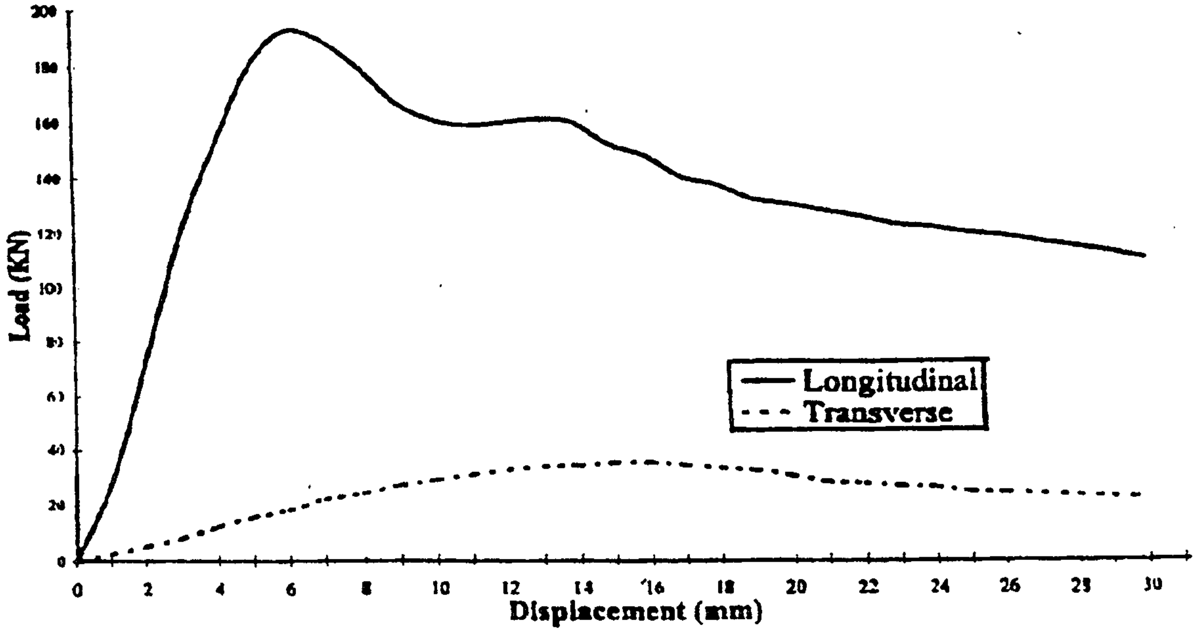

Figure 14.

SHEAR STRENGTH

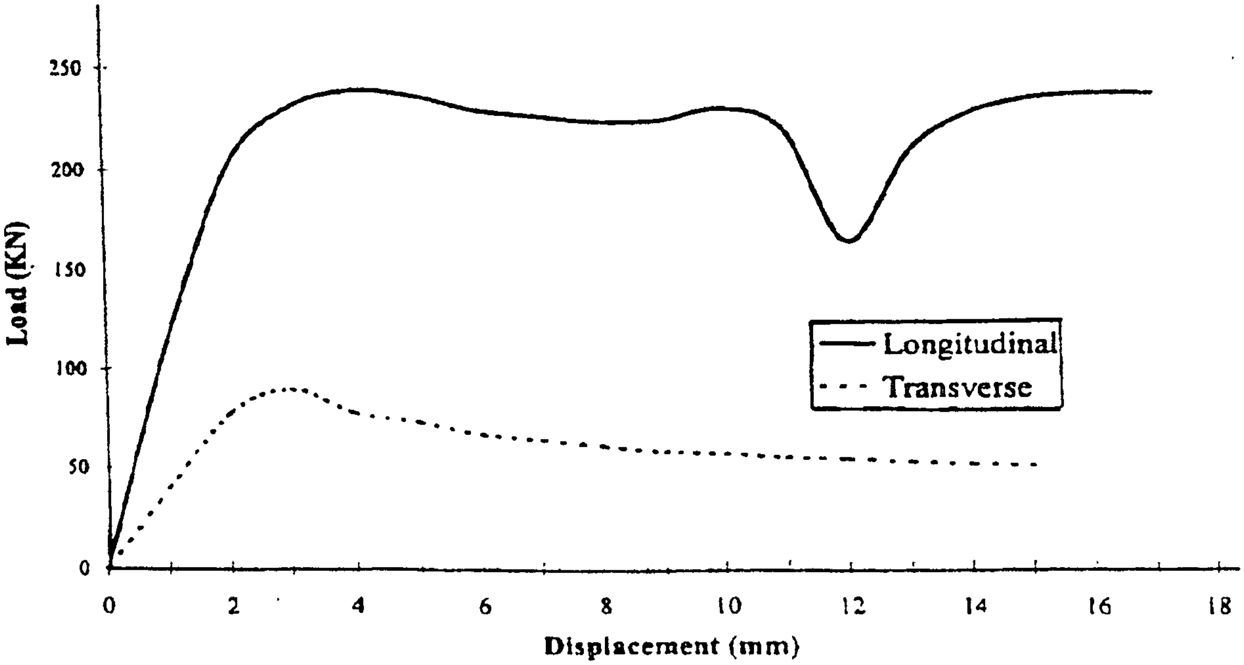

Figure 15.

FLATWISE COMPRESSION STRENGTH

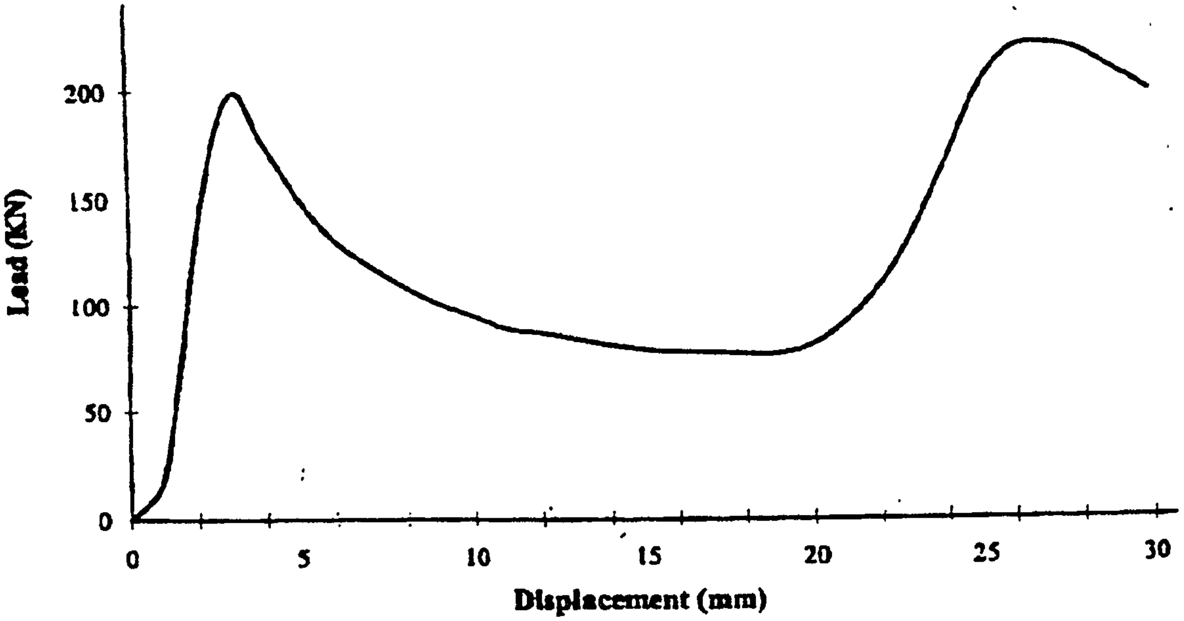

Figure 16.

EDGEWISE COMPRESSION STRENGTH

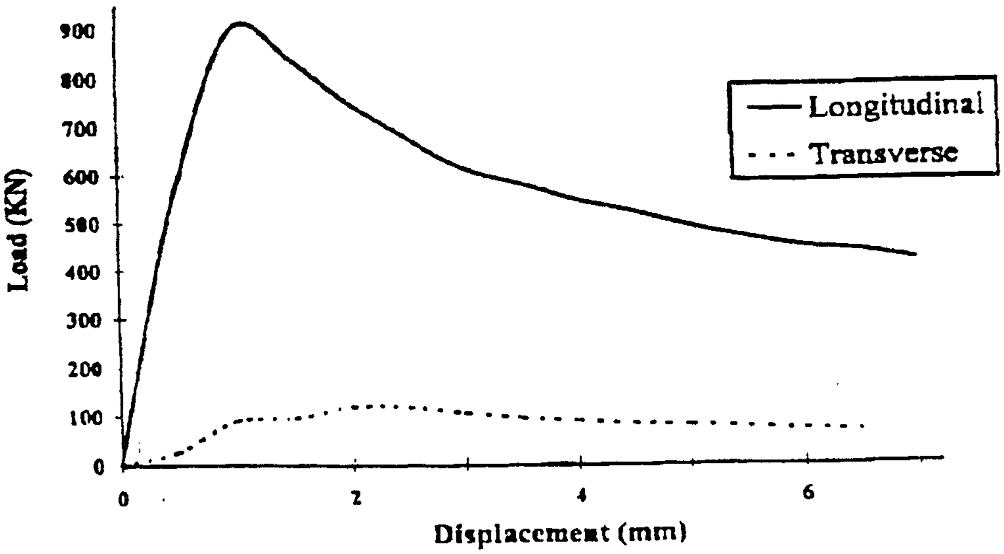

Figure 17.

FATIGUE PERFORMANCE

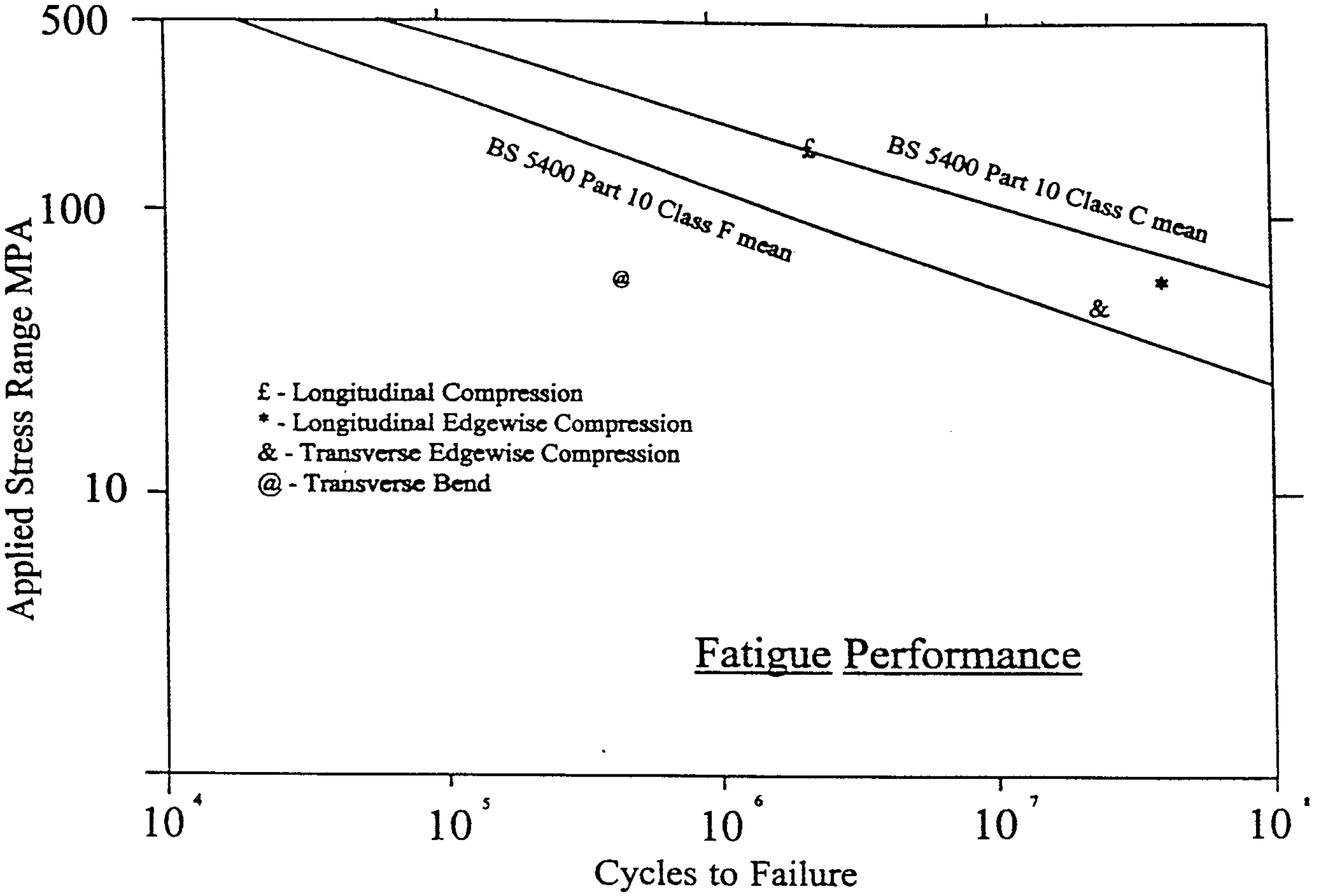

Figure 18.