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JIP - STRENGTHENING, MODIFICATION AND REPAIR TECHNIQUES FOR OFFSHORE PLATFORMS

PHASE II

DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES

FINAL REPORT

DOC REF C15800R025 Rev 1 SEPTEMBER 1997

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"This document has been prepared by MSL Engineering Limited for the Participants of the **Joint Industry Project on Demonstration Trials of Diverless strengthening and Repair Techniques.** This document is confidential to the Participants in the Joint Industry Project, under the terms of their contract in the project."

CONTROLLED DOCUMENT

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FOREWORD

This document has been prepared by MSL Engineering Limited for six sponsoring organisations:-

Mobil North Sea Limited
Chevron U.K. Limited
European Commission
Exxon Production Research Company
Health and Safety Executive
Minerals Management Service

The document addresses demonstration trials of strengthening and repair techniques for offshore installations, implemented using WROV or ADS intervention techniques. A project steering committee including representatives of the sponsoring organisations oversaw the work and contributed to the development of this document. During the life of the project, the following individuals served on the committee.

Mr G Beitch
Mr J Bucknell
Dr J Buitrago
Dr A Dier
Mr D Galbraith (Chairman)
Mr S Gholkar
Dr T M Hsu
Mr M Lalani
Dr J Mitchell
Dr C Smith
Mr C de Souza
Mr C Sparks

The Project Manager at MSL Engineering was Mr J Bucknell.

Mobil North Sea Limited provided information relating to the diverless repair of caissons on the Beryl B Platform which is gratefully acknowledged.

No responsibility of any kind for injury, death, loss, damage or delay, however caused, resulting from the use of any part of this document can be accepted by MSL Engineering or others associated with its preparation.

ABSTRACT

Trials have been successfully undertaken for a group of 6 sponsoring organisations to demonstrate the capabilities and potential for more widespread use of diverless techniques for the strengthening, modification and repair of offshore structures. Trials were conducted by both a work class ROV and an Atmospheric Diving Suit. The demonstrations culminated in trials underwater in a specialist facility recreating the current and poor visibility typically found offshore.

Activities undertaken included repair of tubular joints and repair/addition of brace members within a steel frame representing elements of an offshore structure. Load capacity tests were undertaken following the demonstration trials. Lessons learnt, conclusions and recommendations for both implementation of the techniques and for future work are reported.

CONTENTS

LIST OF FIGURES

Figure N°.	Title

TECHNICAL SUMMARY

The Joint Industry Project (JIP) entitled 'Demonstration Trials of Diverless Strengthening and Repair Techniques for Offshore Installations' was executed by MSL Engineering over the period 1995 - 1997 on behalf of six sponsoring organisations.

Background

In recent years, the use of remote intervention for the implementation of structural strengthening and repair systems has increasingly been recognised as offering substantial benefits over traditional diver intervention. Safety benefits result from removal of man from the water and consequent removal of potential long term health risks associated with hyperbaric exposure. Cost benefits arise from the ability of ever more reliable remote systems to utilise less costly support vessels and smaller operating crews. Technology benefits come from the ability to deploy repair systems at water depths beyond saturation diving limits, a matter of particular relevance for deepwater development. Quality control benefits result from operations being controlled from the surface allowing the engineer direct supervision of subsea operations.

Objective

The JIP was established to demonstrate that strengthening and repair systems can be implemented using remote intervention in a safe, cost-effective and operationally practical manner. The primary objective of the JIP was as follows:

- To conduct large scale in-water demonstration trials of selected structural strengthening and repair systems, using either a work-class remotely operated vehicle (WROV) or an atmospheric diving system (ADS), and including experimental assessment of the effectiveness of the implemented systems.

Scope of Activities

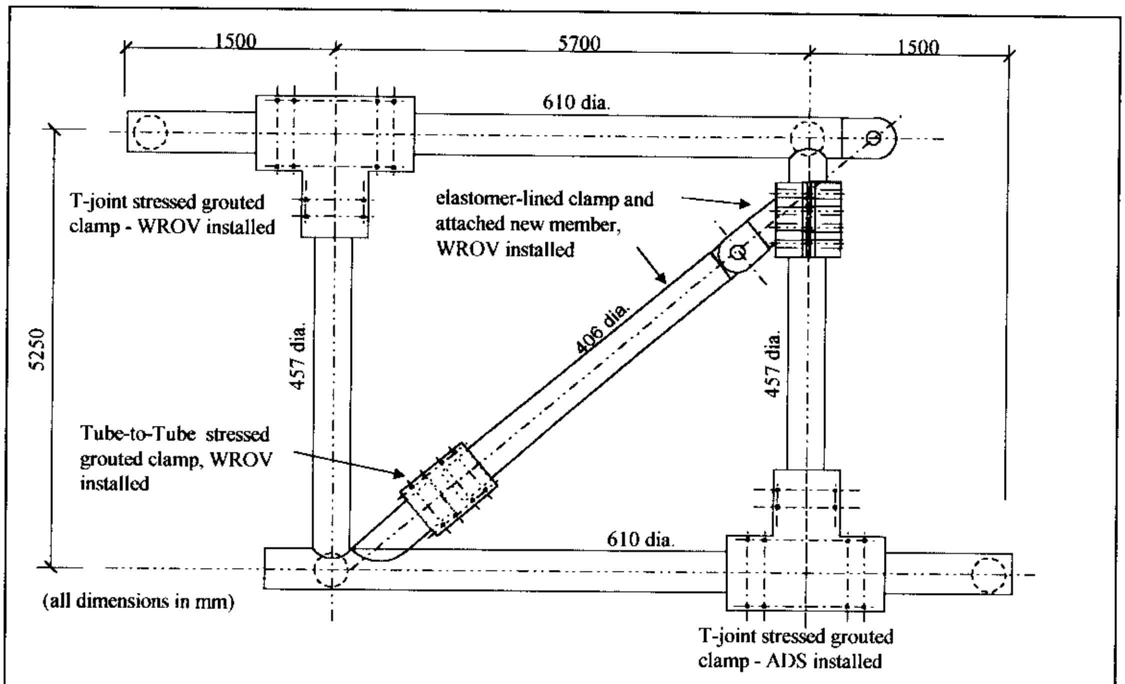
The objective was met through the execution of a scope of work which comprised the design, fabrication, component trials, dry 'fit-up' trials, in-water demonstration trials and experimental assessments for the following strengthening and repair scenarios:

(i) Repair of a T-joint with a stressed grouted clamp using ADS intervention.

(ii) Repair of a T-joint with a stressed grouted clamp using WROV intervention.

(iii) Placement of an additional brace member into a structure, utilising an elastomer-lined clamp and a tube-to-tube stressed grouted clamp and using WROV intervention. This scenario represented, in practice, both the repair of an existing damaged member and introduction of a new brace member.

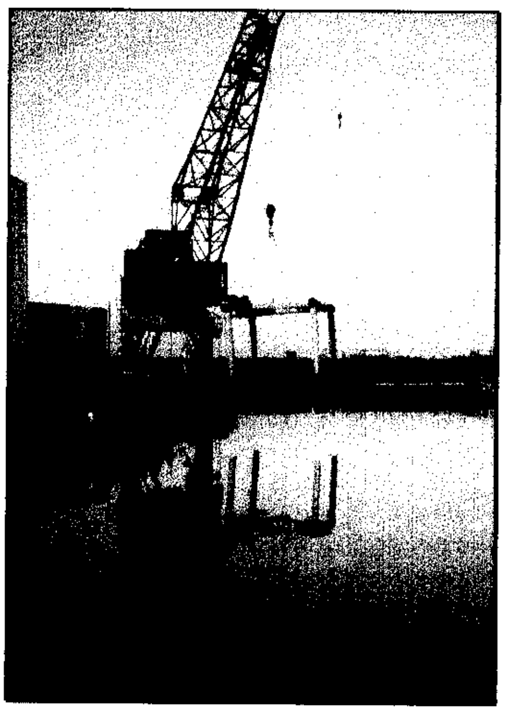
A plan of the test frame, together with the installed strengthening and repair systems, is illustrated in the figure below.



Plan View of the Test Frame and Installed Repair Systems

Component trials were used to confirm the adequate functioning of each of the 'WROV-friendly' installation systems and to develop and refine them as appropriate. Dry 'fit-up' trials were then conducted to confirm adequacy of the installation procedures, to ensure correct interaction of the individual installation systems and to familiarise the WROV/ADS crew with the intervention tasks required of them. The in-water trials were performed to demonstrate the ability of the developed designs and procedures to successfully implement each of the strengthening and repair scenarios identified above.

The demonstration trials were conducted at the Euro-Seas wet test facility located in Blyth, U.K. The facility features a wet test basin, 140m long by 25m wide, which was filled with sea water to a depth of 9m, simulating offshore subsea environmental conditions. The test frame, representative of a full-scale conductor bay of a typical offshore steel jacket structure, is shown opposite, being deployed into the test basin.



The steelwork for the test frame and repair components was designed in accordance with AISC/API recommendations. The clamps were designed using the recommendations from MSL's design manual for strengthening and repair techniques developed as part of a recently concluded JIP. Material procurement and fabrication was carried out in accordance with standard offshore practice.

Intervention

The ADS selected was the NEWTSUIT system; the alternative WASP system is not available in the UK. A detailed paper review was undertaken, which concluded that the two ADS systems possess essentially the same capabilities. The review is reported in Appendix A of this report. A SCORPIO WROV, fitted with two standard manipulator arms (5-function and 7-function respectively), was selected as being representative of non-specialist work-class vehicles currently used for offshore intervention tasks. The strengthening and repair systems installed by WROV were provided with 'WROV-friendly' installation aids to facilitate WROV interface. This necessitated the development of a number of innovative designs. On the other hand, the clamp system installed by the NEWTSUIT ADS was provided with standard diver-friendly aids, in accordance with the instructions, advice and preference of the NEWTSUIT operators.

Results and Observations

Innovative Design

A significant number of innovative designs were introduced to the strengthening and repair systems to make them 'WROV-friendly'. Full details are contained in this report. The innovative designs were subjected to a three stage development process involving independent component trials, dry 'fit-up' system trials and, subsequently, in-water system trials. A summary of each design is presented below:

- Clamp Manifold. A manifold was provided on each strengthening and repair system to allow the WROV to interface with, and provide power to, the clamp hydraulic systems and grouting system.

- Clamp Closure System. The two clamp halves were connected together via structural hinges. Hydraulic cylinders, mounted at each hinge, were used to adjust the orientation of the clamp and to close it around the test frame. Power was supplied to the cylinders via the clamp manifold. Opening and closure were effected from the surface pump control panel.

- Studbolt Restraint and Engagement. This consisted of an interface to permit the WROV to engage and push/wind the studbolts, a retainer to hold the studbolt in an elevated position during deployment of the clamp and a mechanism to hold and align the spherical washer and nut on the underside of the clamp.

- Direct Interface Self Centralising (DISC) Sealing System. This system permitted the WROV to simultaneously centralise the clamp with respect to the enclosed test frame members and seal the ends of the clamp to allow the annulus between the clamp and the test frame to be filled with grout.

- Grouting System. Conventional methods were modified to allow the WROV to control grouting operations from the clamp manifold. Grout sampling points were designed to allow efficient isolation and recovery of grout samples by WROV.

- Studbolt Tensioning. Specialised studbolt tensioners were developed. These tools, powered via the clamp manifold, hydraulically stretched the studbolts. The applied tension was locked into the studbolts by winding an external collar on each tool, a task efficiently performed using the WROV manipulator. The tensioning tools were manufactured by Hydratight Limited. Initial load loses of approximately 7% were measured, well within conventional design assumptions of 10%-15%.

The three stage development process enabled each design to be refined as required. In all cases, the fully developed solutions were shown to operate successfully.

NEWTSUIT ADS Performance

The ADS installed clamp was provided with diver-friendly aids, in accordance with the NEWTSUIT operators' instructions. During the dry 'fit-up' trials the NEWTSUIT was found to be unsuitable for installation tasks which constitute routine operations for divers. These tasks included the operation of tirfors (manual winching/pulling tools), operation of hydraulic quick-connect couplings and handling and winding of standard nuts and studbolts. Therefore, the 'WROV-friendly' operating systems were installed onto the NEWTSUIT clamp. The NEWTSUIT proved effective with the engineered interfaces, completing these operations successfully and with considerable time savings over the WROV. The time savings were derived principally from the following:

(a) The pilot at the work face has full 3D vision affording a significant advantage over the WROV which relied on 2D camera images with limited depth perception. Recent advances in WROV mountable 3D imaging systems look set to reduce this advantage in the near future.

(b) The pilot controls the NEWTSUIT limbs and manipulators by direct arm motion which is more effective than the remote mechanised operation of the WROV manipulators.

(c) The speed of the NEWTSUIT around the work site (where space is limited) was significantly faster than the WROV. The improved spatial awareness of the NEWTSUIT and its substantially lower inertia, compared to the WROV, reduced the risk and potential consequence of impact with the repair components or the structure itself.

It should be noted that some operating companies have concerns about, or operational restrictions on, the use of ADSs, relating principally to a requirement to have a back-up or rescue system available whenever an ADS is in the water. This requirement precludes their deployment from many offshore installations. These concerns and restrictions can make their use less economically attractive than the use of WROVs.

In conclusion, the NEWTSUIT ADS was not able to install a repair clamp using standard diver-installation aids. It is capable of achieving a successful clamp installation, provided each of the installation tasks are engineered to suit its capabilities. It was found that the 'WROV-friendly' operating systems, developed in this JIP to facilitate the WROV installation, are well suited to the NEWTSUIT.

WROV Performance

The strengthening and repair scenarios involving WROV intervention were each successfully completed. In addition to the wealth of lessons learnt relating to the innovative designs developed to make the structural clamps 'WROV-friendly', the following generic observations, relating to WROV intervention, were highlighted:

(i) Dry 'fit-up' trials are an invaluable part of the preparation for deployment and should be included as part of a strengthening and/or repair operation to be implemented offshore.

(ii) In a low current environment the WROV should be configured to maximise manipulator ambidexterity and specified with 7-function manipulator arms as a minimum. This specification, combined with appropriate grab bars is sufficient for successful intervention. In a high energy environment use of a separate station holding device such as a standard hydraulic docking device or a suction 'foot' is preferable.

(iii) Suitable lighting and camera configurations are essential and it is recommended that an additional simple manipulator arm be available for adjustable positioning of such equipment.

(iv) An 'eyeball' (observation) ROV should be specified to assist the WROV pilot with a second visual perspective of both the work site and the WROV itself. The 'eyeball' ROV should be fitted with a device to maintain station as required. Use of a tether management system for the launch of both vehicles should be considered, to minimise potential interference (tangling) of the umbilicals.

(v) The WROV should carry a dedicated work sled containing all tools and fittings required for the completion of the intervention tasks being performed. The tools or fittings should be contained in holsters and readily retrievable by either manipulator.

(vi) Visual indicators are recommended for all tasks requiring WROV observation. Such indicators should be appropriately coloured and graduated to allow accurate reporting and logging of the progression of the task.

(vii) For deepwater applications hydraulic power for the 'WROV-friendly' operating systems should be supplied from a dedicated power supply mounted on-board the WROV.

(viii) Non-productive time associated with malfunction of the WROV may amount to 10% to 15% of the overall installation of a typical strengthening or repair scheme used in this JIP. The impact of this down-time may be reduced by the specification of a standby WROV which should be considered on a cost-benefit basis.

Experimental Verification

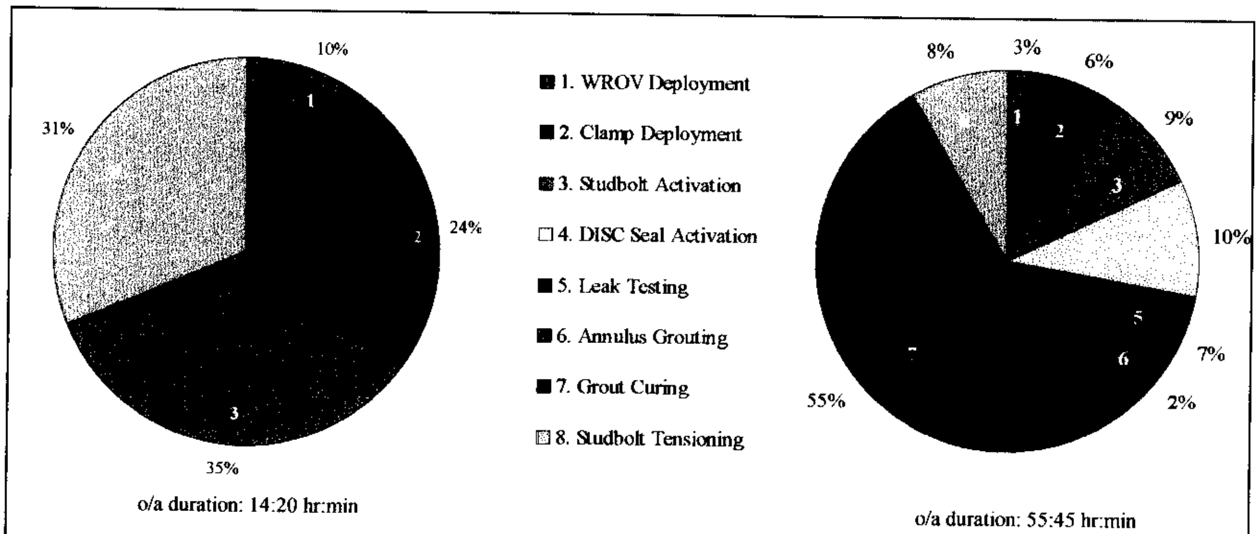
Structural failure (slip) tests were conducted on each of the four clamp strengthening and repair systems installed during the in-water trials. With the single exception of the results for the tube-to-tube clamp (see below), the tests demonstrated that appropriate systems and procedures were used to achieve satisfactorily installed repairs. In addition the tests indicated:

- Torsional slip capacity of stressed grouted clamps appears to be accurately predicted from existing design guidance based upon axial slip strength.
- Slip capacities for elastomer-lined clamps estimated using present day practices may be unconservative and potentially unsafe. A programme of further investigations is recommended.

The exception, mentioned above, relates to the tube-to-tube stressed grouted clamp. Tests showed that the preload was not introduced into the studbolts. Extensive forensic examination revealed that the most likely cause was that the hydraulic pump pressure did not reach the tensioning tools due to an incomplete connection at the clamp manifold following the apparent stabbing of the hydraulic line.

Installation

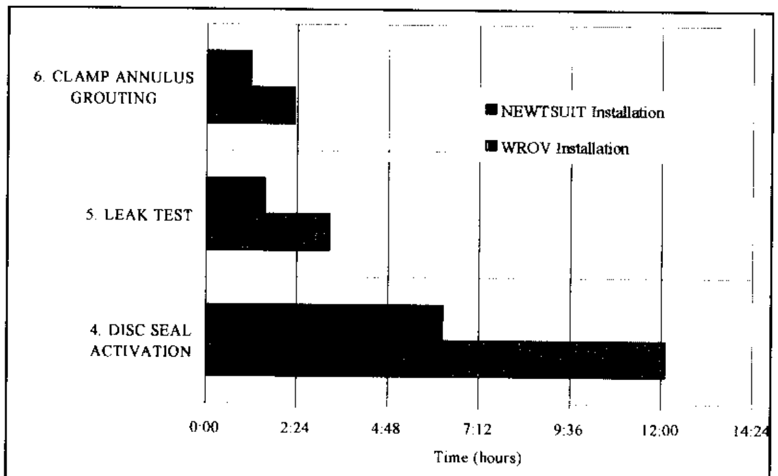
The successful completion of the demonstration trials has allowed the creation of a set of recommended installation procedures, described in detail in this report. The recommended procedures are applicable to clamps of a scale and complexity similar to those installed in this JIP, i.e. 1.5 - 2 tonnes in weight and of 8 - 12 No. studbolt configurations. Estimated task durations from the recommended procedures are illustrated in the pie charts below. The charts relate to an elastomer-lined clamp and to a stressed grouted clamp, respectively.



Elastomer-Lined Clamp   Stressed Grouted Clamp

It can be seen that the overall installation time for a stressed grouted clamp is almost four times that required for the installation of a similar elastomer-lined clamp. Excluding time required for grout curing, when the WROV may be usefully employed elsewhere, an elastomer-lined clamp can be installed in a little over half the time required for a grouted clamp.

Comparative analysis of task durations for the WROV and NEWTSUIT ADS reveals that, provided both intervention methods benefit from a fully engineered remote solution, the ADS can complete similar intervention tasks, in about 50% of the time required by WROV. This is illustrated, for relevant activities, in the bar chart opposite.



WROV and ADS Comparative Task Durations

Inspection and Maintenance

Clamps for offshore installation are generally fitted with sacrificial anodes designed to cathodically protect the clamp against corrosion. Similar protection is required for remotely installed clamps where the protection system should be designed to include the clamp manifold. The hydraulic studbolt tensioners and the hydraulic stab connections should be individually protected with push-fit covers packed with waterproof grease. Periodic inspection of the installed clamps can be performed remotely and should involve, in addition to visual examination, re-tensioning of studbolts via the clamp manifold and replacement of the protective covers.

Diver Intervention

Certain of the innovative designs developed to facilitate remote implementation can offer considerable benefits to diver intervention. The DISC sealing system, which was proved to operate considerably more effectively than traditional clamp sealing systems is readily operable by divers without modification. The studbolt tensioning system also offers some advantages over standard diver-friendly systems, including ease of operation and the potential for re-use during planned inspections. Consideration should be given to the inclusion of each of the other installation systems on a case by case cost/benefit basis.

Closure

The JIP has been successfully executed and the objective has been met. A recommended set of designs and installation procedures have been created as the principal deliverable, fully developed through a three-level tier of functional, dry and in-water demonstration trials. These recommendations can now be used for the offshore deployment of clamp strengthening and repair systems using either an ADS, a WROV or both.

1. INTRODUCTION

This document has been prepared by MSL Engineering Limited (MSL) and represents the final report of the Joint Industry Project (JIP) entitled 'Demonstration Trials of Diverless Strengthening and Repair Techniques for Offshore Installations'.

In recent years, the offshore industry has seen a change in intervention philosophy for subsea activity from manned diving to remotely operated systems. There are a variety of inter-related factors which have contributed to this change, viz:-

- Diving operations at any water depth have been recognised as potentially hazardous. Remote intervention permits the direct safety risk to divers to be removed.

- Long term health risks associated with hyperbaric exposure, as experienced by divers in medium to deepwater, are, as yet, unquantified. This is becoming an increasing concern to regulatory authorities throughout the world and is reflected in restrictions on depths to which diver-based intervention is permissible.

- Technological developments over the last decade have established opportunities to extend exploration and production operations to deepwater, often beyond the permissible, practical and/or economic limits for manned diving.

- Direct economic comparison often favours a remote intervention solution, particularly with the improved reliability of remote systems and their ability to be deployed from the installation being worked, or to use less costly support vessels and smaller operating crews.

The JIP was established in light of the above, with specific focus on strengthening, modification and repair (SMR) techniques and was executed over the period 1995 to 1997.

The primary objective of the JIP has been to conduct large scale in-water trials, of selected structural SMR techniques, using either a work-class remotely operated vehicle (WROV) or an atmospheric diving system (ADS), including experimental assessments of the effectiveness of the developed and implemented systems.

The above objective has been fully met through the execution of the following principal activities:

- Selection of the SMR scenarios for the trials (Section 2)

- Detailed structural design and engineering (Section 3)

- Materials and fabrication (Section 4)

- Selection and design of intervention systems and installation aids (Section 5)
- Component trials (Section 6)
- System trials in air (Section 7)
- System trials in water (Section 8)
- Verification testing of the systems installed in water (Section 9)

The remainder of this document deals with each of the above principal activities carried out in this JIP. A significant number of lessons have been learnt from the various trials. These are catalogued in detail in Sections 6 to 9 as appropriate.

2. SMR SCENARIOS

At the outset of the project, both the sponsoring organisations and MSL recognised that structural clamps, of all SMR techniques, are best suited to remote intervention. Further, historical experience over the past two decades indicates that structural clamps represent a popular choice and have a wide application. Structural clamps have been used in the following SMR applications:

- Strengthening of tubular joints. This need may arise, for example, as a result of code update, underdesign, new environmental information or change of use for platforms.
- Repair of tubular joints. This need may arise as a result of damage from, for example, ship impact, environmental overloads, fatigue cracks, dropped objects, fabrication defects or corrosion.
- Repair of corroded or dented structural members.
- Repair of corroded caissons.
- Replacement of an existing damaged or understrength member.
- Addition of new members.
- Addition of new conductor guides.
- Attachment of retrofit risers to existing structures.

The world's first application of structural clamps using remote intervention techniques was carried out on Mobil's Beryl 'B' platform[1 & 2]. Fire water caissons, damaged from corrosion, were repaired using elastomer-lined clamps. MSL was the Consulting Engineer for this project.

The primary objective in selecting the SMR scenarios for the underwater trials was to encompass as many of the above applications of clamp systems as possible. On the basis of the Beryl 'B' application and experience, discussions with the sponsoring organisations and a review of all options, the following SMR scenarios were selected:

- Repair of tubular joints.
- Addition of a new member.
- Replacement of an existing member.

It can be observed that, singularly or in combinations, the above selected scenarios permit the use of the findings from this JIP across the range of applications of clamp systems. Further details of the selected scenarios are presented below.

(i) Repair of tubular joints (Figure 2.1)

This scenario represents a fatigue-induced crack on the chord side of the intersection weld between two tubular members (T-joints). It is assumed that the brace is severed from the chord, from the standpoint of clamp design.

The selected repair solution is a stressed grouted T-joint clamp. The repair is designed to transmit the brace loads through the clamp and into the chord, by-passing the severed intersection. The strength of the clamp is derived from the studbolt preload which applies normal forces at the interface with the tubular member. These forces generate friction at the interface to permit the brace loads to be transmitted into the clamp steelwork. The grouted annulus between the tubular members and the clamp saddle is required to provide sufficient tolerance to allow for lack-of-fit of the clamp around the damaged T-joint.

(ii) Addition of a new member (Figure 2.2)

This scenario involves the installation of a new tubular brace into an existing structure. The new member incorporates clamps for attachment to the structure. In order to accommodate the potentially large lack-of-fit across the span of the member, structural hinges are incorporated into the system. Accommodation of the lack-of-fit is provided by the hinges, allowing rotation of the member. As there is now a reduced potential lack-of-fit, elastomer-lined clamps can be used.

(iii) Replacement of an existing member (Figure 2.3)

This scenario represents the replacement of a tubular member which has suffered damage. The tubular joints at each end of the damaged member are assumed to be intact.

It is assumed that the damaged section has been cut out, leaving stubs protruding from the joints. The replacement member is deployed between the stubs and temporarily held in position by simple curved catcher plates welded to, and overhanging, the ends of the member. The member is then clamped permanently to the stubs at each end. The clamps are designed to span across the connections to develop sufficient strength to transfer axial loads from the intact stubs to the replacement member. To accommodate potential misalignment between the stubs and the replacement member, stressed grouted clamps are specified. This type of clamp also permits sufficient annulus thickness to encompass the catcher plate, thereby allowing the plate to remain in-situ.

During the course of the review leading to the above selections, it became clear that two separate clamp systems were required for the tubular joint repair, one designed to permit WROV implementation and the other for ADS implementation. Further, it also became clear that, within the context of this JIP, the addition of a new member and replacement of an existing one can be combined into a single set of trials through adoption of a hybrid of the two schemes without compromising the objectives. A hybrid scheme was therefore adopted, as illustrated in Figure 2.4.

Consideration has been given to the adaption of the system to allow installation of the replacement member into a frame which lies in the vertical plane. In this case the lower most catcher plate may be replaced by a conical stabbing guide, as illustrated in Figure 2.5.

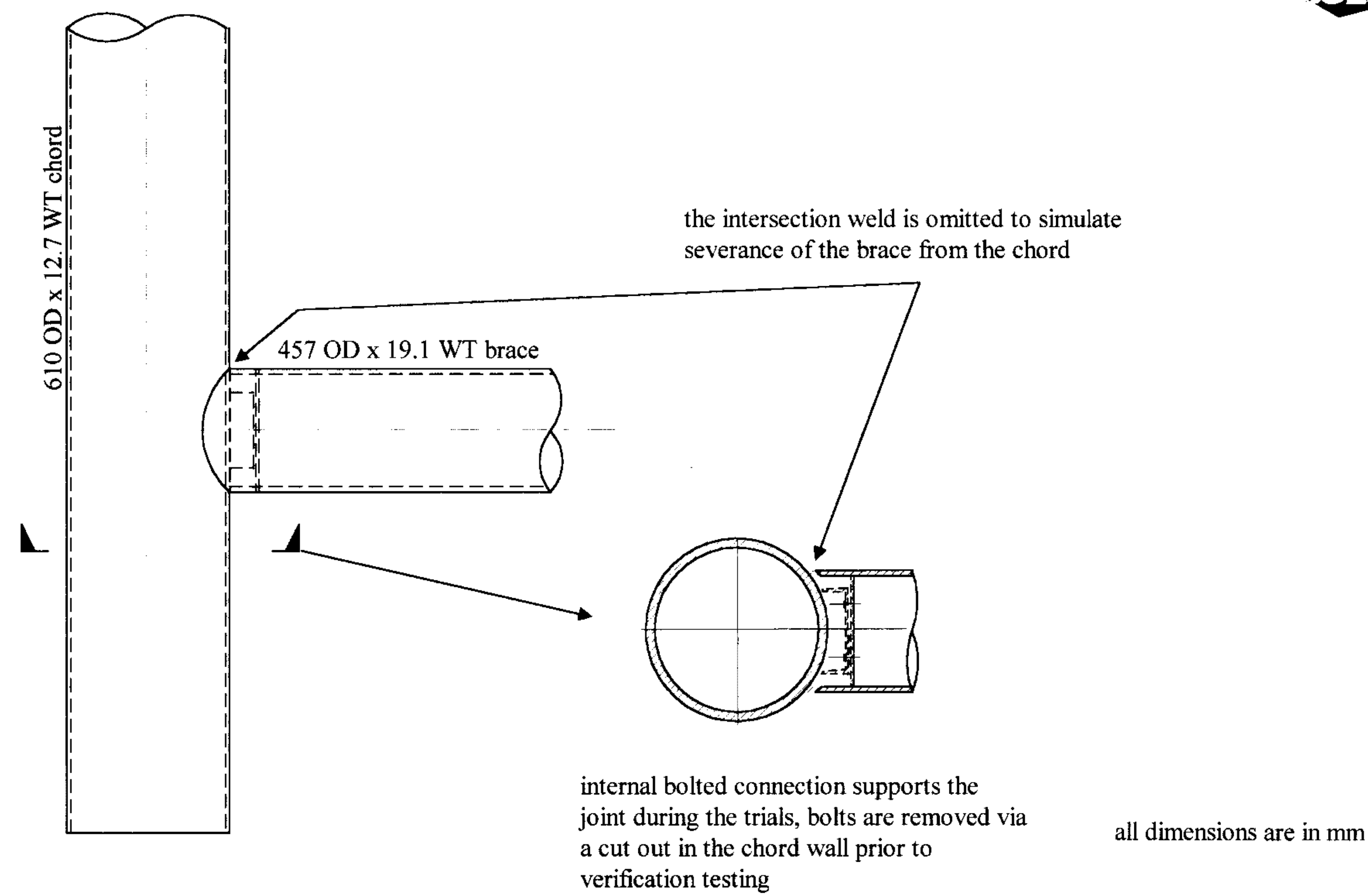


Figure 2.1: Repair of Tubular Joints

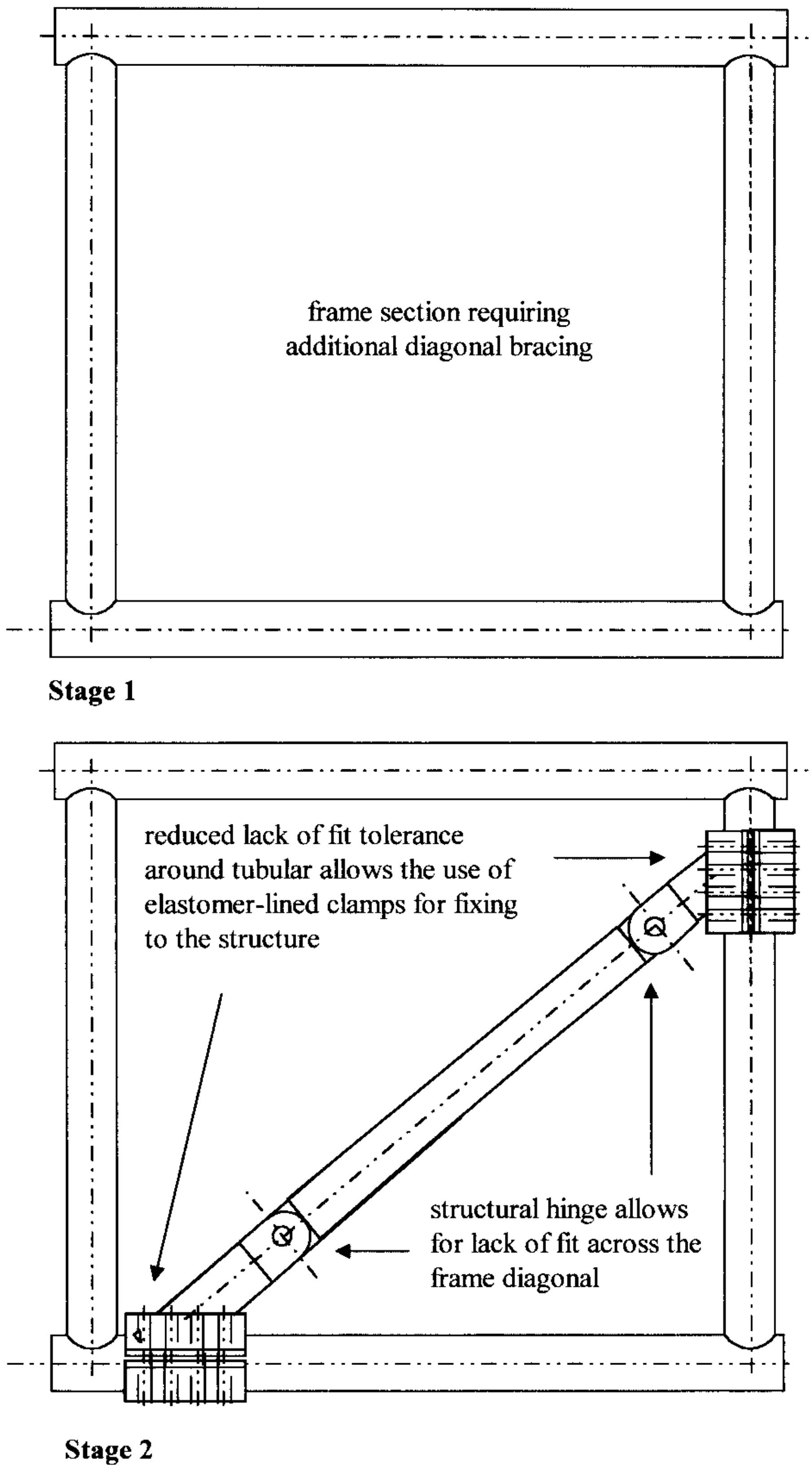
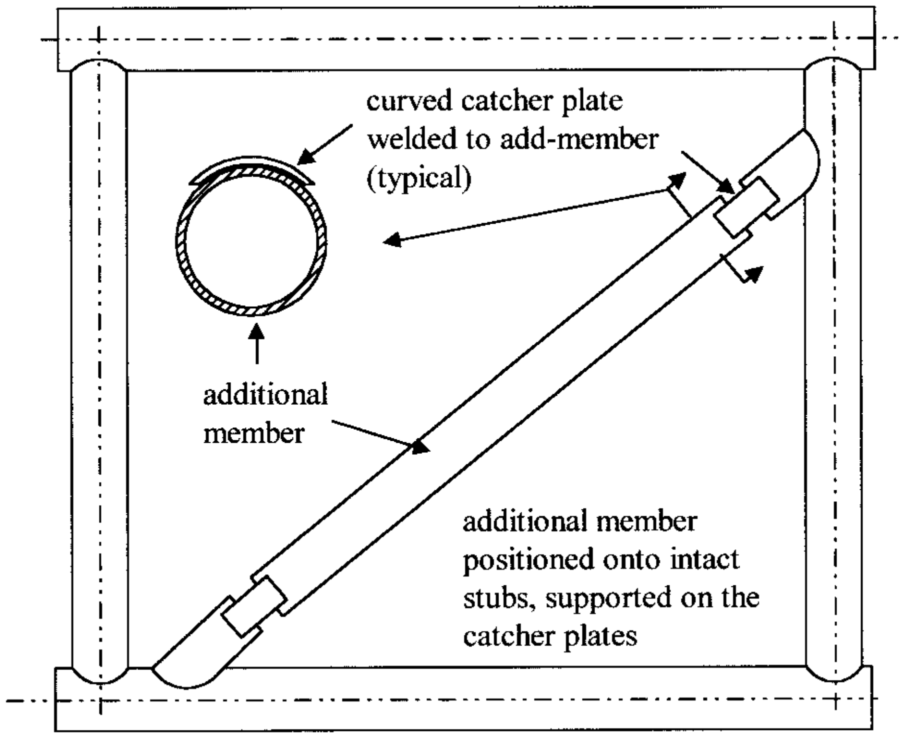
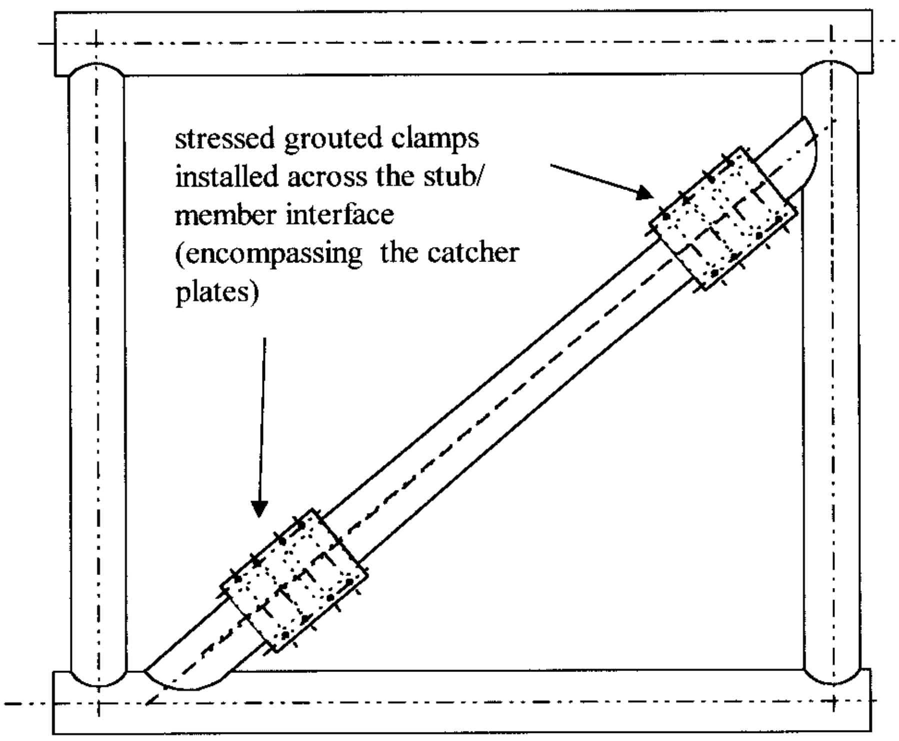


Figure 2.2: Addition of a New Member

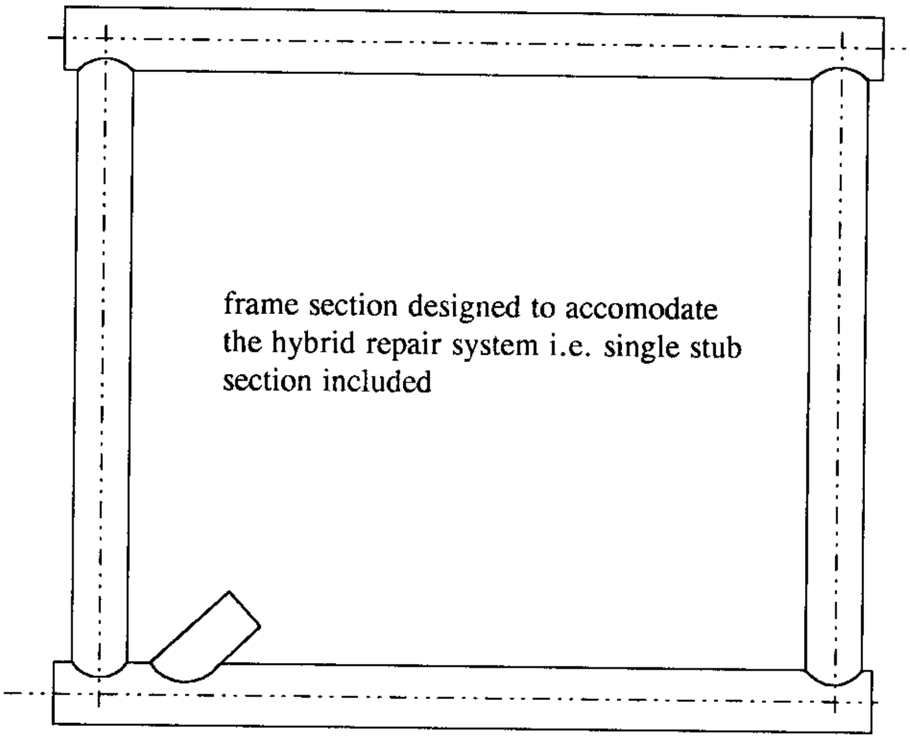


Stage 1

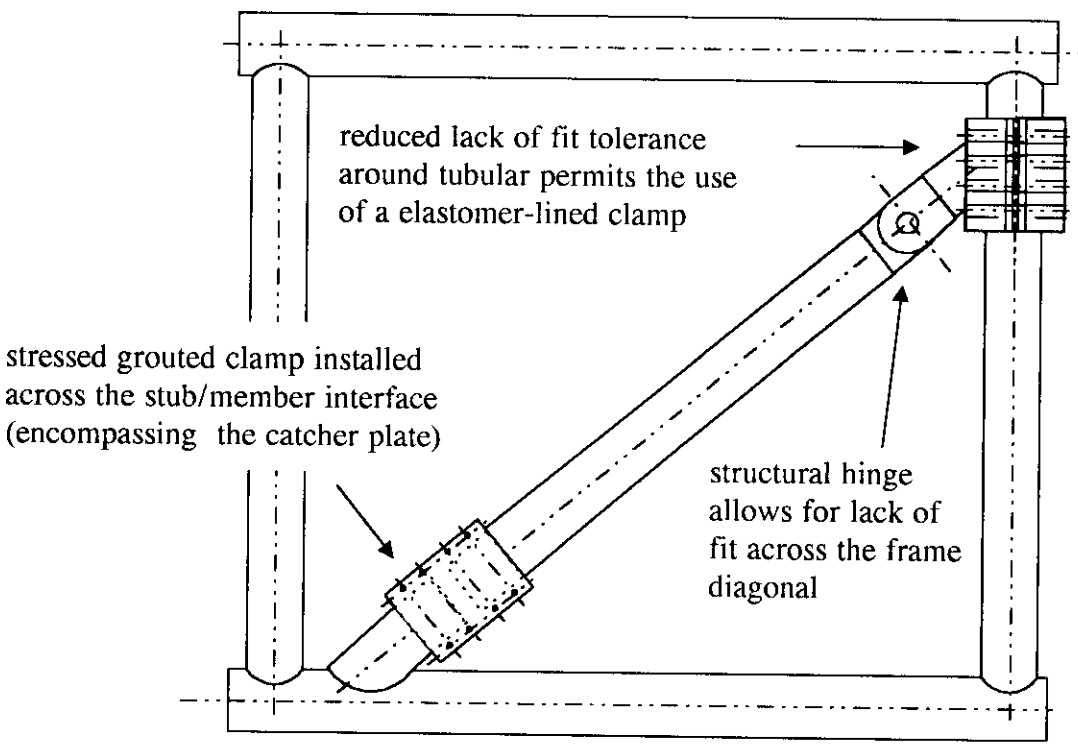


Stage 2

Figure 2.3: Replacement of an Existing Member

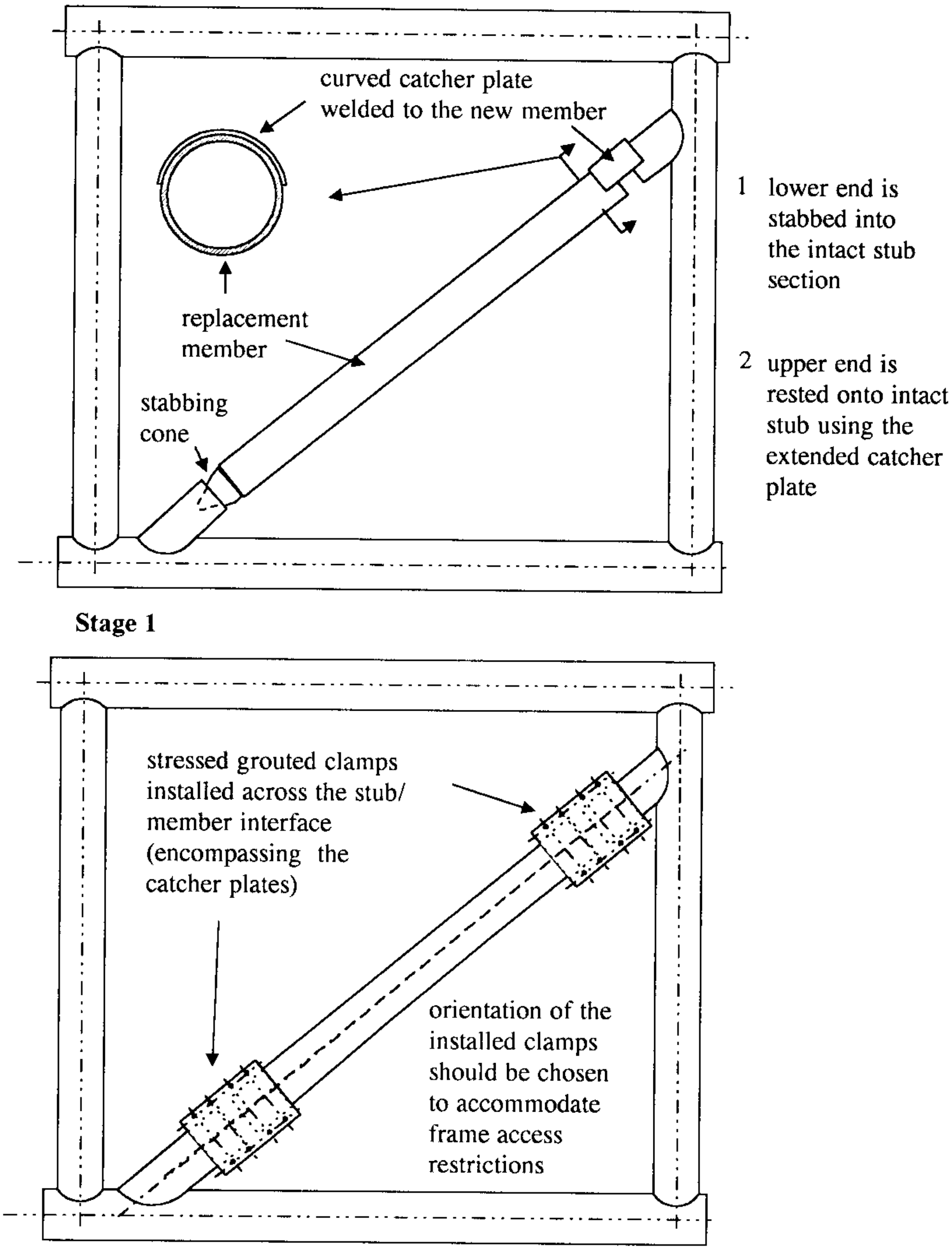


Stage 1



Stage 2

Figure 2.4: Hybrid Member Addition/Replacement



Stage 2

Figure 2.5: Installation of a New Member into a Vertical Frame

3. STRUCTURAL DESIGN

3.1 General

In general, structural steelwork was designed in accordance with the following codes and standards:

- AISC 9th Edition[3]
- API RP2A 20th Edition[4]

There was no requirement to design for fatigue loading. However, steelwork details were designed in accordance with standard offshore practice.

Slip strengths of stressed grouted and stressed elastomer-lined clamps were determined in accordance with MSL Engineering's design manual[5].

Detailed calculations are contained in the Design Report in Appendix B.

A series of fabrication drawings were prepared as a result of the detailed engineering activities. A catalogue of these drawing is presented below:

MSL Drawing Number	Title
C158/001	Test Frame GA & Details
C158/002	T-joint Clamp (ROV Installation) GA
C158/003	T-joint Clamp (ADS Installation) GA
C158/004	Addmember Clamp GA
C158/005	Addmember GA and Details
C158/006	Tube-to-tube Clamp GA
C158/007	Clamp Seal GA and Details
C158/008	General Clamp Details
C158/009	Bolt Details

The above drawings are reproduced in this report before Appendix A.

3.2 Test Frame

The test frame was designed to represent a partial plan of a typical steel jacket structure. The size of the frame's sections and their configuration were selected to be representative of a full-scale conductor bay, or similar. Figures 3.1 and 3.2 illustrate the test frame in the unrepaired and fully repaired conditions, respectively. The frame consisted of two 610mm diameter (ϕ) chord members at 5.25m centres. Brace members of 457mmϕ connected the chord members to form four T-joints in the resulting frame. The intersection of the tubulars at two of the T-joints were detailed to have no weld connection between the brace and the chord. Instead, the chord and brace members at each of these T-joints were connected via an internal bolted detail. Once the repair clamp was installed the bolts were removed. Access was provided for removal of the bolts via a cut-out in the wall of the chord member. The two T-joints were geometrically identical to allow each to be repaired with a structurally identical clamp to facilitate direct comparison of the WROV and ADS systems.

A stub (406mmϕ by 610mm long) protruded, at an angle of 40°, from one of the chord members. The stub section and the adjacent joint were designed to represent the intact section of a damaged member (which is simulated to have been cut and removed from the frame) to permit the installation of a new member consistent with the objectives of the replacement member repair scenario. The replacement member incorporated a catcher plate at one end, for alignment with the stub. On the joint, diagonally opposite, no stub was provided. Here, the replacement member had an elastomer-lined clamp connected via a structural hinge. The clamp was designed to be installed into the frame diagonally opposite the stub, consistent with the objectives of the additional member installation.

The frame also incorporated several bolted flanges and a reinforced lug. These were designed to suit the testing rigs used during the post-trial verification testing of the repair clamps. Padeyes were provided to facilitate on-site handling of the frame. The plan section of the test frame was connected via bolted flanges to tubular legs. The legs positioned the test frame at mid-water height, see Figure 3.3, and were removable to facilitate safe operations on dockside during dry trial fit-up installations which preceded each of the in-water trials.

The test frame was designed to resist the following loads:

(i) Clamping Forces

The frame tubulars were checked for compressive hoop stresses induced by clamp studbolt loads.

(ii) Lifting Induced Loading

The test frame was designed to be deployed using the dockside crane. Subsequent to each subsea installation, the frame was removed to permit the dry fit-up of the next repair. To facilitate this repeated handling, the frame incorporated lifting padeyes. Adjustable (clutched) lifting chains were used to accommodate the constant shifting of the system centre of gravity associated with each successive repair installation. The maximum lift weight of the fully repaired frame was 12.5 tonnes.

(iii) Impact

Test frame impact scenarios considered in the design included both docking loads and accidental collision loads from in-water WROV operations. Set down of the frame by the crane was also considered.

(iv) Verification Testing

Specific attachments, flanges and frame sections were designed to resist clamp failure loads determined from upper bound characteristic equations and corresponding safety factors of unity.

3.3 Clamps

The structural clamps were designed in accordance with the following procedure:

(a) Design loads for the clamps were chosen as a percentage of the full capacity of the test frame members being repaired. Relatively heavy walled tubulars were used within the test frame to accommodate the high loads associated with the verification testing.

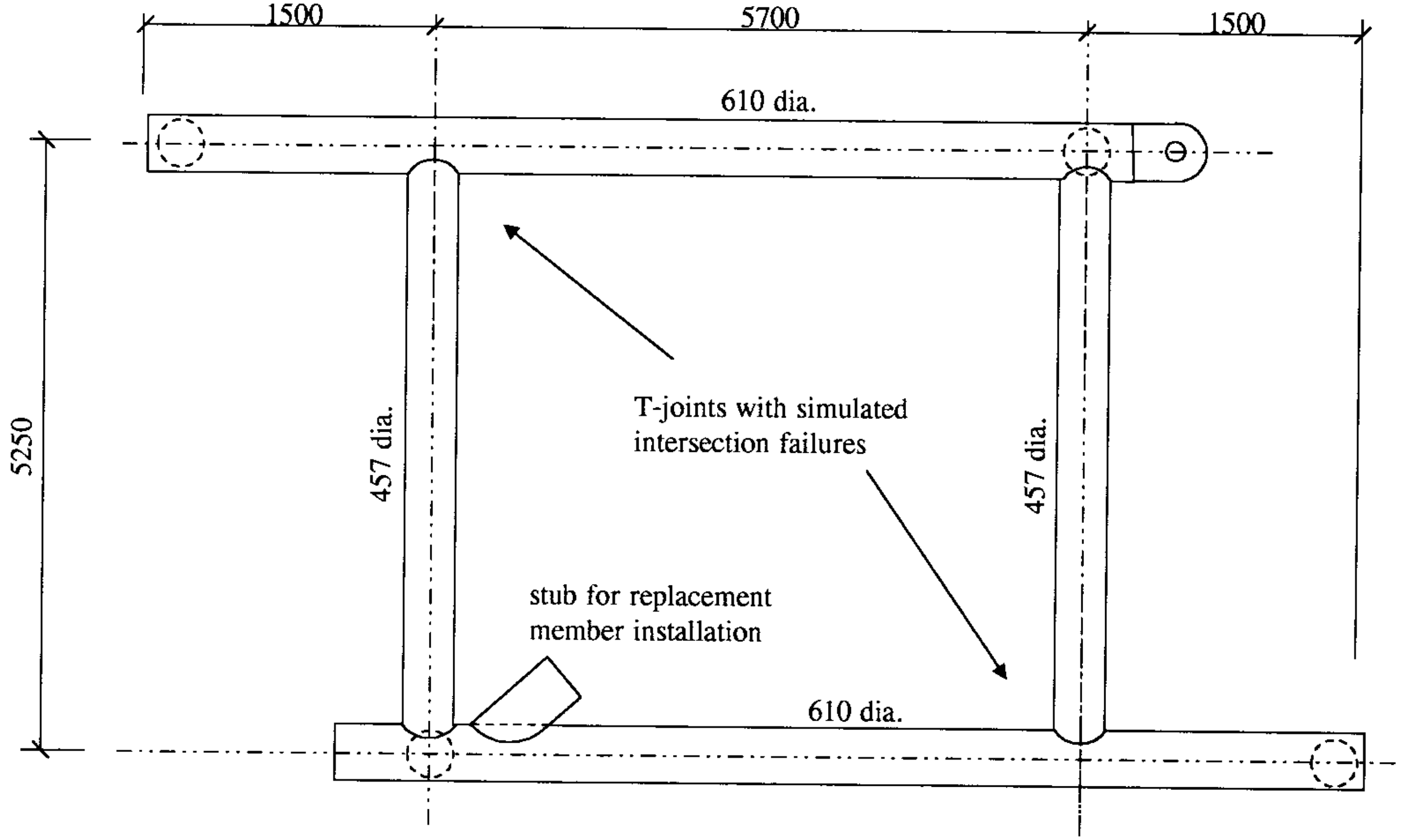
(b) Clamp geometries and studbolt configurations were determined in accordance with design equations given in Reference 5.

(c) Clamp structural steelwork was designed to resist the maximum studbolt loads.

(d) Clamp sealing systems were designed to prevent leakage during the grouting of the annulus between the clamp saddle and the chord/brace surface.

In order to design appropriate test rigs for the verification tests, an assessment of the clamps ultimate capacity was required. This was performed using upper-bound characteristic strength equations, contained within Reference 5, with corresponding factors of safety of unity.

Clamps for offshore installation will generally include a cathodic protection system to prevent corrosion of the steelwork. Although anodes were not fitted to the clamps used in the demonstration trials, checks were performed to ensure the installation systems did not preclude their attachment to the clamp. For remotely installed clamps the corrosion protection system should be designed to include the clamp manifold to facilitate its re-use during periodic inspections.



all dimensions in mm

Figure 3.1: Plan View Showing Test Frame Configuration

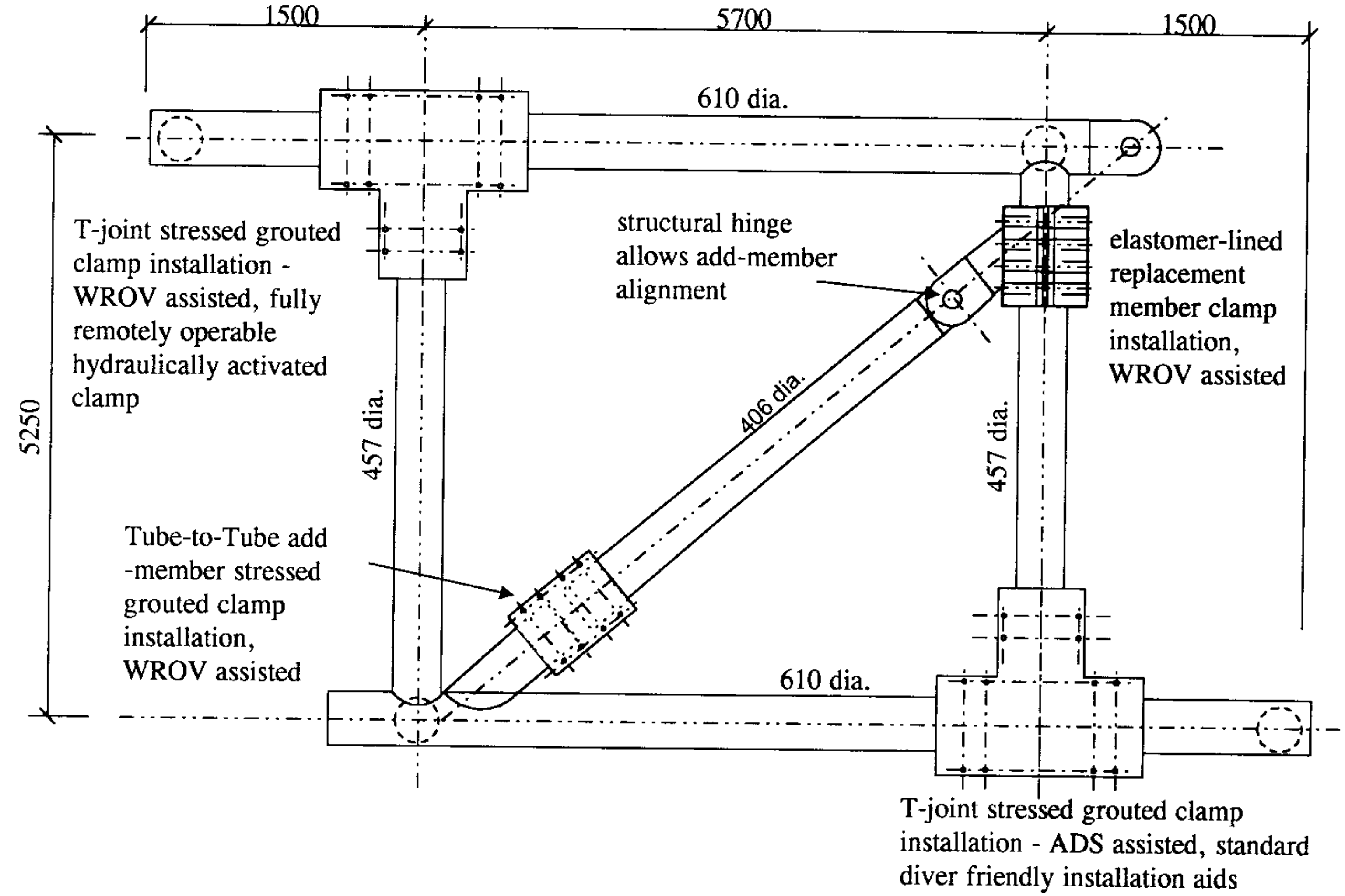


Figure 3.2: Plan View of Test Frame Showing Installed Repairs

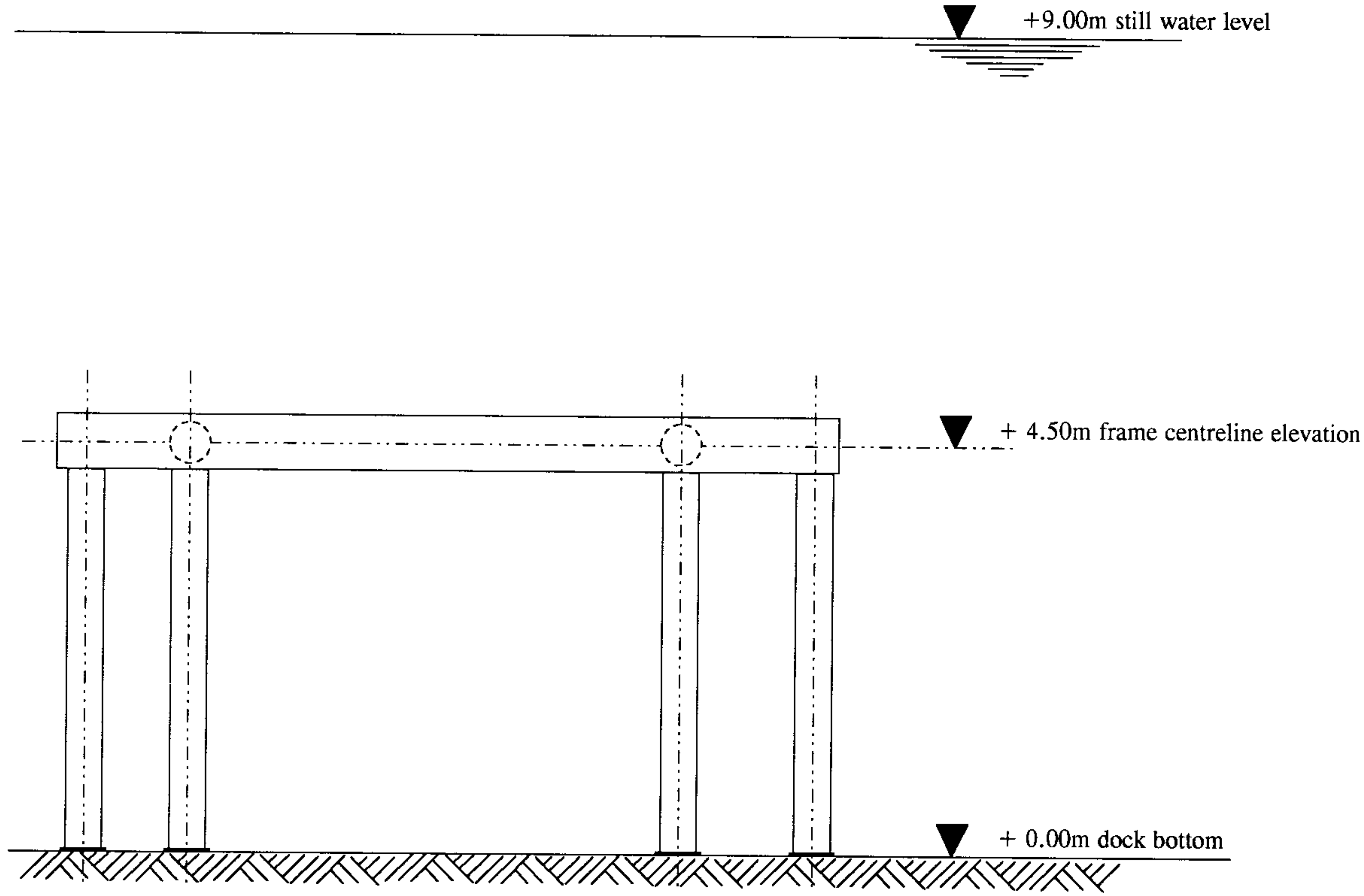


Figure 3.3: Elevation of the Test Frame in the Wet Test Facility

4. MATERIALS AND FABRICATION

4.1 Materials

Structural steel was supplied in accordance with the following standards:

- rolled tubular sections - API 5L Gr X52 and Gr X56
- plates - BS 4360 50D / BS7191 Gr 355 EMZ

The following material and component specifications for specialised application were produced as part of this JIP:

(i) Specification for the manufacture and testing of studbolts nuts and washers.

(ii) Specification for clamp lining and bonding.

(iii) Clamp seal specification and seal bonding.

(iv) Grouting procedures and specification for grout materials.

The above specifications, which follow offshore practices, are presented in Appendix C. All materials procured followed the above specifications.

4.2 Fabrication

Steelwork fabrication was carried out by AKD Engineering Limited of Lowestoft, UK. Their selection was based primarily on previous experience in fabricating to offshore specifications and, in particular, to the tight tolerances associated with clamp fabrication.

Structural fabrication was performed in accordance with the requirements of the EEMUA offshore fabrication specification[6].

Additional requirements and recommendations, specific to the fabrication of offshore repair clamps, and concerned primarily with dimensional control and sequence of fabrication, were separately specified by MSL in a fabrication addendum document, a copy of which is enclosed in Appendix D.

The as-built drawings for the clamps, test frame and component steelwork are enclosed herein after the Figures and before Appendix A. A dossier on material procurement and fabrication prepared by AKD resides at MSL and can be supplied on request.

5. INSTALLATION DESIGN

5.1 Intervention Systems

Two fundamental systems were identified for the subsea remote intervention tasks:

- work class remotely operated vehicle (WROV)
- atmospheric diving system (ADS)

An ADS maintains the pressure experienced by the operative (pilot) to a single atmosphere which reduces the principal health risks associated with traditional deepwater diving. Nevertheless, the system requires the pilot to work subsea and, therefore, is not strictly diverless. The ADS system was used for the installation of a T-joint repair clamp which was structurally identical to the one installed by WROV. The intent has been to provide a back-to-back comparison of the capabilities of the two systems.

Two types of ADS system are commonly employed in the offshore oil and gas industry. These are the NEWTSUIT, marketed in the UK by GMC Candive and the WASP, operated and marketed in the United States by Oceaneering Limited. The WASP system dominates the North American market and is used extensively in the Gulf of Mexico. The NEWTSUIT is more commonly used in Europe. Due to the non-availability of the WASP system in the UK, the NEWTSUIT was selected for use in the demonstration trials. A comparative paper study of the two systems has been undertaken, the findings of which are reported in Appendix A. It can be observed from Appendix A, that the NEWTSUIT and WASP systems are similar in their capabilities.

The selected subcontractor for the provision and operation of the NEWTSUIT was GMC Candive of Aberdeen, UK. The NEWTSUIT system is shown in Figure 5.1.

The supply and operation of the WROV and provision of necessary tooling was provided by Submersible Television Surveys Limited (STS) of Aberdeen, UK. STS was selected principally on the basis of its previous diverless operational experience. The WROV vehicle used during the trials was an uprated SCORPIO fitted with a left front mounted 5-function manipulator and a right front mounted 7-function manipulator. In keeping with the overall intervention philosophy, both the vehicle itself and the manipulators were standard equipment, typical of those used offshore for non-specialist intervention tasks. The vehicle used for the demonstration trials is shown in Figure 5.2.

5.2 Installation Tasks

The selected scenarios involve the installation of various types and configurations of structural clamps. The basic steps required to install any clamp, whether remotely or with the use of divers, are as follows:-

(i) Deploy the system to the work site.

(ii) Position the two clamp halves around the subject member(s).

(iii) Bring the clamp studbolts into position.

(iv) Centralise the clamp relative to the member(s).

(v) Seal the clamp along its longitudinal edges and at each end.

(vi) Inject grout into the clamp annulus and allow to partially cure.

(vii) Simultaneously tension all clamp studbolts to their design preload.

Steps (iv) to (vi) are not applicable to elastomer-lined clamps.

It is recognised that, in practice, the chosen method of deployment of an SMR system to the work site is dependent upon circumstances particular to that application, including water depth, currents, location within the structure, topsides cranage facilities, available vessel support and contractor preferences. For this reason, in this JIP, deployment to the strengthening/repair location was performed with the dock crane at site. Orientation and positioning of the repair system, however, was performed either with WROV or ADS intervention.

5.3 Intervention Philosophy

As expected, it became clear during discussions with the WROV supplier that standard WROVs were not able to perform any of the above installation tasks using methods typically employed by divers. Innovative solutions were, therefore, developed for each operation. The general philosophy adopted, based on detailed engineering assessment with full input from subcontractors and WROV manufacturers, was to make the clamp 'WROV-friendly' and use the WROV to interface with clamp-mounted installation systems. To this end, a clamp manifold was developed to provide a single interface for the WROV. The clamp manifold, designed to be interchangeable between the various clamps, is shown in Figure 5.2.

GMC Candive, following their review of the planned trials, advised that their NEWTSUIT ADS was capable of performing the same in-water tasks as a diver, and would be able to install a standard clamp without the use of sophisticated installation aids. Therefore, the philosophy adopted in this instance was to provide only the standard aids typically required for a diver-installed system.

In summary, one T-joint clamp and the hybrid member system were extensively engineered to provide a full range of aids to permit installation using a WROV. In contrast, the other T-joint clamp was engineered to a standard diver-installation level, for implementation using an ADS.

5.4 Installation Systems for WROV Intervention

The design of the operating systems, was conducted within the context of the above philosophy for remote WROV intervention. For each of the general installation tasks, itemised above, a range of alternative conceptual design solutions were considered. Some of the alternative solutions considered for each installation activity are described below. The preferred solution, which is identified for each activity, is described in further detail in Section 6 following component trials.

(i) Deploy the clamp/repair system to the work site

Clamp/repair systems were deployed to the work face using the dock crane, as discussed in Section 5.2.

(ii) Position the two clamp halves around the subject brace members

Clamp hinges were used on each of the repair clamps, similar to those used on recent diver-installed clamps to assist with subsea handling. To effect closure of the clamp around the test frame, divers rely on complex rigging arrangements and tirfors (manual lifting/pulling machines, operated by applying a reciprocating action to a lever) or similar jacking systems. This is not possible with a WROV. Therefore, designs for the remote closure system concentrated on two general concepts:

- Mechanical geared winding mechanisms. These systems proved overly complex and heavy, and were prone to potential installation damage.

- Hydraulic cylinders, several configurations of which were investigated before selection of the preferred solution, see Section 6.

(iii) Locate clamp studbolts into position

Some of the concepts considered for the installation of the studbolts, after closure of the clamp around the test frame, are as follows:

- Mounting of the studbolts onto a cassette to be 'dropped' into location. This solution does not lend itself well to more complex clamp shapes and requires excessive stroke in the studbolt tensioners to take up slack in the bolts, see Figure 5.3. In addition it requires complex 'handling' tasks to be performed by the WROV.

- Fixing studbolts to a hinge plate to be hydraulically lowered into position through slotted bolt holes in the clamp flange plates. This solution was rejected due to the significant risk of damage to the bolts during installation, see Figure 5.3.

- Retainment of the studbolts at an elevation clear of the clamp centreline, then wound/pushed into location. This solution was found to be the most practical, particularly when considering its interaction with the subsequent tensioning operations. Because the bolts are wound into position, the system is able to remove any slack from the bolts prior to tensioning. This allows the tensioning jack to have a standard length stroke of 20-25mm which is a considerable advantage. The operation is easily reversible. The preferred detail is described further in Section 6.

(iv) Centralise the clamp relative to the brace members

Conventional clamp centralising systems were considered but found to require disproportionate amounts of time for WROV operation. They had the added disadvantage that they required to be retracted prior to bolt tensioning. By incorporating the centralisation as an automatic function of the end sealing system, an entire operation was eliminated with significant time savings.

(v) Seal the clamp along its longitudinal edges and at each end

Conventional longitudinal seals, using neoprene channel sections bonded along the clamp split line are activated automatically by the action of pulling together the clamp halves with the studbolts. This system was, therefore, ideally suited to remote intervention. The only modifications required were to facilitate the interface with the new end seal concept.

Several types of end sealing system have been used on conventional clamps, including grout socks and external and internal Sorbothane seals. Discussions with installation contractors and video footage of previous clamp trials showed the systems to be somewhat ineffective for WROV intervention. An alternative end seal system was designed with the intention of achieving an adequate seal, whilst conforming to the maximum potential lack-of-fit between the clamp and the test frame. This was achieved by compressing the seal directly against the test frame member and allowing the seal to expand laterally, under the applied compression, against containment plates attached to the clamp saddle. The solution had the added benefit of simultaneously centralising the clamp and is referred to, herein, as a Direct Interface Self Centralising (DISC) seal. The DISC seal and its operation are detailed in Section 6. This development has the benefit that it can also be specified for diver-installed clamps.

(vi) Inject grout into the clamp annulus

Conventional clamp grouting operations were modified to bring the hose connection and the inlet/bypass valve handles to a central manifold to facilitate WROV operation from a single position. Grout sampling tubes were modified to allow WROV recovery. Otherwise, the system was similar to conventional clamp operations. Other systems, including electronic valve control were rejected as unnecessarily complex. Grouting operations are discussed further in Section 6

(vii) Simultaneously tension all clamp studbolts to their design preload

Consideration was given to torquing of the studbolts. However, it was concluded that this was not practical due to the necessity of revisiting any single studbolt a number of times and the difficulties in obtaining an even load distribution. Exhaustive investigations were undertaken into the remote tensioning of the studbolts, in association with the major offshore bolting contractors including Hydratight and Hedley Purvis. Among the concepts considered were:

- Standard diver-friendly tensioners, found to be inoperable by WROV due to the requirement to access the captive nut and rotate it with a tommy bar.

- Standard diver-friendly tensioner with modified captive nut detail to permit WROV operation. The considered modifications included, vaning the nut to allow rotation with water jet and a modified nut for interface with a geared winding mechanism. Several configurations of the latter solution were developed. The system was rejected as being insufficiently reliable for this crucial operation.

- Specialised studbolt tensioners. Systems for locking the applied tension, including resin-filling and insertion of spacers were considered. These introduced additional complex subsea tasks for remote operation. The adopted solution replaced the captive nut with an external collar, suited to direct operation with the WROV manipulator jaw without any interface tool. The system and its operation are described in Section 6.

5.5 Installation Systems for ADS Intervention

As discussed in Section 5.3, no specific installation aids were introduced for the ADS intervention. However, standard diver-friendly installation aids including hinges, hinge stops, rigging guides and lifting points were provided.

Subsequent to the dry trials it was discovered that 'WROV-friendly' installation aids were required for a successful ADS clamp installation, see Section 7.

5.6 Installation Procedures

In parallel with the design, construction and component trials of the repair systems, substantial engineering effort was directed towards the creation of installation procedures for the trials. The preparation of the procedures was necessarily and extensively interactive with the WROV and ADS operators.

On conclusion of the component trials, and prior to the dry 'fit-up' trials, the procedures were updated to reflect the lessons learnt from the component trails. Likewise, on conclusion of the dry trails (see Section 7), the procedures were updated to reflect the lessons learnt. These updated procedures are presented in Appendix E. The following matters are worthy of note:-

(i) Four sets of in-water trial procedures are enclosed, in Appendix E, which relate to the following:-

- Installation of stressed grouted T-joint clamp by ADS.
- Installation of stressed grouted T-joint clamp by WROV.
- Installation of new member plus elastomer-lined clamp by WROV.
- Installation of tube-to-tube stressed grouted clamp by WROV.

(ii) During the course of the in-water trials, a number of changes were made to the procedures, where operations did not progress in line with expectations. These changes, which essentially reflect the lessons learnt from the in-water trials, are annotated in the four sets of procedures with notes in italics.

The primary intent in the creation of the installation procedures was that they were, firstly, easily adaptable to each of the four trials and, secondly, readily amenable to application in practice with site-specific adjustments. The same systematic installation methodology has been applied to each of the trails. For the trails which used WROV intervention, the following global approach was adopted:-

- Deployment

  The clamp/repair system was lowered to the work face supported from the dock crane. The lift configuration was designed to maintain the top flange of each clamp in the horizontal attitude with the lower clamp half at a 50° angle to the upper half. Once the clamp was adjacent to the structure the WROV was used to ensure correct orientation and final positioning by holding the grab handles on the clamp manifold. With the WROV pilot controlling crane movements, the clamp/repair system was set into position on the test frame.

- Closure

  The hydraulic feed and return lines were retrieved from the surface by the WROV and stabbed to the clamp manifold. The hydraulic closure cylinders were activated from the surface control panel under instruction from WROV control. The clamp was thus closed around the test frame.

- Studbolt Engagement

  Using a hydraulic impact wrench, powered by on-board hydraulics, the WROV commenced driving the studbolts, from their retracted deployment position, into the captive nuts until all slack was removed. To facilitate the engagement of the socket on the hex nut, the socket was attached via a universal joint and the end was flared out a short distance.

- Longitudinal Seal Activation

  With the studbolts fully engaged, each was given two additional rotations to bring the longitudinal seals into tight contact all around to make them fully effective.

- DISC Seal Activation

  Again using the impact wrench, the WROV engaged the DISC seal activation bolts in the sequence prescribed in the procedures to centralise the clamp and activate the DISC seals at each end.

- Grouting

  With the clamp centralised and fully sealed, the WROV stabbed the grout line to the clamp manifold. Grouting operations were preceded by a leak test and performance of any necessary remedial actions (defined within the procedures). Following a successful leak test the annulus was grouted by a sequence of carefully planned valve operations by the WROV. The WROV was also required to isolate grout samples in pre-attached sample tubes and retrieve the tubes to the surface for testing.

- Studbolt Tensioning

  Following a suitable grout curing period, the WROV was required to stab the bolt tensioning hydraulic feed to the clamp manifold. Hydraulic pressure was applied from the surface control panel and maintained while the WROV wound up each of the external collars on the tensioners. The interface to the collars was performed with a fabricated socket held in the jaws of the WROV manipulator. The collars were required to be brought into firm contact with the reaction disc, however, it was not necessary to apply any significant torque. The system was de-pressurised and re-pressurised three times in accordance with procedures. Disconnection of the hydraulic feed was performed by the WROV on completion of the clamp installation.

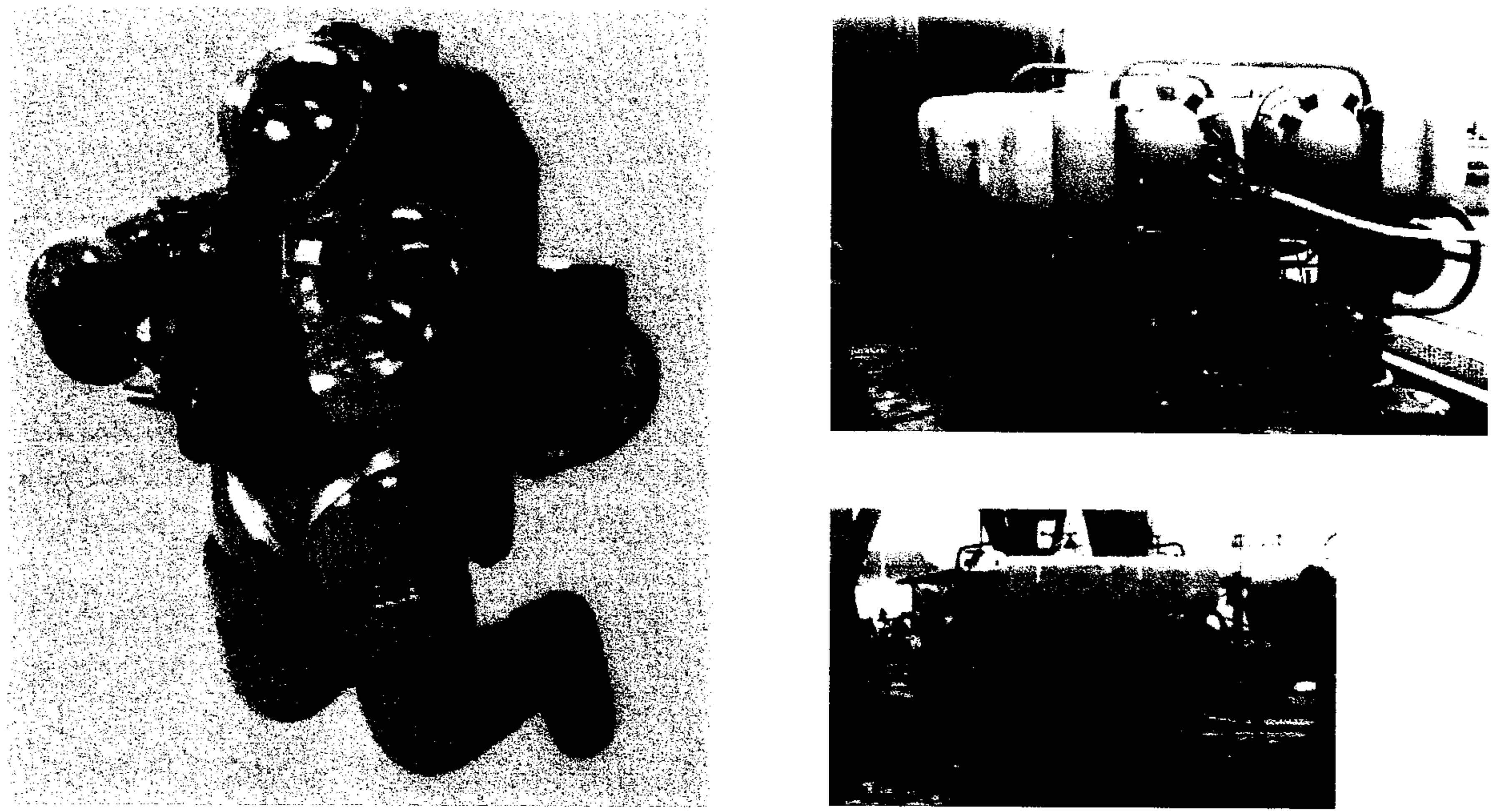


Figure 5.1: NEWTSUIT ADS and SCORPIO WROV

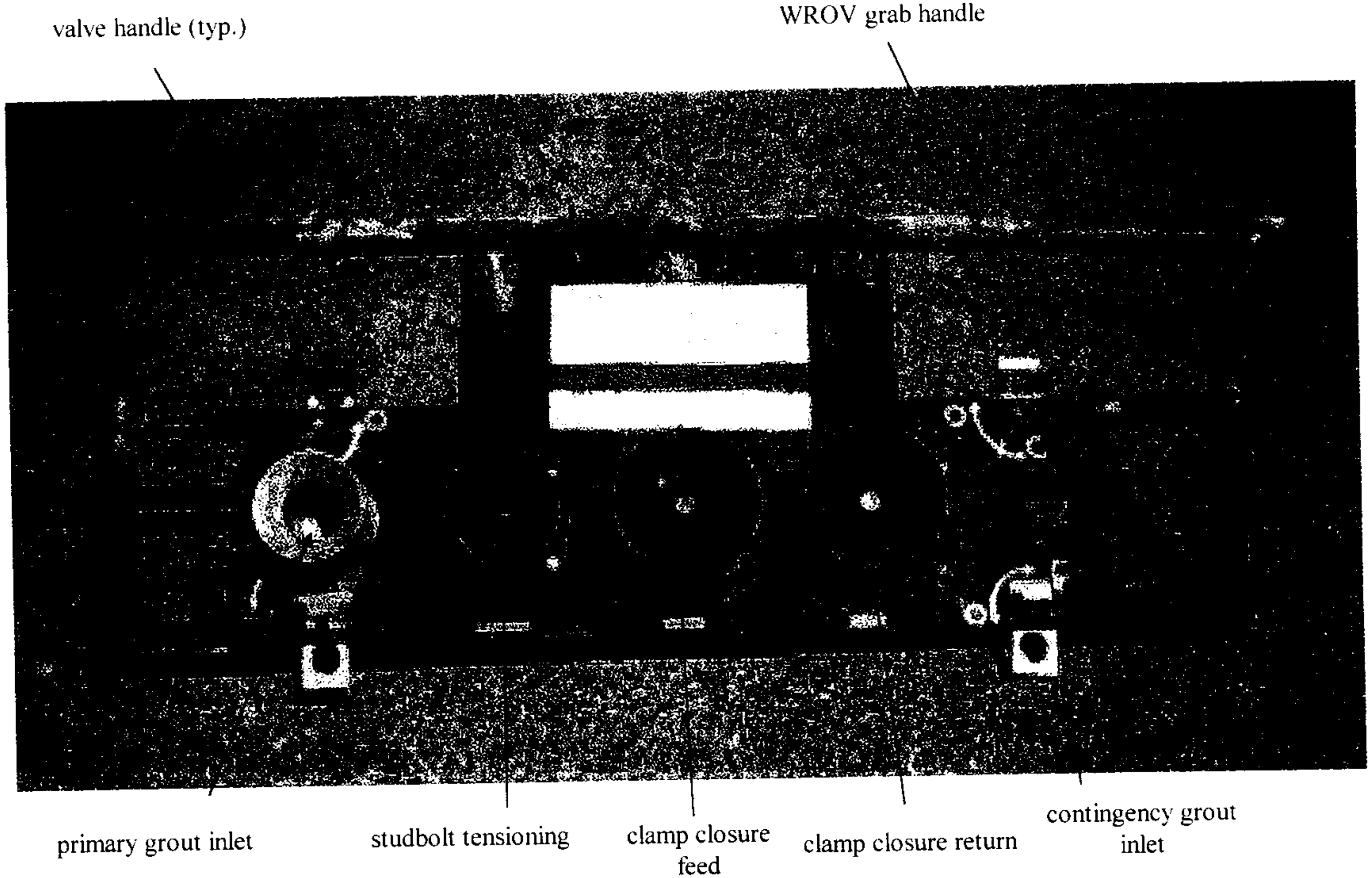


Figure 5.2: Clamp Manifold for WROV/Clamp Interface

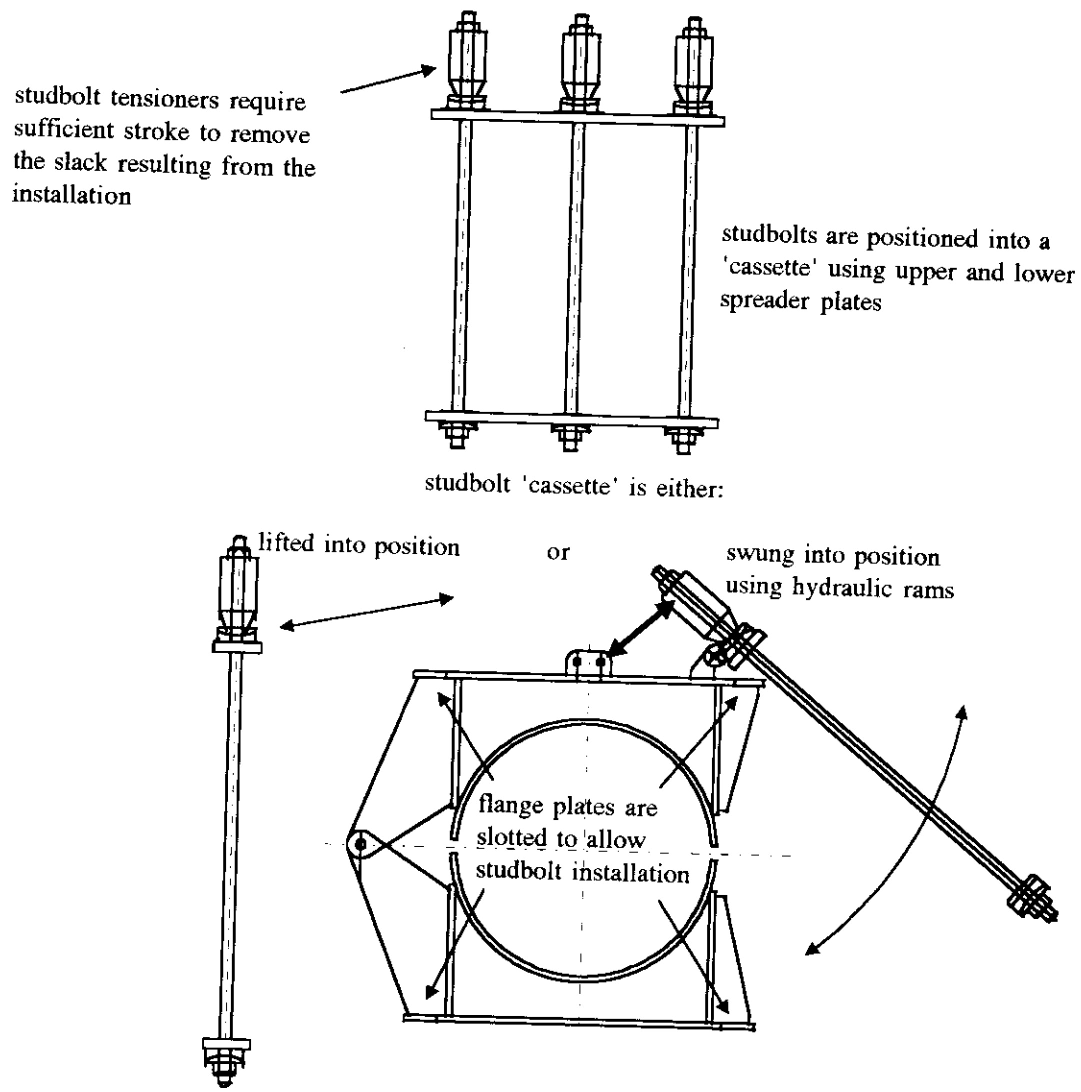


Figure 5.3: Alternative Studbolt Engagement Systems

6. COMPONENT TRIALS

6.1 General

Each of the clamp operating systems was tested prior to the demonstration trials. The objectives of the component trials were twofold:

- To ensure the systems operated in accordance with the design intent.
- To refine the systems to eliminate design flaws and optimise their operation.

The findings of these component trials and refinements made to the various systems are presented below.

6.2 Manifold Stab System

The clamp manifold, used to minimise the interfaces between the WROV and the clamp operating systems, is shown in Figure 5.2. The clamp closure system and bolt tensioning system relied upon hydraulic power for their operation. For the purposes of the in-water trials, the hydraulic power for each system was supplied from surface mounted pumps. (For deepwater applications, the power could equally be supplied by hydraulic units mounted on a work sled integral to the WROV). To facilitate the subsea connection of the hydraulic feed/return lines to the clamp, the on-clamp systems were connected via flexible hoses to the clamp manifold. The WROV was then able to stab the hydraulic lines running from the surface to the manifold to provide system power. The method of hydraulic stab used for the trials is shown in Figures 6.1 and 6.2. Stab fittings for the studbolt tensioning hydraulic circuit were a different size to the clamp closure hydraulic circuit. This was to ensure the WROV could not stab the wrong feed to either system, as they operated at different pressures. The on-clamp grouting system was also piped back to the clamp manifold to facilitate stabbing of the grout hose by the WROV. The grout stab is discussed below.

Trials of the manifold system were successful.

6.3 Clamp Closure System

Each of the repair clamps were fitted with hinges to allow them to be presented to the test frame in an 'open' attitude. Existing flange stiffeners were extended at appropriate locations and used to form the hinge plates on the clamps. A typical hinge plate detail is illustrated in Figure 6.3. It should be noted that a slotted hole is included for the hinge bolt and the lower clevis bolt which permit relative movement between the two clamp halves during tensioning of the clamp studbolts.

On the ADS installed T-joint clamp, the upper hinge plates were extended and a hinge stop incorporated, also illustrated in Figure 6.3. This addition prevented excessive opening of the clamp which would affect clamp orientation during lifting and the stability of the clamp when resting on the test frame prior to closure.

The hinge stop was not provided on the WROV installed clamps; the hydraulic cylinders were relied upon to prevent excessive opening. The hydraulic cylinders were positioned between pairs of hinge plates so as to provide maximum protection against impact from the WROV or against the test frame during deployment. The two-way acting closure cylinders were connected in parallel to a manifold mounted on the underside of each clamp. The system was designed to be interchangeable between each of the WROV installed repair clamps. During the component trials it was discovered that, because the hydraulic cylinders were required to hold the clamp 'open' during deployment, the closure system was necessarily pressurised at this time. It was, therefore, not possible for the WROV to stab the hydraulic feed and return lines to the clamp manifold against this system pressure. In order to maintain the flexibility of not having the hydraulic lines connected during deployment, it was necessary to fit a pilot check valve into the hydraulic circuit. This valve was designed to relieve the pressure at the manifold while maintaining system pressure in the cylinders, enabling the WROV to stab to the manifold. The operation of the modified circuit is illustrated in Figure 6.4.

It should be noted that the inclusion of a hinge stop on the clamps (as used on the ADS clamp) would have allowed the clamp to be deployed with the closure system de-pressurised and removed the requirement for the check valve. Alternatively, the clamp could be deployed with the feed and return lines pre-connected. The solution adopted, however, provides the greatest flexibility in practice to variations in deployment methodology which, as discussed in Section 5, will be dependent on the specifics of the actual application.

6.4 Studbolt Restraint and Engagement System

The overall studbolt restraint and engagement system is illustrated in Figure 6.5. The system essentially comprises three components, as follows:

(i) Interface to permit the WROV to engage and drive the studbolt up or down. The solution adopted was to weld a standard 36A/F hex nut to the top of the studbolt. This required the WROV to engage a socket, mounted on an impact wrench, to the nut to wind the studbolt in the appropriate direction. The assembly is illustrated in Figure 6.4. The hex nut is non load-bearing in the final installed clamp. Studbolt load is carried by the threaded reaction disc which is wound into firm contact with the hex nut.

(ii) Studbolt retainer, illustrated in Detail 2, Figure 6.6, designed to:

- hold the studbolt in the elevated deployment position

- allow the studbolt to be wound (or pushed) downwards to engage the lower captive nut

- align the studbolt to ensure smooth engagement into the lower captive nut

- allow the studbolt to be retracted (wound upwards) should reversal of the installation be required

- allow the studbolt to 'slip' through the connection during tensioning to prevent load being transferred away from the lower portion of the studbolt.

Experimental trials were conducted at City University to optimise the system used to retain and align the studbolts. Consideration was given to the use of threaded nylon tubes and elastomer-lined steel tubes. The former proved to be vulnerable to stripping of the nylon thread during bolt tensioning rendering the installation non-reversible. The latter option allowed insufficient adjustability to accommodate misalignment of the bolt holes (resulting from fabrication tolerances) in the upper and lower clamp halves.

Component trials for the preferred solution (Detail 2, Figure 6.6) showed the system to be sensitive to the thickness of the neoprene packer and to the size of hole. Flexibility of alignment was provided by enclosing the neoprene between steel plates incorporating oversized holes. The studbolt could be positioned at any location within the oversized hole to ensure engagement with the lower captive nut. The containment plates offered the additional advantage of being adjustable at site. This allowed adjustments to be made during dry 'fit-up' trials to accommodate any minor racking of the clamp halves due to impact during transportation and/or handling. By varying the tension in the bolts, the neoprene compression could be increased or decreased to optimise the 'grip' on the studbolt to suit the WROV torque applicator.

(iii) The detail to hold and align the lowermost spherical washer and nut is illustrated in Detail 3, Figure 6.6. The system was tested in a vertical orientation and performed reasonably well. However, the nut and washer were considered to be loose, with the potential for misalignment and hence cross threading of the nut on the studbolt. This problem was alleviated by packing the space between the nut holding plate and retaining plate with silicon gel. Further potential problems were identified, during the dry trials, when the studbolts were horizontal, see Section 7.

6.5 Clamp Sealing System

The Direct Interface Self Centralising (DISC) sealing system is illustrated diagramatically in Figure 6.7. Component trials were conducted using two hardnesses of Sorbothane, Shore No. 50 and Shore No. 70. The softer Shore No. 50 material proved more effective. The system was found to be successful in centralising the clamp with respect to the brace member. Hydrostatic tests, however, demonstrated minor leaks at the clamp split line, see Detail 2, Figure 6.8. Although the leaks were not excessive, it was decided to extend the compression plates adjacent to the clamp split line, in an attempt to eliminate the leaks.

The channel section neoprene longitudinal seals proved successful in the trials although some problems were observed with de-bonding, particularly in the area local to the DISC seal containment plates, at the clamp split line. This tended to compound the leakage problem associated with the DISC seals. The adopted solution was to fabricate short steel plates designed to hold in-place the neoprene longitudinal seals in the vulnerable areas. The operation of these plates is illustrated in Detail 1, Figure 6.8.

6.6 Clamp Grouting Operations

- Grout Hose to Clamp Manifold Connection

  The system for connection of the grout hose to the clamp manifold is shown in Figure 6.9. The female receptacle is mounted in the clamp manifold and incorporates a retaining pin which is engaged once the male hose connector is fully inserted into the female. During component trials, it was discovered that the O-ring located on the male hose connector was liable to snag on the groove for the retaining pin. To overcome this problem the female receptacle was machined to accept an internal O-ring. Positioning the O-ring on the inside also helped to keep it clean and to improve sealing.

- Grout Inlet and Bypass Assemblies

  The grout inlet assemblies, illustrated in Figure 6.9, were positioned on the underside of the clamps and consisted of a lower bypass valve and an upper inlet valve. The handles for operation of the valves were connected via extension T-bars to the front of the clamp manifold. The system worked effectively during component tests although the valve seatings required lubrication with silicon grease to maximise the ease of their operation.

- Grout Sampling and Outlet Assemblies

  The grout sampling and outlet assemblies are shown in Figure 6.10. A grout sample tube, having a ball valve at each end is connected to a male fitting. This fitting is stabbed into a female receptacle connected via a ball valve to the top of the clamp. The male and female fittings are identical to the grout hose connection fittings, shown in Figure 6.9. Closure of the valves either end of the sample tube, while grout is flowing through the tube, traps a column of grout in the sample tube. This sample can then be removed from the female receptacle, by withdrawing the retaining pin, and recovered to the surface for testing. Closure of the valve below the female receptacle shuts the outlet point, an operation which is performed once satisfactory quality grout is measured at the outlet. The male/female connection was modified in the same manner as the hose to manifold connection described above. Otherwise the system was found to work effectively.

- Grout Strength Assessment

  The standard specification for grout materials is contained in Appendix C. The specification also gives details relating to the testing of grout strength. Because of the cold conditions at the site and the possible effects on grout cure, grout test cubes were manufactured at site, in advance of the trials, and allowed to cure submerged in the test basin. The water temperature in the test basin was measured as 5-6°C. Figure 6.11 shows that after 36 hours the grout strength was well below 7.5MPa, the minimum required before the clamp studbolts could be tensioned. As a result of these low results, the following steps were instigated to reduce the curing time:

  - Sikament H.E 200 plasticiser and accelerator was added to the mix.
  - Cement bags were stored at 20°C prior to use.
  - Temperature of mix water was maintained above 20°C prior to use.

  The rates of strength gain for the standard and modified grout mixes are shown on Figure 6.11. The figure shows a reduction in grout curing time to approximately 24 hours to achieve the target strength. To allow for possible variation between cube strength and actual grout strength in the clamp annulus, the grout cure time for the in-water trials, using the modified mix, was set at 30 hours. Manufacturers guarantees were obtained to ensure that the admixtures did not increase shrinkage or bleed in the grout and that they did not contain chlorides or other chemicals liable to precipitate steel corrosion. A gel test on the modified mix was undertaken to confirm that the mix would remain pumpable for a minimum of one hour.

6.7 Studbolt Tensioning System

The tensioning solution and its operation is illustrated in Figure 6.12. The system works by applying hydraulic pressure beneath the piston which is pushed upwards to bear against the reaction disc, threaded onto the studbolt. Suitable hydraulic pressure is applied to stretch the studbolt to the desired preload. While the pressure is maintained, the external collar is wound upwards to bring it into firm contact with the reaction disc. Hydraulic pressure is removed and the studbolt tension is carried through the collar into the body of the tensioner and into the clamp flange plate.

Component trials were successfully performed on each of the tensioners. Tests indicated the initial transfer losses, incurred upon release of the hydraulic pressure, were in the region of 7%. This is consistent with that expected from a standard diver-friendly bolt tensioner. The tensioners were designed to be connected in series to provide equal load to each of the studbolts simultaneously. Tests indicated a maximum studbolt load variation for the T-joint clamp, which incorporates 13 No.

studbolts, of 5% when tensioning the studbolts to 70% of their yield load. This was mainly due to a small drop in pump pressure during the time taken to wind up all 13 No. external collars.

The tensioners incorporate an integral spherical washer to minimise bending moments induced due to misalignment of the studbolts. The lower concave section of the spherical washer was designed to be screwed to the clamp flange plate to secure it in the correct position and prevent displacement or rotation during the installation of the clamp. The upper convex section is loosely trapped by the lower concave section by a rebated threaded arrangement. The effectiveness of spherical washers was brought into question during the dry 'fit-up' trials, see Section 7.

A feature of the tensioning tools is that they remain in position on the clamp following installation. This offers the advantage that they can be re-used during periodic platform inspection to confirm studbolt tensions. To facilitate their re-use push-fit protectors packed with waterproof grease should be fitted, following completion of the installation. Similar protection should be given to the hydraulic stab fitting on the clamp manifold. Protectors of this type are commonly employed in offshore application for the protection of bolt threads and suitably adapted versions can be readily supplied by Hydratight, the manufacturers of the tensioning tools.

6.8 Summary Of Lessons Learnt from Component Trials

The following points summarise the specific lessons learnt during the component trials, which were subsequently incorporated into the procedures used for the dry fit-up trials:

- Two-way acting (push and pull) hydraulic cylinders used to operate the clamp closure system, and required to be 'stabbed' while pressurised, must include a pilot check valve within the hydraulic circuit, as illustrated in Figure 6.4.

- A studbolt retainment system of the type employed for the trials, illustrated in Figures 6.5 and 6.6, is sensitive to the thickness of the neoprene packer and the size of the hole through the packer. Component trials are required to establish design values for the specific studbolt size and length.

- The captive nut detail, illustrated in Figure 6.6, requires modification to positively align the nut and washer with the studbolt. This problem was addressed by packing the space between the nut holding plate and retaining plate with silicon gel. A more permanent fixing of the nut to the retaining plate in a defined attitude to the studbolt is recommended for use in future.

- Calculations for the determination of the required 'hardness' of polychloroprene (Sorbothane) for DISC seals, contained within the Design Report, Appendix B, proved accurate. The optimum 'hardness' value, for the clamp sizes used in the trials, was Shore No. 50.

- Close attention is required to the detailing of the interface between the DISC seals and the longitudinal seals at the clamp centreline. The detail used for the trials is illustrated in Figure 6.8.

- O-rings used to seal grout stab fittings (and any similar details) should always incorporate the O-ring internally on the female receptacle. This reduces the potential for damage, helps to keep it clean and generally improves sealing.

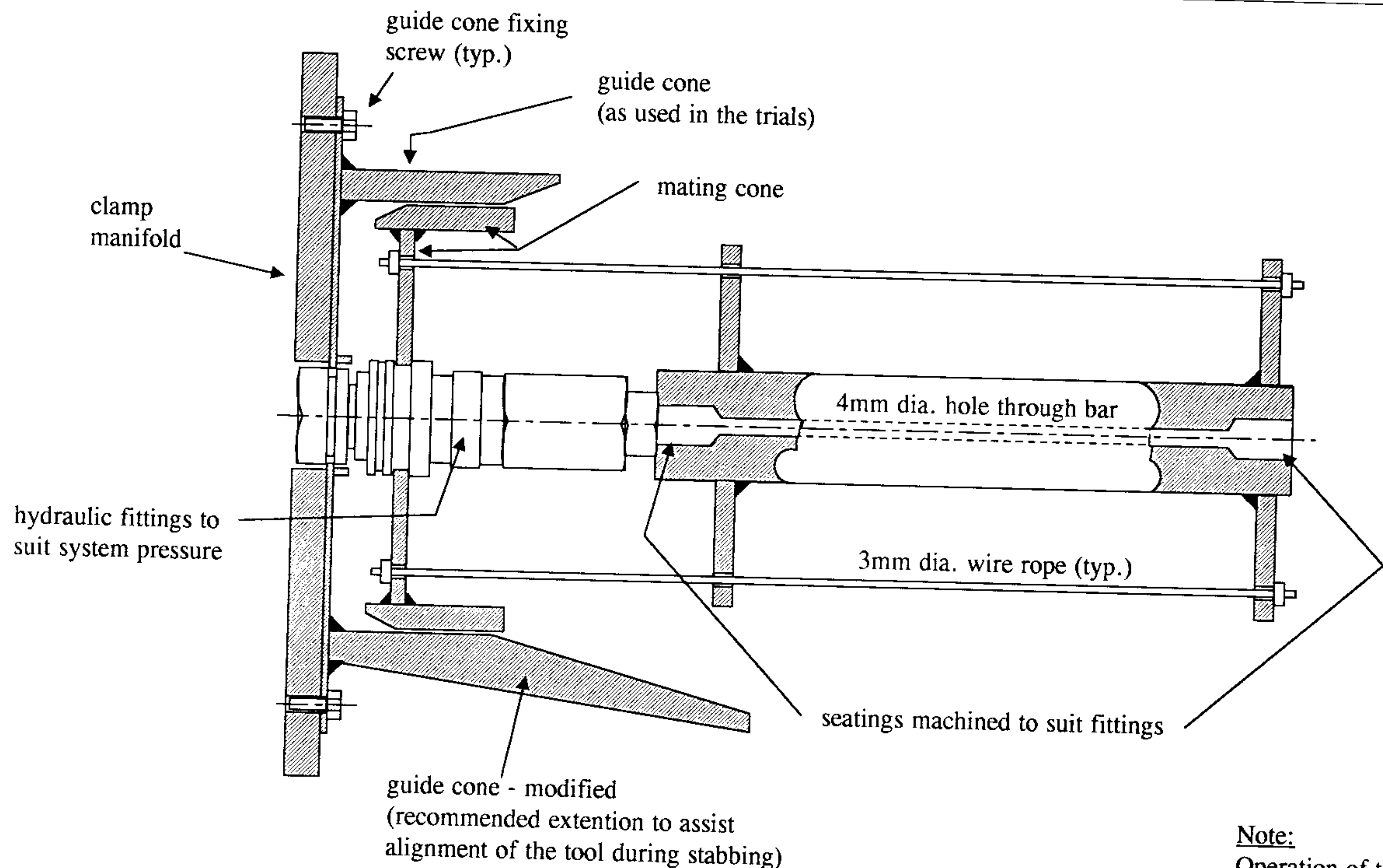
- A grout mix for offshore use should be selected following specific mix trials to determine the expected curing time at the ambient water temperature. It is possible, as found during the demonstration trials, that a combination plasticiser/accelerator may be required if cure times prior to bolt tensioning are required to be kept within 24 to 36 hours. The following additional steps were required to bring cure times below 30 hours for the demonstration trials:

  - Cement bags were stored at 20°C prior to use.

  - Temperature of mix water was maintained above 20°C prior to use.

  Care should be taken to ensure that the admixtures do not increase shrinkage or bleed in the grout and that they do not contain chlorides or other chemicals liable to precipitate steel corrosion. A gel test on the modified mix is necessary to confirm the mix will remain pumpable for the period required to complete the grouting operation including a reasonable contingency for performance of remedial measures.

- Tests on the hydraulic studbolt tensioning system confirmed that the allowance of 10 to 15% commonly used in design for initial loss in studbolt load is reasonable for a wide spectrum of studbolt configurations. Tests on the studbolts used in the trials showed the losses to be of the order of 7%.

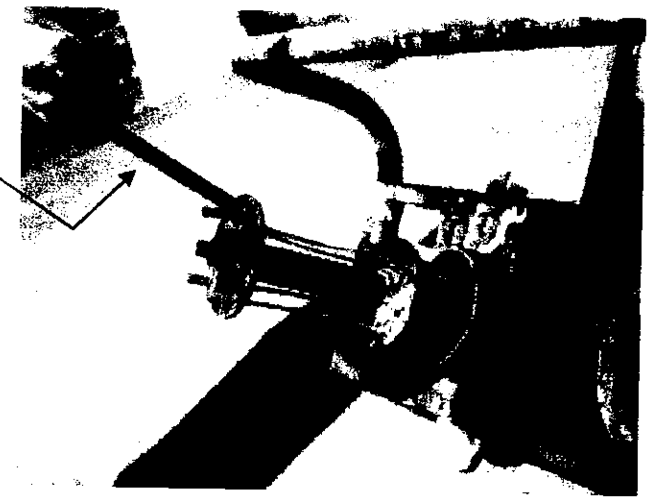


Note:
Operation of the system is illustrated in Figure 6.2.

Figure 6.1: Hydraulic Stab System

T-bar handle for WROV manipulation

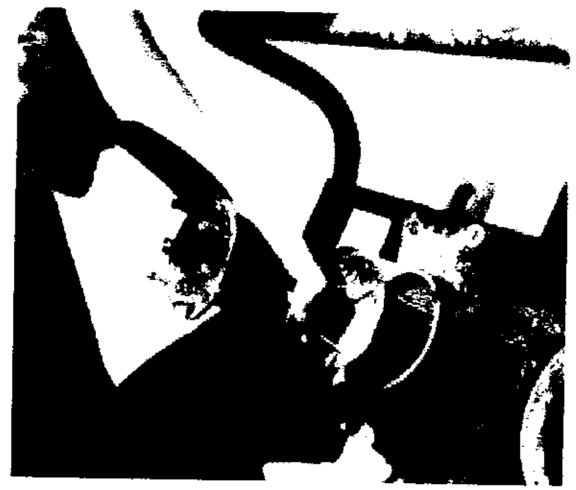
Male 'Stab' Tool for Tensioning System
(clamp closure 'stab' similar)



the stabbing tool self engages to the manifold when presented and aligned by the WROV

stabbing would have been greatly facilitated by increasing the lead-in on the manifold to assist the WROV with alignment of the stab tool (post in-water trial observation)

Stab Tool Engagement



the stabbing tool is disengaged by the tensioning of the cables, achieved by grabbing the tool as illustrated (using WROV manipulator jaws)

Stab Tool Disengagement

Figure 6.2: Hydraulic Stab Operation

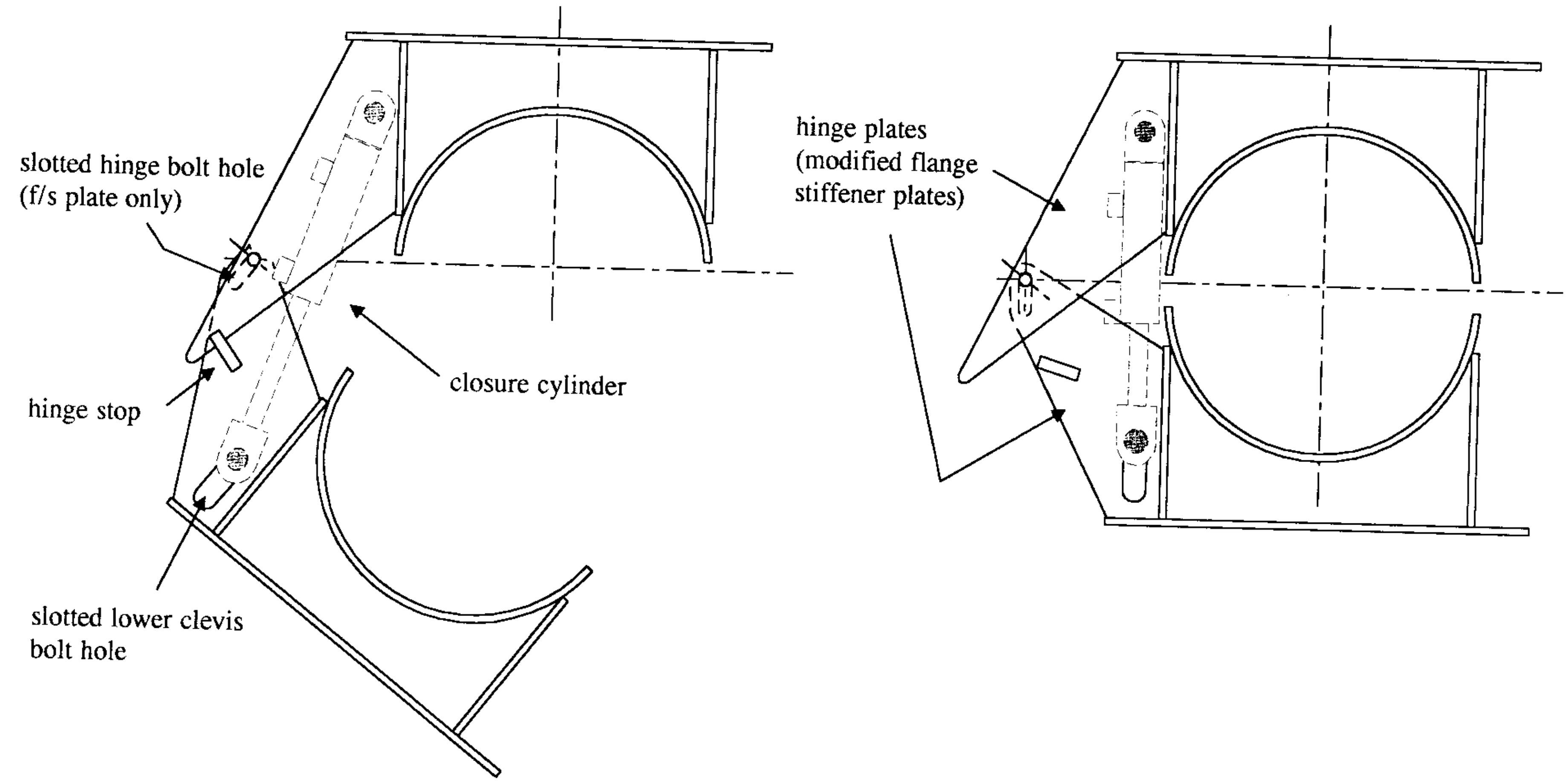


Figure 6.3: Clamp Closure System

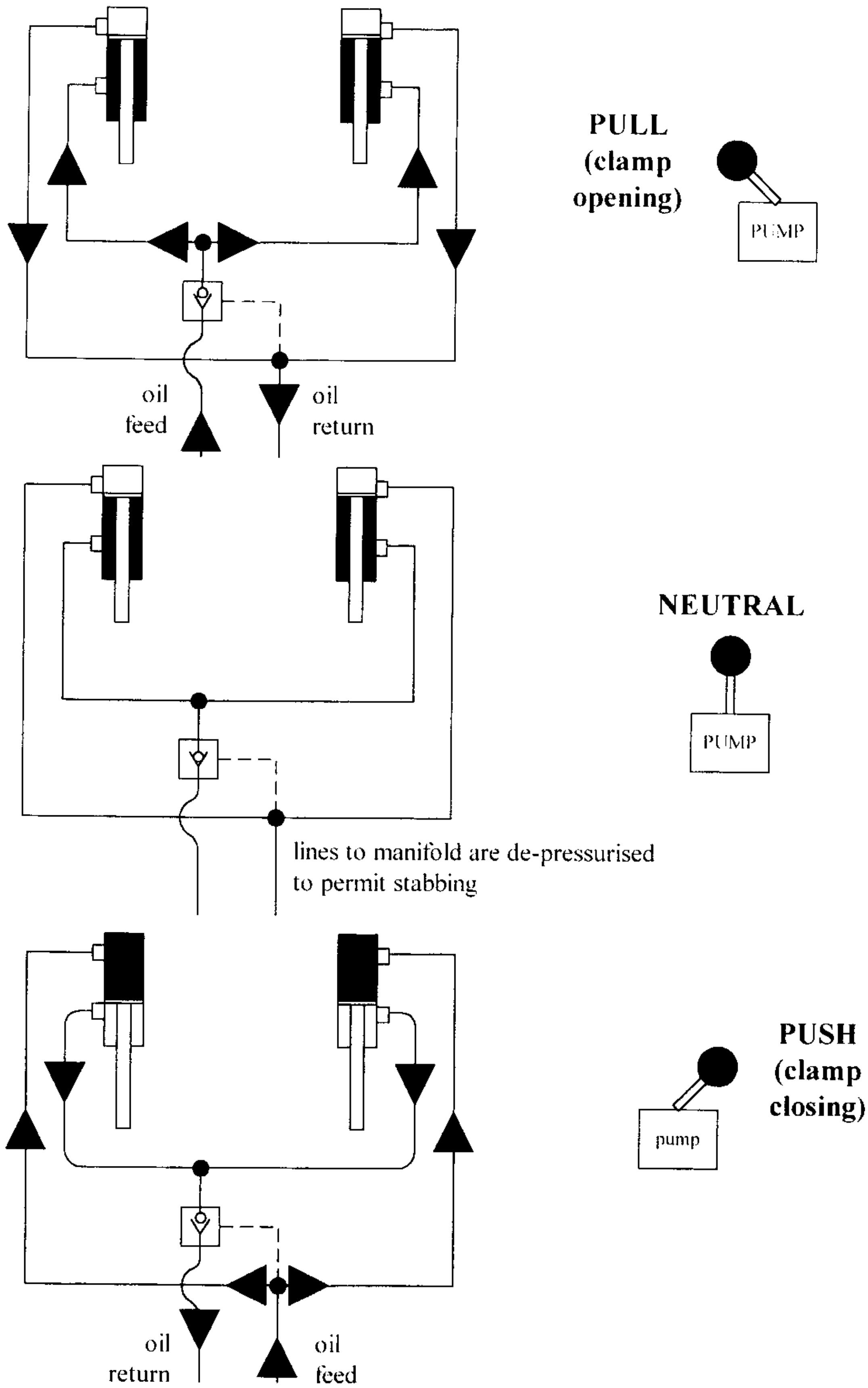


Figure 6.4: Hydraulic Closure System, Circuit Operation

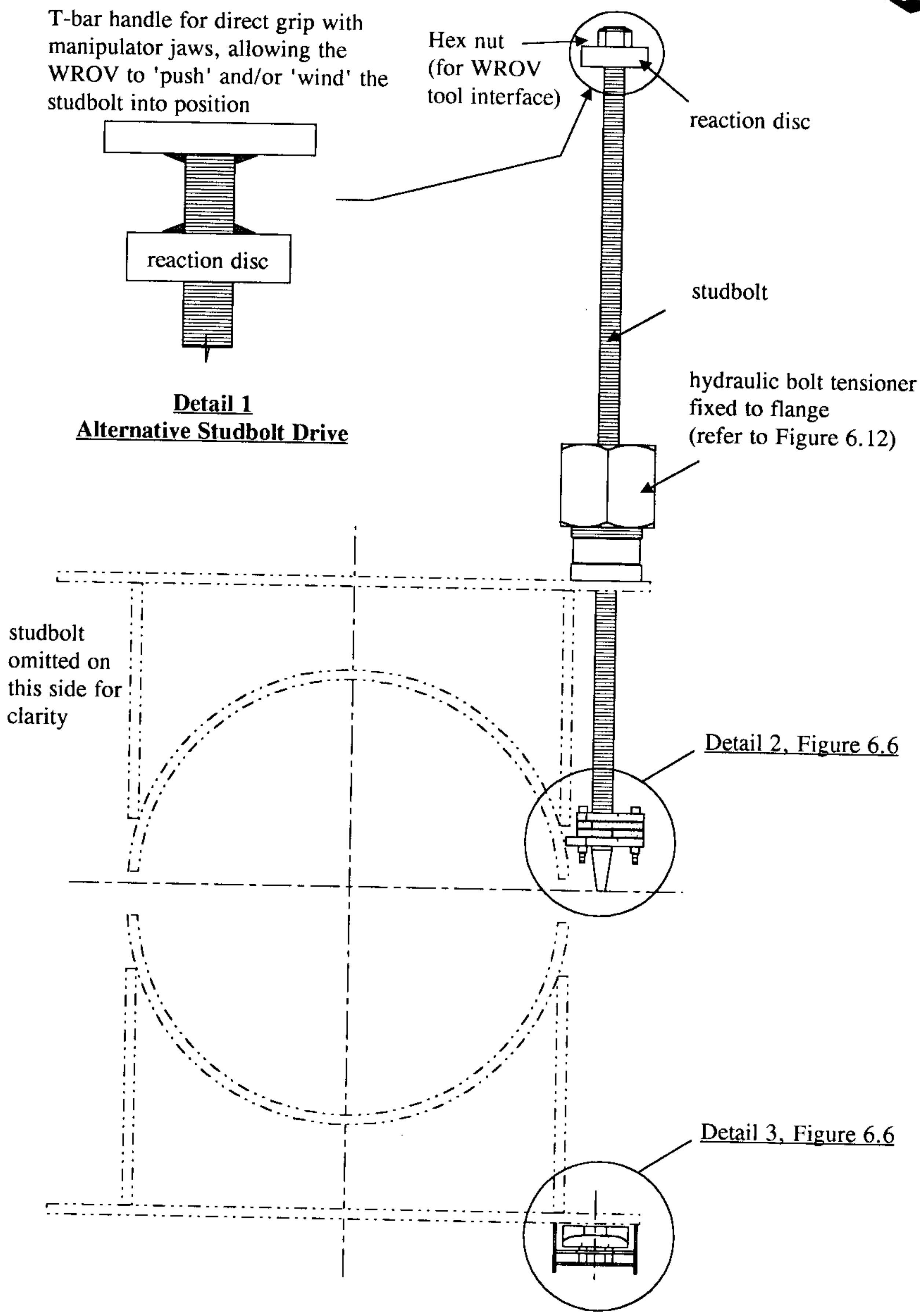
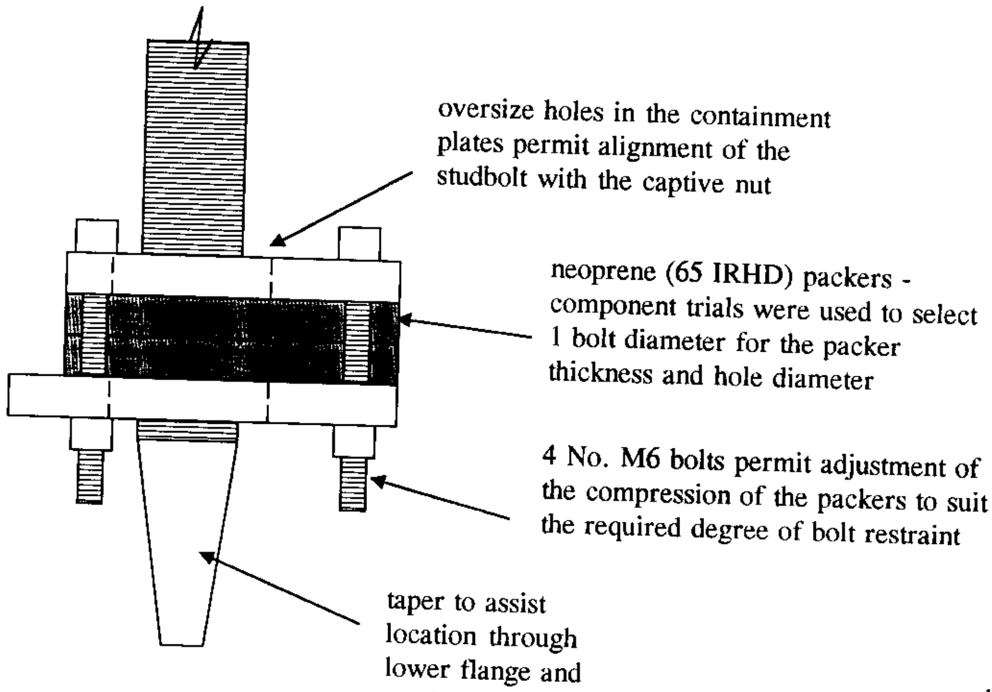
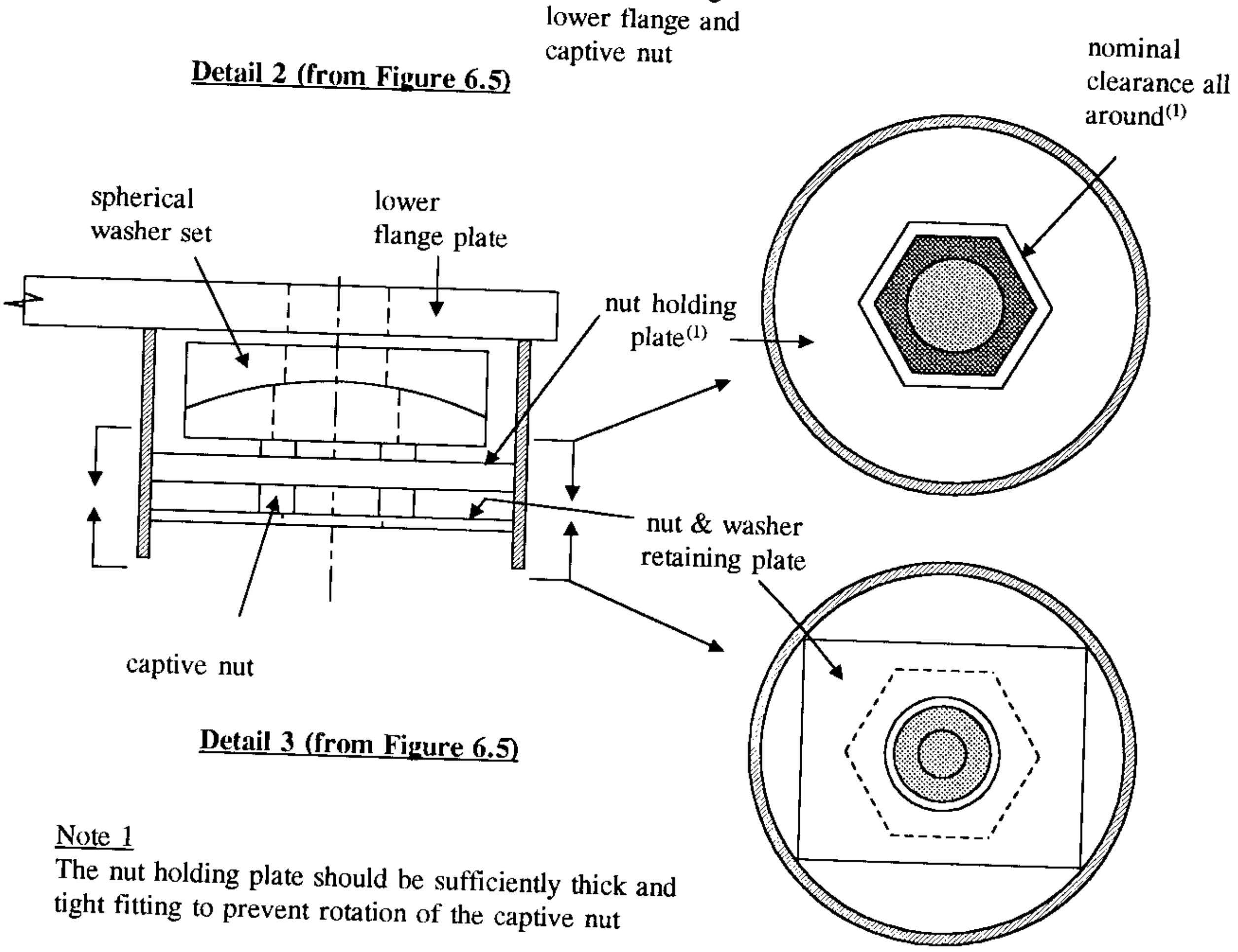


Figure 6.5: Studbolt Restraint and Engagement System



Detail 2 (from Figure 6.5)



Detail 3 (from Figure 6.5)

Note 1
The nut holding plate should be sufficiently thick and tight fitting to prevent rotation of the captive nut

Figure 6.6: Studbolt Restraint and Engagement System Details

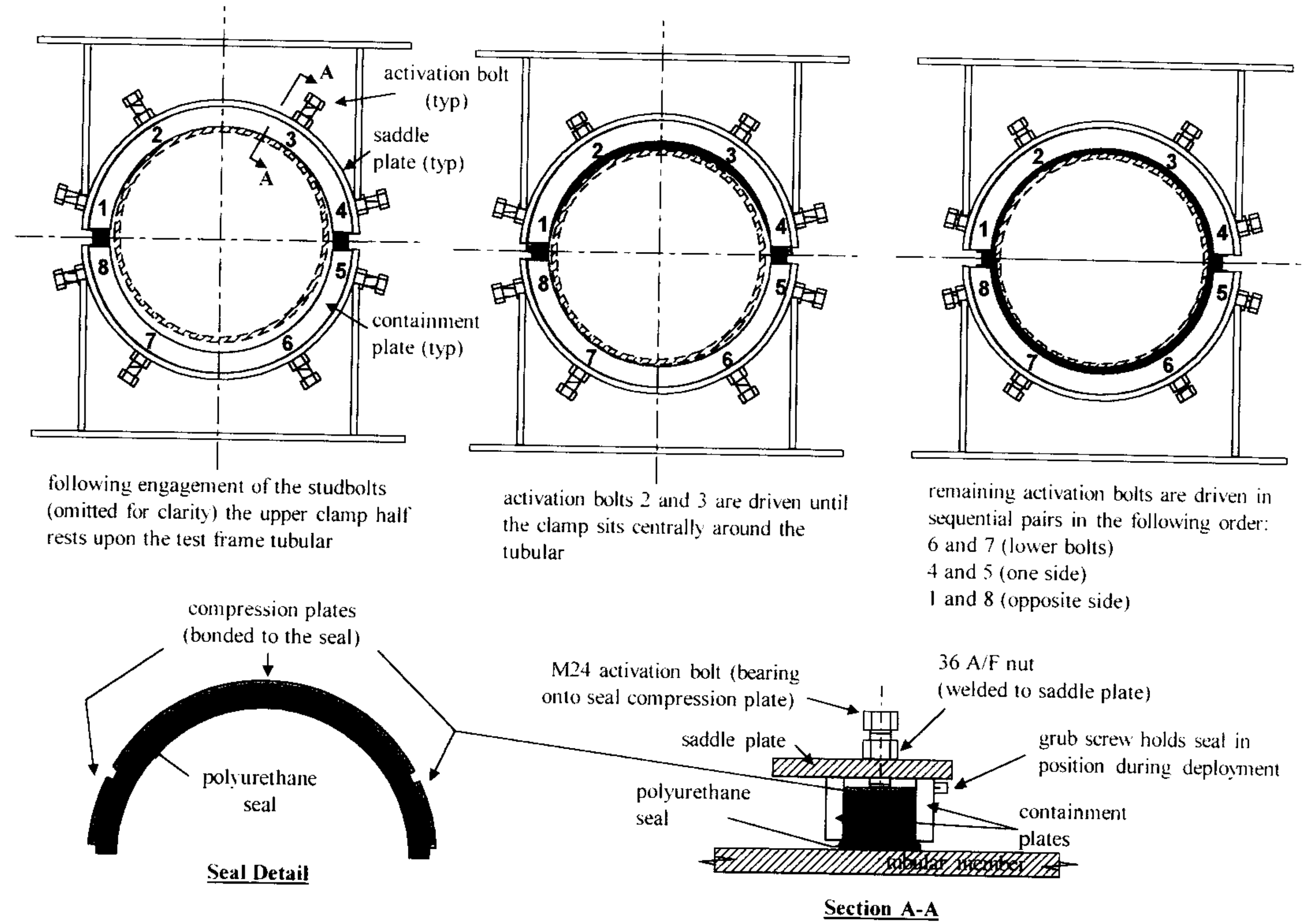


Figure 6.7: DISC Sealing System

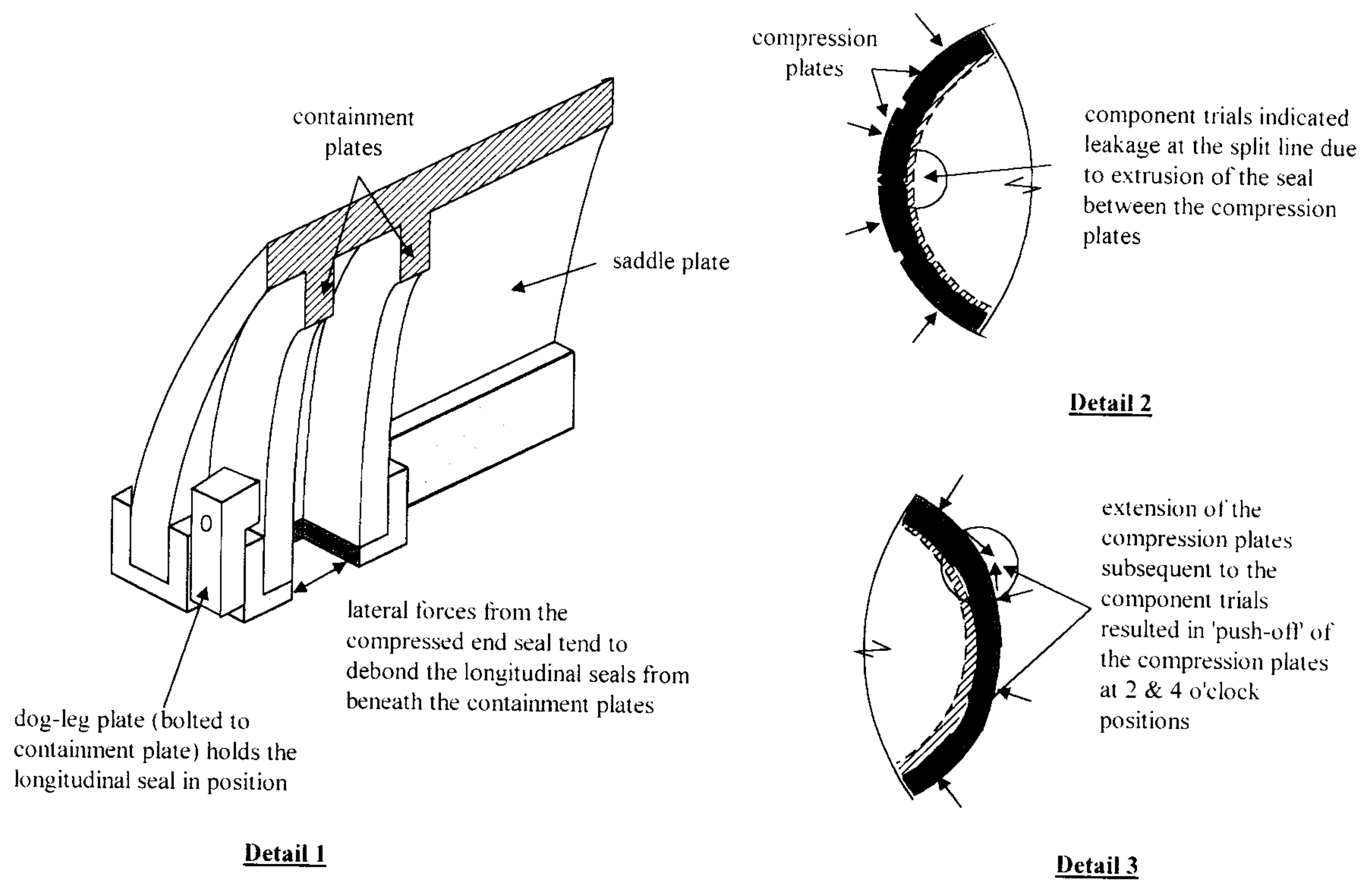


Figure 6.8: Clamp Split Line Sealing Details

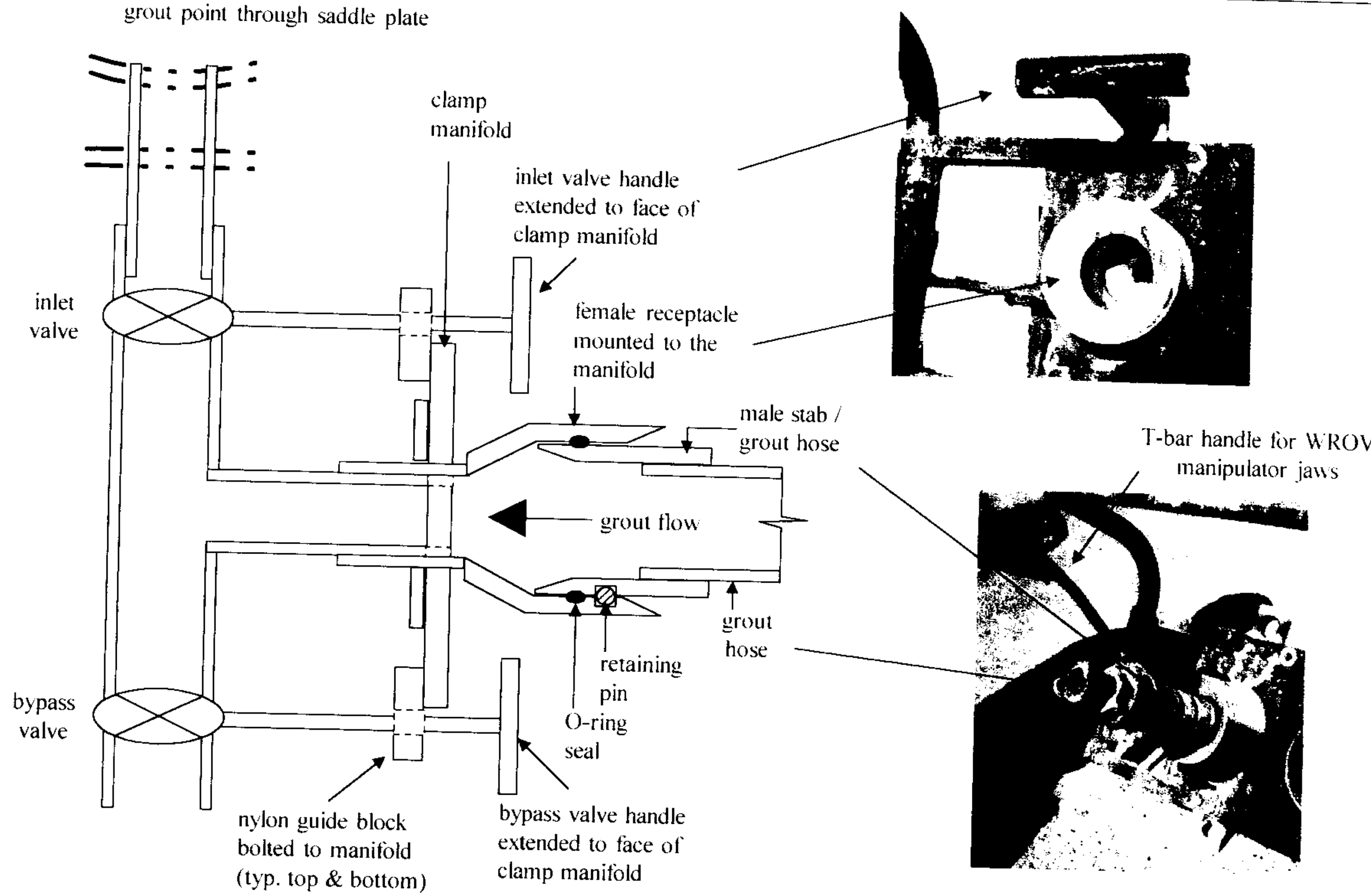


Figure 6.9: Grout Inlet Assembly

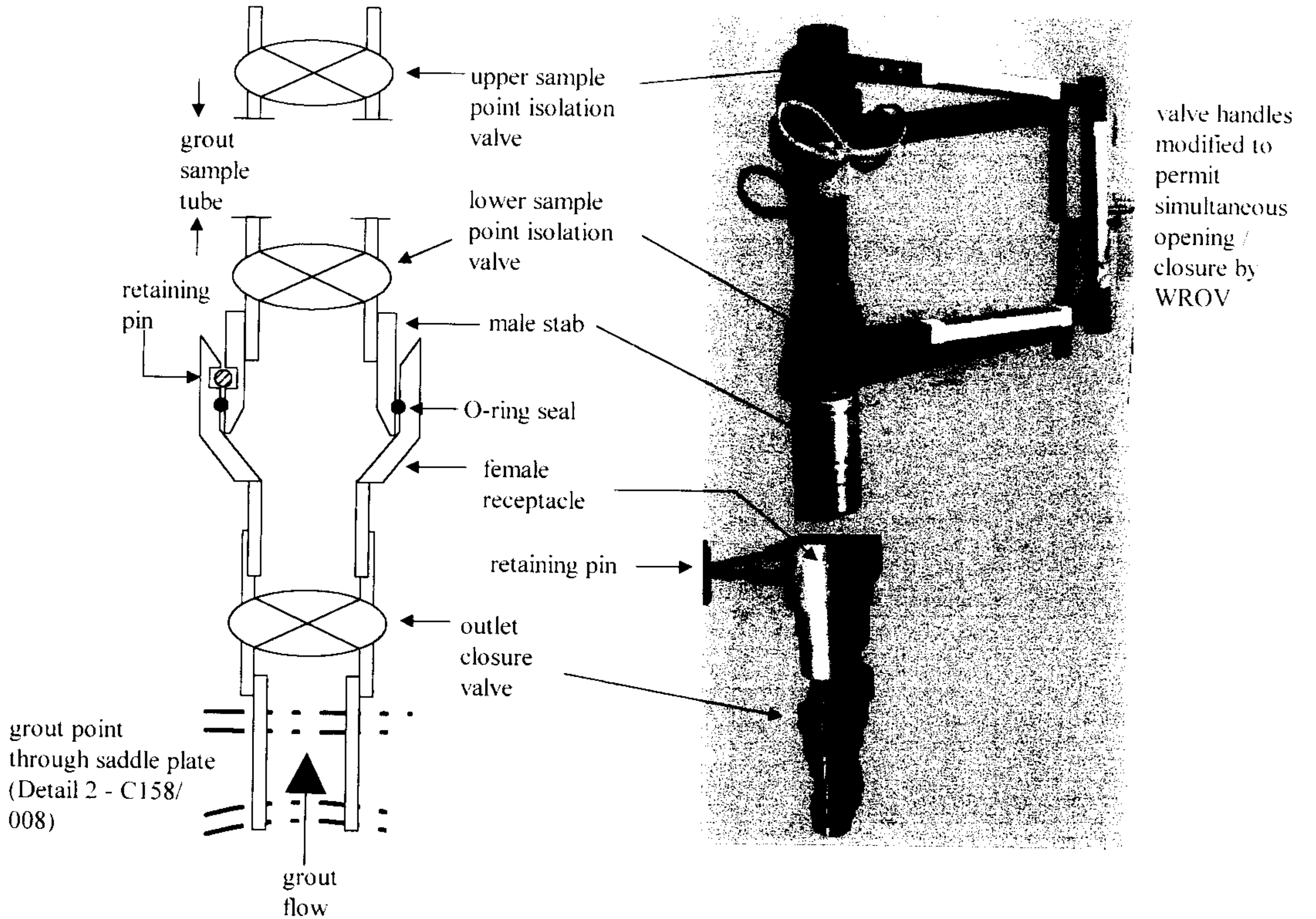


Figure 6.10: Grout Outlet and Sample Point Assembly

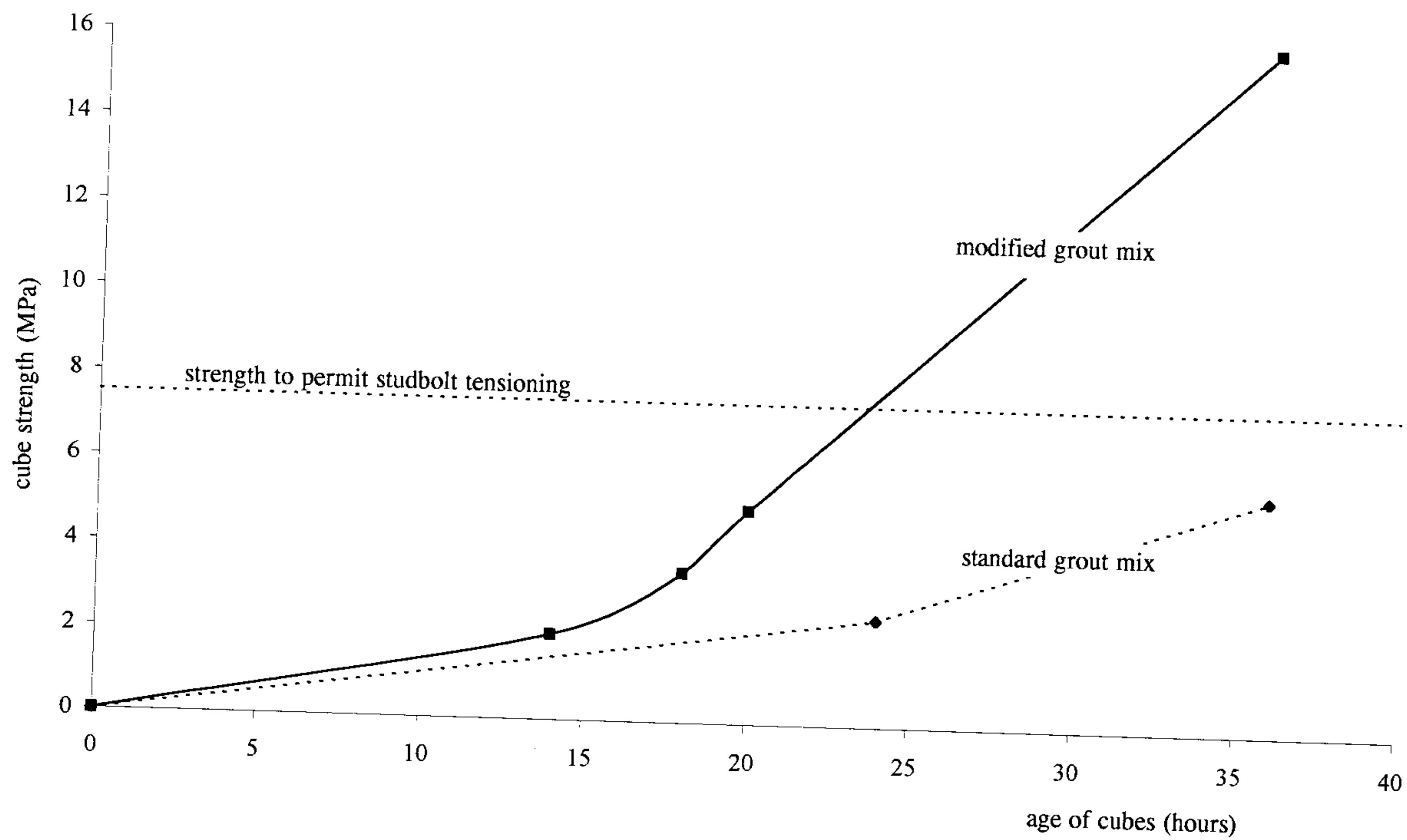
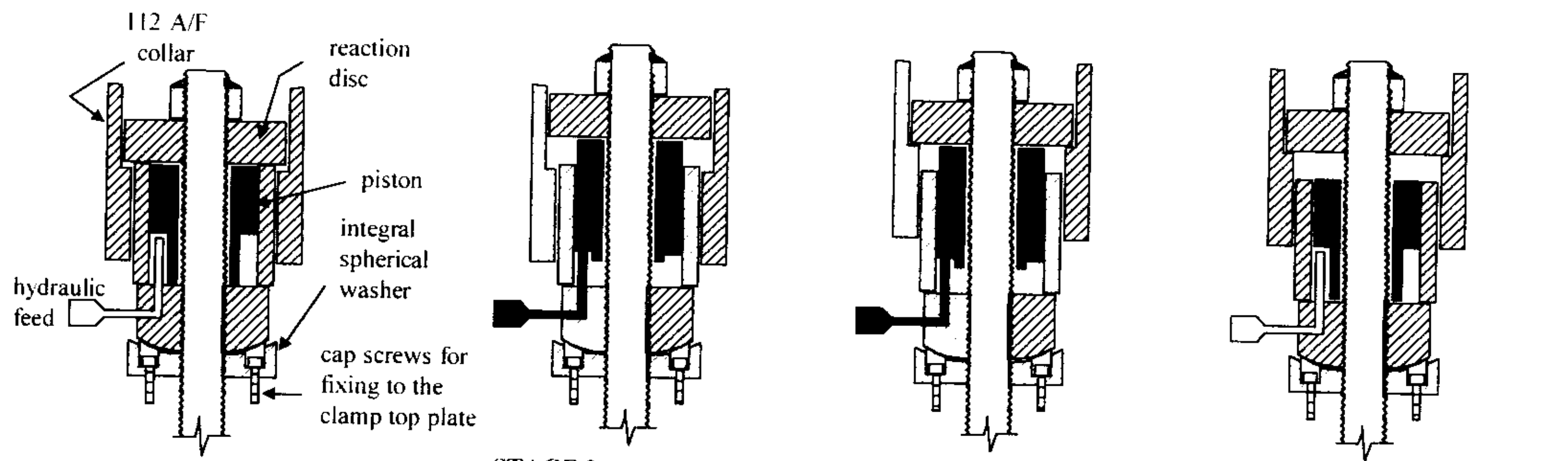


Figure 6.11: Rate of Gain of Grout Strength



STAGE 1
The studbolt is wound down to remove slack and bring the reaction disc into firm contact with the piston

STAGE 2
The hydraulics are powered to raise the piston which reacts against the reaction disc, stretching the studbolt

STAGE 3
The hydraulic pressure is maintained while the collar is wound upwards into firm contact with the reaction disc.

STAGE 4
The hydraulic pressure is released locking in the studbolt tension via the body of the hydraulic nut

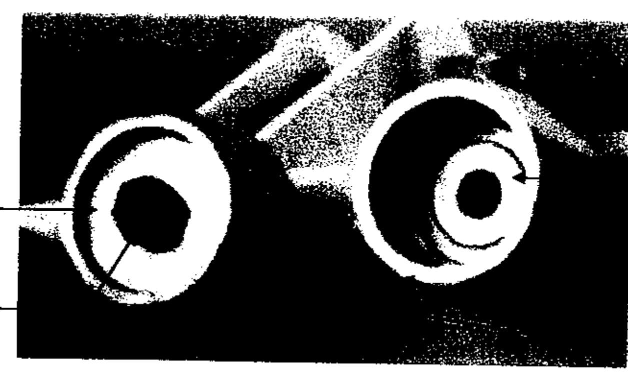


Figure 6.12: Diverless Studbolt Tensioning System

7. DRY 'FIT-UP' TRIALS

7.1 Scope

Prior to each in-water trial, trials on the dry dock were conducted. These trials involved the installation of the appropriate repair clamp onto the test frame in accordance with the developed procedures. The intervention tasks were performed manually by the WROV or ADS pilots. It should be noted that the ADS is not operable 'in-air' hence the ability to perform tasks relied upon the experience and judgement of the pilot. The objectives of the dry trials were as follows:-

(i) To test the installation procedures which were updated following conclusion of the component trials.

(ii) To check that all components were functioning as expected.

(iii) To familiarise the WROV and ADS teams with each task to be performed during the in-water trials.

A wide-ranging number of lessons were learnt during the course of the dry trials. These experiences were used to update the installation procedures prior to the in-water trials. The updated procedures appear in Appendix E. The lessons learnt are described below.

7.2 Lessons Learnt from Dry 'Fit-Up' Trials - Generic

The following generic lessons were learnt during the dry fit-up trials:

(a) Dry trials are invaluable in assisting pilot orientation with respect to the work face, particularly when in-water visibility is expected to be poor (as was the case for the in-water trials).

(b) Clamps must be clearly labelled with a logical alphanumeric sequence in order that the procedures can refer, unambiguously, to specific areas of the work face. The typical alphanumeric labelling system adopted for the trial clamps is illustrated in Figure 7.1.

(c) Specific attention must be given to the positioning of grab handles or positive docking devices for stabilisation of the WROV to facilitate intervention tasks.

(d) In general, any item on the clamp which can be damaged during installation operations will be. It is essential, therefore, that all items are either adequately protected or sufficiently robust to resist damage.

(e) In lieu of the use of sophisticated 3D viewing systems, not currently in general commercial use in offshore applications, every operation requiring WROV observation should be provided with clear, colour coded visual indicators.

(f) It is recommended that the WROV (or a full scale mock-up of the WROV) be introduced to the work face during fit-up trials to ensure that sufficient clear access is available for completion of each intervention task.

7.3 Lessons Learnt from Dry 'Fit-Up' Trials - ADS Intervention

Unlike the WROV-installed clamps which were provided with 'WROV-friendly' aids, the ADS-installed clamp was provided with diver-friendly aids. This was directly in line with the advice and instruction of the ADS operators and personnel as discussed in Section 5. The following lessons specific to ADS intervention were learnt during the dry fit-up trials:

(i) The ADS pilot advised that the NEWTSUIT was not able to generate enough power to operate the standard diver-friendly tirfors. An alternative method was devised whereby the ADS attached rigging to the crane hook in-water to permit the crane to close the clamp around the test frame

(ii) ADS operational personnel decided to abandon the manual installation of individual studbolts (as used for diver installation). This necessitated installation of a WROV-style bolt retainment system.

(iii) It was decided to activate the DISC seals using a ratchet drive socket wrench. To this end, sockets were wired to the DISC seal activation bolts to permit the ADS to positively engage the square drive into the socket.

(iv) The ADS pilot advised he would need to utilise the clamp mounted manifold to facilitate stabbing of the grout line from the surface and stabbing of the hydraulic feed for bolt tensioning. Both these decisions constituted a departure from their intention to use only standard diver-friendly installation aids.

7.4 Lessons Learnt from Dry 'Fit-Up' Trials - Operating Systems

The following lessons specific to the clamp operating systems were learnt during the dry fit-up trials:

(a) Clamp seal leak tests showed that the extension of the compression plates on the DISC seals, following the dry fit-up trials, caused the containment plates to come into contact around the entire circumference resulting in 'pop-off' of the plates (and hence the seals) at the 2 o'clock and 4 o'clock positions as illustrated in Figure 6.7, Detail 3. The result was minor leaks at these locations. This was remedied by shortening the compression plates adjacent to the split line. The large forces generated in the compression plates as a result of their circumferential contact caused some plastic deformation, necessitating re-cambering of the plates prior to the in-water trials.

(b) Consideration was given to the use of fine sawdust in the water supply during the leak test to seal minor leaks. In the event, this was not required. However, it is an area which could be given further consideration as a remedial measure in offshore applications. The effect of any included material on the integrity of the grout should be carefully considered in this instance.

(c) The lack of a hinge stop on the WROV installed clamps allowed the clamp to be opened excessively. This caused the hose fitting on one of the hydraulic cylinders to clash with the hinge pin, resulting in a minor hydraulic oil leak. The procedures were modified to allow continued observation of the suspect fitting throughout clamp closure operations. A practical and effective hinge stop detail, as used on the ADS installed clamp, is illustrated in Figure 6.2.

(d) It was identified that the lower clevis mounting for the closure cylinders should be slotted to allow the two clamp halves to move towards each other during studbolt tensioning operations even if the cylinders were pressurised. The procedures were modified to ensure the closure cylinders were fully de-pressurised prior to disconnection of the feed and return lines. The preferred detail is illustrated in Figure 6.2.

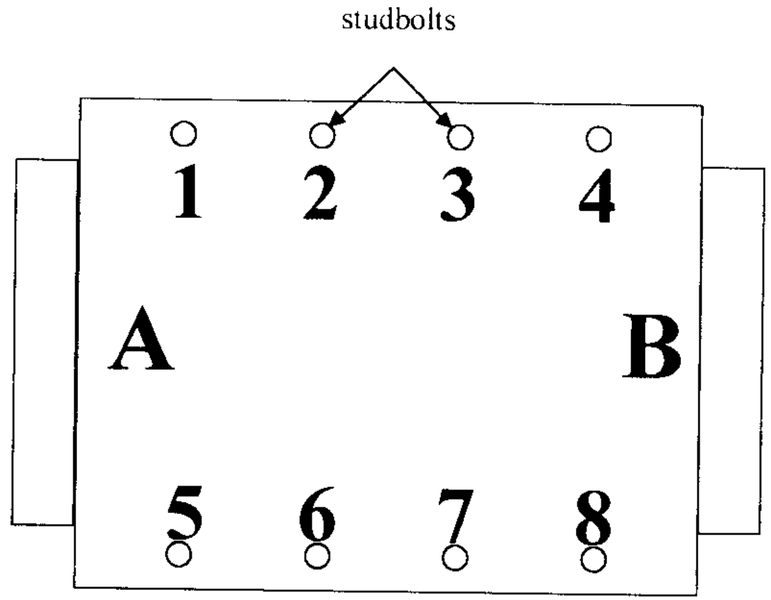
(e) The supplied PVC valve handles on the grouting system were found to be insufficiently robust. This was remedied by bolting the handles to the valves to prevent them coming adrift during activation.

(f) The time required for the WROV to isolate a sample of grout in a sample tube, a process involving the closure of a ball valve above the sample tube and one below the sample tube, was found to be excessive. This was remedied by modifying the valve handles to enable the simultaneous closure of the two valves with a single manipulator function. This modification is illustrated in Figure 6.9.

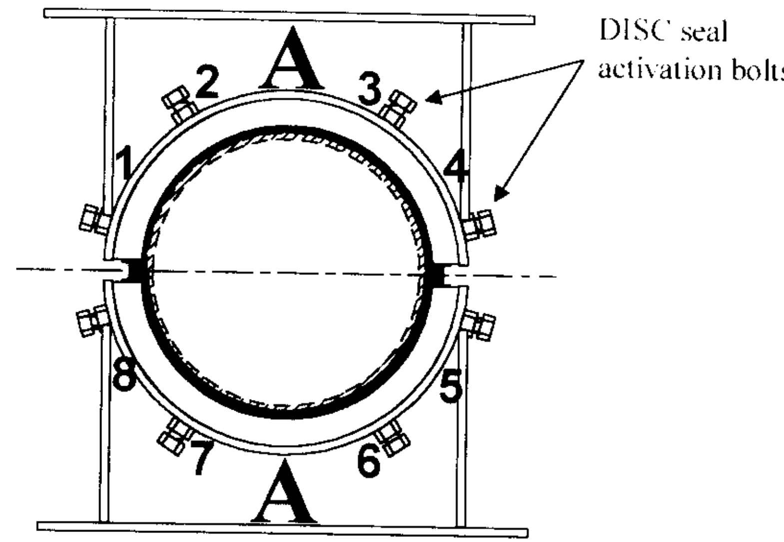
(g) During the installation of the horizontally aligned studbolts on the elastomer-lined clamp, it became apparent that the captive nuts were susceptible to cross threading. The hex hole in the nut holding plate was oversized, allowing the nut to tilt out of alignment with the studbolt. The adopted solution was to install rubber alignment tubes positioned to hold the nut and washer concentric to the hole in the flange plate and square to the studbolt. The alignment tubes were designed to be pushed clear by the advancing studbolts although they were not 100% reliable. The solution, in practice, is to ensure the nut holding plate, shown in Figure 6.5, Detail 3, is sufficiently thick and close fitting around the nut, to prevent the nut rotating.

(h) During the trial studbolt tensioning of the elastomer-lined clamp the studbolts were observed to bend. It appeared that the spherical washers were ineffective in compensating for the bending induced by the minor eccentricity of the axial load. It is recommended that a nominal bending allowance be included in design checks for clamp studbolts to prevent overstressing.

(i) During the trial studbolt tensioning of the elastomer-lined clamp it was required to re-stroke the hydraulic studbolt tensioning tools. This task simply involved releasing the hydraulic pressure to the tools, winding down the studbolts by 6-8 rotations i.e. 18-24mm and then reapplying the hydraulic pressure.



Typical Clamp Plan View Number Sequence



Typical Clamp End View Number Sequence

Figure 7.1: Typical Clamp Numbering Sequence

8. IN-WATER TRIALS

8.1 General

The in-water demonstration trials were conducted at Euro-Seas Centre for Offshore Technology in Blyth Northumberland, U.K. The trials were performed during November/December 1996. They were conducted in two stages as described below:

- Stage 1 of the trials involved intervention by NEWTSUIT ADS.
- Stage 2 of the trials involved intervention by WROV.

Appendix E contains the installation procedures, together with annotations which reflect observations made during the in-water trials.

8.2 Stage 1 - Intervention by NEWTSUIT ADS

As discussed in Section 3, the ADS procedures were developed by the ADS operator on the basis that the NEWTSUIT was capable of the in-water operation of standard diver-friendly installation aids typical of a conventional clamp. Following the on-shore dry fit-up trial it became apparent that this basis was fundamentally flawed. Some of the specific shortcomings, and the solutions engineered, on-site, to overcome them, have been described in Section 6 and 7. The in-water trial observations are noted in Appendix E.

Figure 8.1 shows the times taken for the various tasks involved in the ADS T-clamp installation. The times shown, with the exception of grout curing, are based upon 12 hour work shifts and exclude non-working hours. The overall time of approximately 50 hours is dominated by the 30 hour grout curing period. In general, where the NEWTSUIT was required to operate diver-friendly systems such as, for example, tirfors for clamp closure and standard hydraulic bolt tensioners, it was unable to complete the tasks. In all such cases it was necessary to recover the frame to the surface for completion. Where it was possible to install the 'WROV-friendly' installation systems developed for the WROV clamps, such as, for example, the grouting system and hydraulic stabbing system for bolt tensioning, the NEWTSUIT was extremely efficient with significant time savings over the WROV.

Figure 8.2 shows a comparison of the times taken for each task by the NEWTSUIT and the WROV. The tasks of DISC seal activation, leak testing and annulus grouting were each completed by the NEWTSUIT in approximately 50% of the time taken by the WROV. The figure confirms that, where direct comparisons are relevant, the NEWTSUIT offers significant time savings compared to WROV intervention. In order to achieve these, however, the NEWTSUIT requires a fully engineered remote solution. The time savings resulted directly from the three major advantages the NEWTSUIT offers over an WROV, namely:

- 3-dimensional vision of the work face

- rapid mobility around the work site
- improved dexterity through direct manipulator jaw operation.

8.3 Stage 2 - Intervention by WROV

In general, each of the clamp installation systems were successfully operated by the WROV. Specific areas were identified where modifications may reduce in-water task durations for future operations; these are discussed below.

The overall times noted for the various installations relate to actual working hours. They are inclusive of non-productive effort due to, for example, WROV breakdown, but exclusive of non-working hours except in the case of grout curing for which a total period of 30 hours is included.

8.3.1 Installation of Stressed Grouted T-Joint Clamp

Figure 8.3 illustrates task durations for installation of the WROV T-joint clamp. The times shown, with the exception of grout curing, are based upon 12 hour work shifts and exclude non-working hours. The overall time for completion of the installation was just less than 68 hours, inclusive of 30 hours for grout curing.

It was found that connecting the clamp closure hydraulic stabs prior to deployment would allow the horizontal attitude of the clamp to be adjusted, by opening/closing the clamp, which would have assisted with its placement onto the frame. The in-water stabbing operation, although successful, would have been improved by making the stab connector neutrally buoyant and increasing the length of lead-in taper on the manifold to cause the stab to self align. This modification is illustrated in Figure 6.1.

The task of driving down the studbolts involved the WROV engaging a modified socket (fitted to an impact wrench) onto a standard hex nut. The task was hindered by poor positioning of the WROV grab bars, requiring the WROV to engage the socket whilst free swimming. The system proved time consuming due to difficulties in engaging the socket and keeping it engaged on the nuts. Durations could have been significantly reduced by adapting the studbolt drive for direct operation with the WROV manipulator jaws without need of the socket or impact wrench (see Figure 6.4, Detail 1). This would allow the WROV to 'push' the studbolt into position with the manipulator and then use the 360° continuous wrist rotate function to wind the studbolt and engage the captive nut to remove slack. It is estimated that this, combined with better positioning of grab bars, would reduce the task duration by approximately 50%.

Activation of the DISC seals required similar interface of a socket onto a hex bolt. This task was also successfully completed by the WROV, however, the limited access to some of the DISC seal bolts on the underside of the clamp and the problems of socket engagement (as experienced during the studbolt driving) made this activity unduly time consuming. Replacement of the DISC seal activation bolts with miniature subsea hydraulic rams, operated via the clamp manifold, would remove WROV interface with the DISC seals. It is estimated this modification would reduce the duration of this task by approximately 75%. There would, however, be a consequent increase in the complexity of the on-clamp hydraulics required to supply the cylinders at each DISC seal and a resulting increase in hardware costs. This should be assessed on a cost-benefit basis. The benefit will be greatest where WROV access to the DISC seals is restricted by the structure being repaired.

Grouting operations had to be aborted just prior to completion when grout failed to emerge from the outlets at the top of the clamp. Following recovery of the test frame, it was discovered that a contingency (unused) inlet valve had been left open, allowing grout to escape from the bottom of the clamp. The error was not detected at the time because the valve handle, which was checked and confirmed to be in the closed position, was subsequently found to have been fabricated 90° out-of-phase. The low visibility (approximately 1m) did not make it possible to observe the emitted grout. Procedures were modified to extend pre-deployment checks to include the physical checking of all valve phases. The clamp was flushed and grouting operations repeated to fully grout the annulus.

Bolt tensioning operations were performed successfully, in accordance with procedures. The WROV interface with the tensioners, i.e. winding up the external collars, was successful both with the fabricated socket and with the manipulator jaws. In the low-current environment of the test site the operation could be simply performed without the requirement for grab bars. In high energy environments, offshore, WROV pilots advised that a central grab bar along the clamp would provide adequate station keeping ability. The WROV disconnected the hydraulic feed upon completion of studbolt tensioning before recovery of the test frame to the dockside.

8.3.2 Installation of Stressed Elastomer-Lined Clamp and Additional Member

Figure 8.4 illustrates task durations for installation of the additional member and the attached elastomer-lined clamp. The overall time for installation was 17.5 hours. Deployment of the assembly occupied approximately one third of this time, an activity which was compounded by the low visibility (1.5m) and breakdown of the 'eyeball' (observation) ROV. This ROV was required to allow the WROV pilot to position the clamp while continuing to observe (via the 'eyeball' ROV video) the catcher plate alignment. Nevertheless, inclusion of guide bumpers onto the clamp to bear on the test frame chord member and positively locate the clamp in the preferred position would have assisted this task. A potential guide/bumper configuration is illustrated in Figure 8.5. Other tasks were successfully and efficiently performed during the installation. Clamp installation systems were generally identical to those used for the T-Joint clamp with the exception that grouting was, of course, not required. The above comments, relating to potential improvements to installation systems for the T-joint clamp, apply equally in this case.

8.3.3 Installation of a Stressed Grouted Tube-to-Tube Clamp

Figure 8.6 illustrates task durations for installation of the tube-to-tube stressed grouted clamp. The overall time for installation was 50 hours. This duration is again dominated by the 30 hours required for grout curing. Remote installation tasks were performed successfully. The systems, generally identical to the T-Joint clamp, are subject to the same comments made previously in Section 8.3.1.

It was discovered during the post-trial verification testing, discussed in Section 9, that although the studbolt tensioning procedures were followed, the preload was not introduced into the studbolts. Forensic examination of the video footage of the trials revealed that the external collars of the studbolt tensioners were wound only a fraction of a revolution to bring them into contact with the reaction disc. This provides evidence that the studbolts were not stretched (tensioned) by the applied hydraulic pressure. Possible explanations include:

- faulty hydraulic pump
- operator error with regard to the operation of the hydraulic pump
- the pump was applying pressure against a blockage or against the clamp manifold due to an incomplete connection during the stabbing of the hydraulic line.

The hydraulic pump was serviced upon return to the supplier, who reported it to be in working order. The second option was discounted, on the basis that the technicians had experience acquired during the three previous installations and had, in accordance with procedures, continuously advised pump pressure readings to operational control where they were recorded in the event logs. The third option is the more probable explanation. Final in-water procedures have been modified to provide visual indication of the minimum anticipated studbolt stretch in order to highlight possible lack of preload during future operations.

Figure 8.7 shows a useful comparison between the installation of the tube-to-tube clamp and the elastomer-lined clamp. The two clamps are structurally similar with the exception of the medium for transfer of studbolt load to the structure. It can be seen that the removal of the grouting requirement makes the overall installation time of a elastomer-lined clamp approximately one third of that for a similar grouted clamp. This is despite the increased times required to deploy the addmember assembly and activate the studbolts, illustrated in Figure 8.7. The delays in these tasks were a result of the catcher plate not effectively engaging the test frame stub and were independent of the clamp configuration. Removing grouting operations also eliminates the following two risks, the second of which was experienced during the T-joint installation:

- Damage to grout seals during deployment.
- Incomplete grouting due to blockage or valve/pump failure.

Both of the above require abandonment of the installation and recovery to surface for remedial operations with the corresponding impact on offshore schedules.

8.4 Summary Of Lessons Learnt from In-Water Trials

The lessons learnt from the in-water trials are summarised below:

(a) Clamps should preferably be deployed with the hydraulic connections for the closure system pre-connected.

(b) Lead-in guides for hydraulic and grout hose stabs should be sufficiently long and tapered to self align the stab mechanism (see Figure 6.1).

(c) Visual indicators should be included to assist every installation operation requiring WROV observation, including clamp closure and studbolt tensioning.

(d) WROV interface with studbolts should be modified as illustrated in Figure 6.4, Detail 1. For this revised detail, procedures should dictate that the studbolts be 'pushed' into location until they contact the lower capture nut. This will ensure the studbolts are not damaged by the WROV holding and twisting the extended studbolt. Where a WROV is required to engage a socket, the hex nut should be double depth to help engage, align and retain the tool.

(e) Activation bolts for the DISC seals may, beneficially, be replaced with miniature subsea hydraulic rams operated by the WROV via the clamp manifold.

(f) Pre-deployment procedures should include physical checking of all valve operations on the grout system e.g. by inserting wire into assumed open valves.

(g) Where clamp final positioning is not self determining (as in the case of the elastomer-lined clamp), the clamp should be fitted with guide bumpers to provide positive location (see Figure 8.5).

(h) The presence of an 'eyeball' (observation) ROV greatly improves in-water task times by providing an additional visual perspective for the WROV operator and by allowing the WROV to remain at the work face while the 'eyeball' ROV observes remote operations. Consideration should be given to the use of tether management systems for both the ROV and WROV to minimise the risk of entanglement of their respective umbilicals.

(i) The 'eyeball' ROV should, preferably, be fitted with a simple grab manipulator or suction 'foot' to assist with station holding. This is important when working in the vicinity of the WROV thrusters or other variable current.

(j) WROV should carry a dedicated tool box containing holstered tools which can be removed for use as-required and replaced upon completion. This reduces the requirement to recover and re-deploy the WROV.

(k) The tool holster should be suitable to include grout sample tubes for insertion into grout outlet points as-required to replace sample tubes removed for surface testing.

(l) The elastomer-lined clamp fitted tightly around the brace member, requiring significant studbolt load to pull the clamp fully around the brace. This problem may be overcome by increasing the lack-of-fit tolerance or by increasing the gap between the two clamp halves at the split-line.

(m) Surface supply systems should have 100% back-up systems on standby during operations. This is important for the grouting spread and hydraulic pumps.

(n) Grout emitted from the outlet points tended to contaminate the exposed studbolt tensioners on the top surface of the clamp. This should be prevented with simple guides around the outlets which funnel the overflow away from the clamp surface.

(o) Visual indication of studbolt tensioning is required to ensure suitable tension is applied when the hydraulic tensioning tools are activated. This may be achieved by the use of extensometers fitted to either the studbolt or the tensioning tool. In its simplest form this may involve counting the flats as the external collar on the tensioner is rotated by the WROV.

(p) Protrusions from installed clamps provided potential snags to the WROV umbilical and hydraulic hoses. When more than one clamp is to be installed, consideration should be given to the use of a shield which can be 'dropped' over the installed clamp. The system should be designed to permit future inspection of the installed clamp including checking of studbolt tensions.

(q) The WROV used in the demonstration trial utilised a 5-function and a 7-function manipulator. The amount of repositioning of the WROV would be reduced by specifying two 7-function manipulators (as a minimum) to allow the WROV greater ambidexterity.

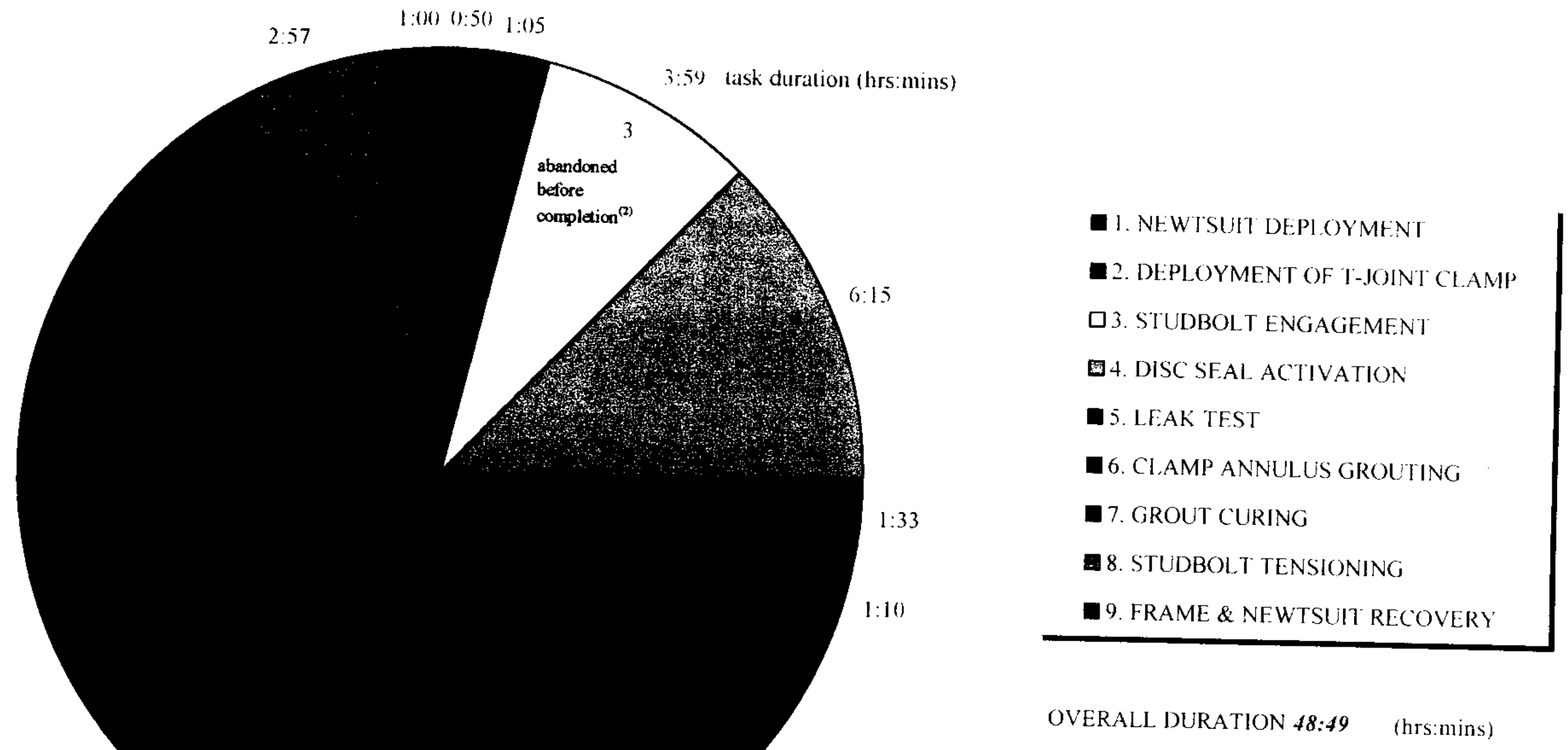
(r) A clear chain of operational control and communications, fully understood by all parties, is essential for smooth in-water operations. The required team spirit and understanding was developed with daily briefings and debriefings attended by all operational personnel.

The above lessons have been incorporated into a recommended set of installation procedures, see Appendix F. These procedures incorporate the lessons learnt during the component and dry fit-up trials of each repair.

The estimated task durations for the recommended installation procedures, based upon experience gained through the underwater trials, are summarised below.

		DURATION (hrs:min)	
		Grouted Clamp	Elastomer Clamp
1.	INTERVENTION SYSTEM DEPLOYMENT	1:30	1:30
2.	CLAMP/REPAIR DEPLOYMENT	3:30	3:30
3.	STUDBOLT ACTIVATION	4:50	4:50
4.	DISC SEAL ACTIVATION	5:20	n/a
5.	LEAK TESTING	3:45	n/a
6.	ANNULUS GROUTING	1:20	n/a
7.	GROUT CURING	30:00	n/a
8.	STUDBOLT TENSIONING	4:30	4:30
	TOTALS	54:45	14:20

The demonstration trials were conducted in a low visibility (1-3m) and low-current environment. Site specific environmental factors and their impact on operational tasks should be considered on a case by case basis. Generally WROV operational personnel at the trials advised that in a high energy environment, approaching the operational capacity of the WROV, task times may increase by up to 50%.



Notes:

1. With the exception of grout curing, which includes non-working hours, task durations are based on operational times i.e. working hours including down-time.

2. Tasks 3 and 8 required interface with diver-friendly studbolt tensioners which proved inoperable by ADS

Figure 8.1: Demonstration Trial of NEWTSUIT ADS T-Joint Clamp Installation

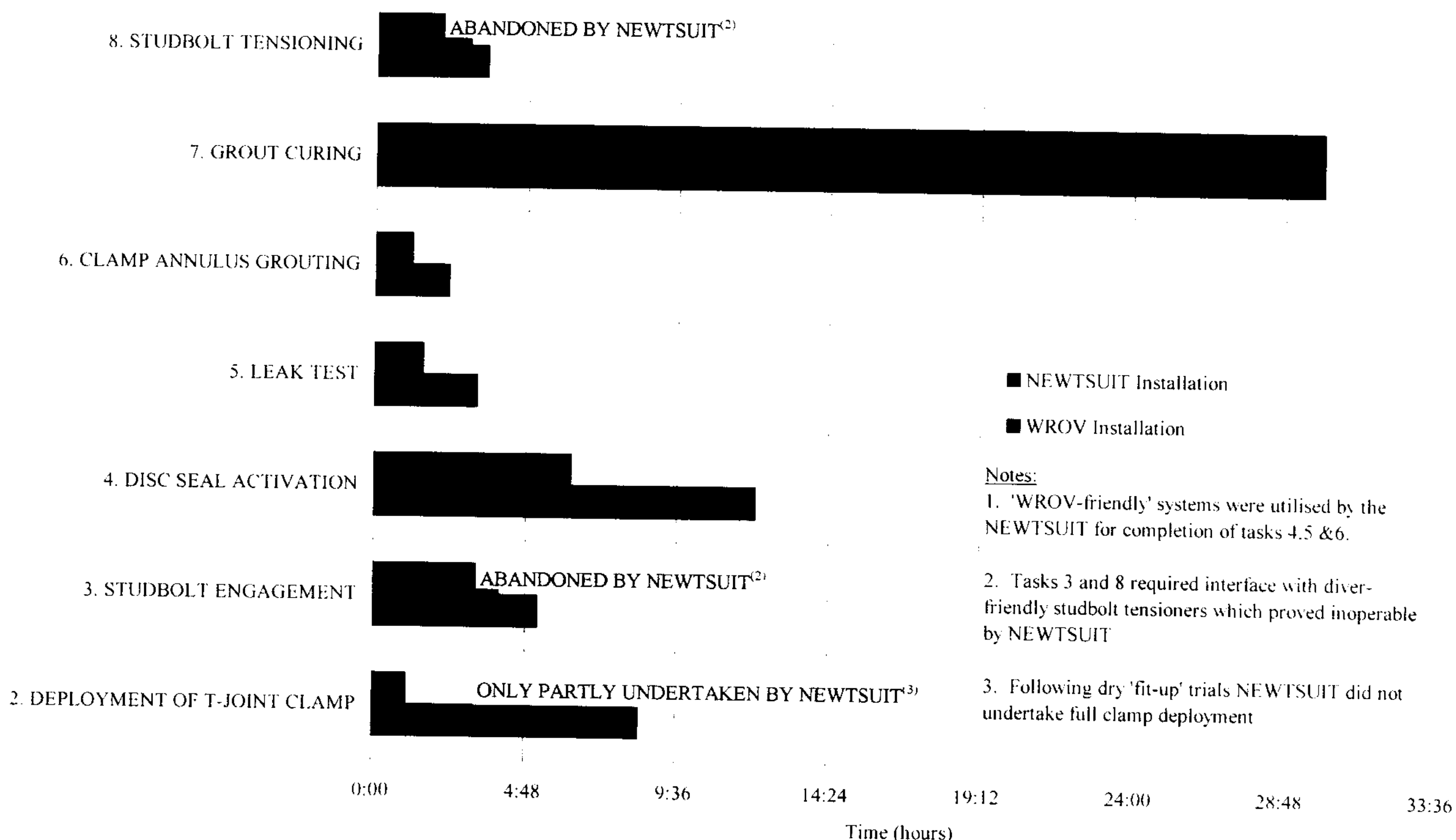
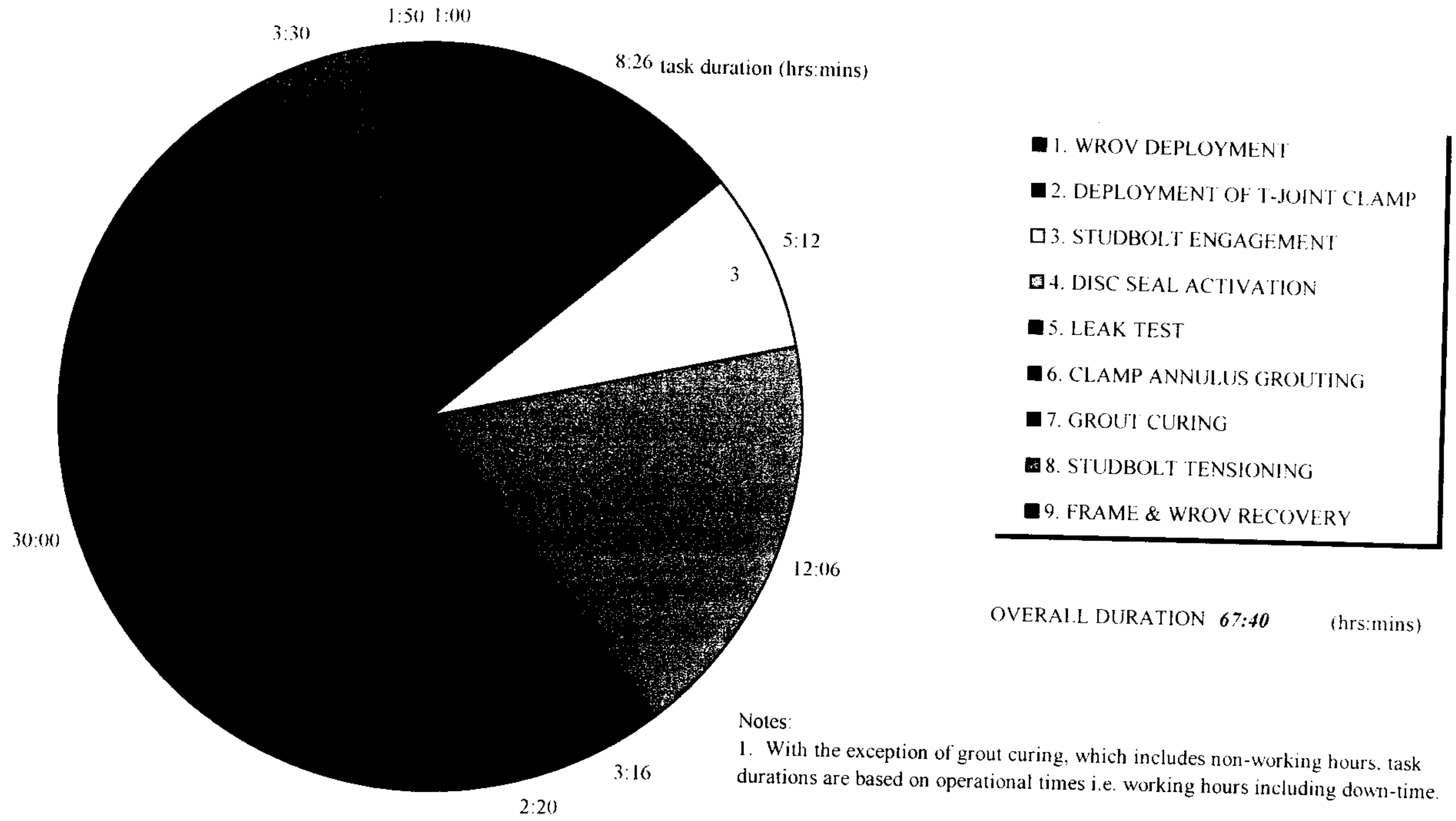


Figure 8.2: NEWTSUIT ADS versus WROV Clamp Installation

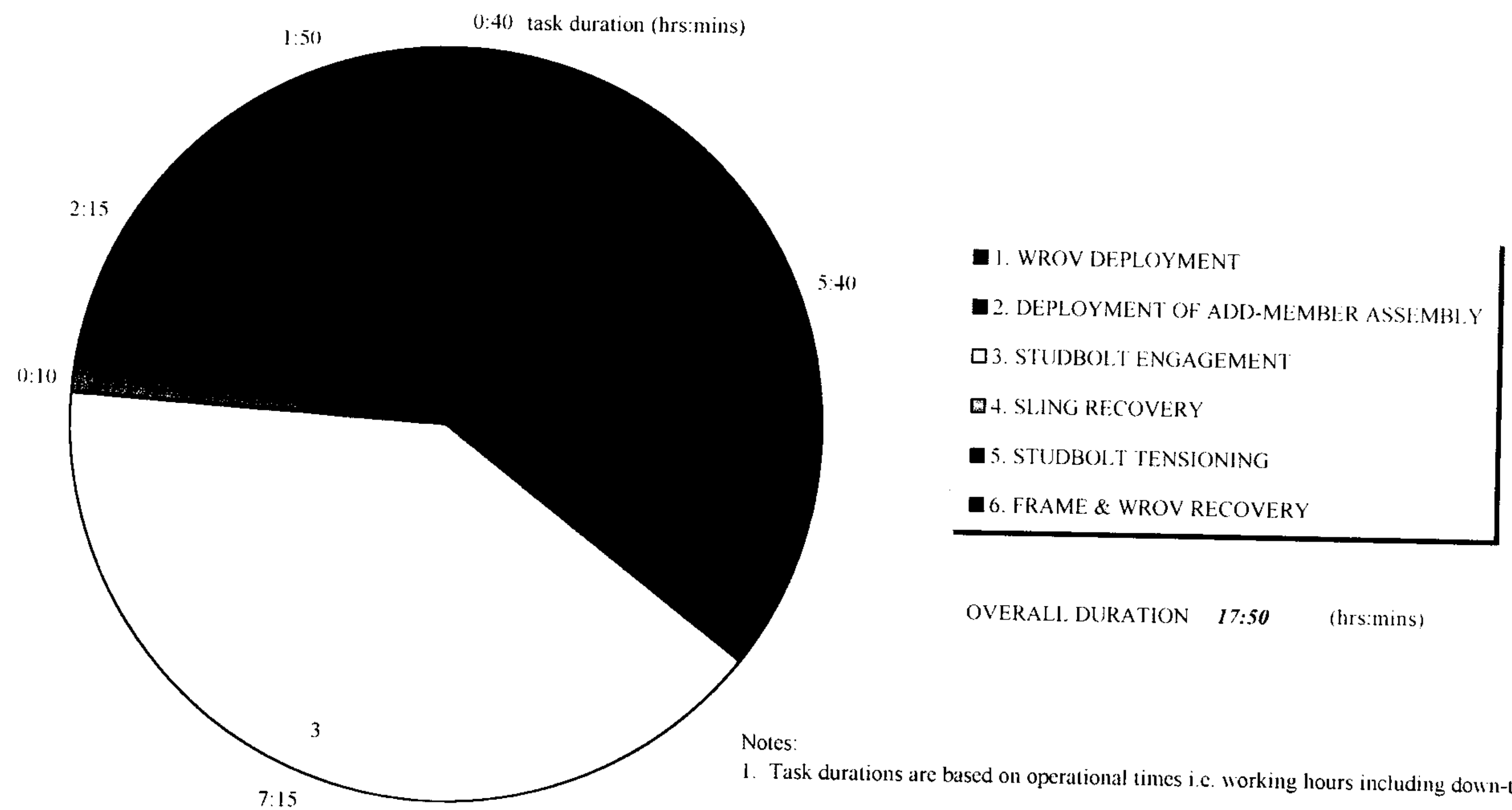


OVERALL DURATION ***67:40*** (hrs:mins)

Notes:

1. With the exception of grout curing, which includes non-working hours, task durations are based on operational times i.e. working hours including down-time.

Figure 8.3: Demonstration Trial of WROV T-Joint Clamp Installation



Notes:
1. Task durations are based on operational times i.e. working hours including down-time.

Figure 8.4: Demonstration Trial of Addmember Assembly Installation

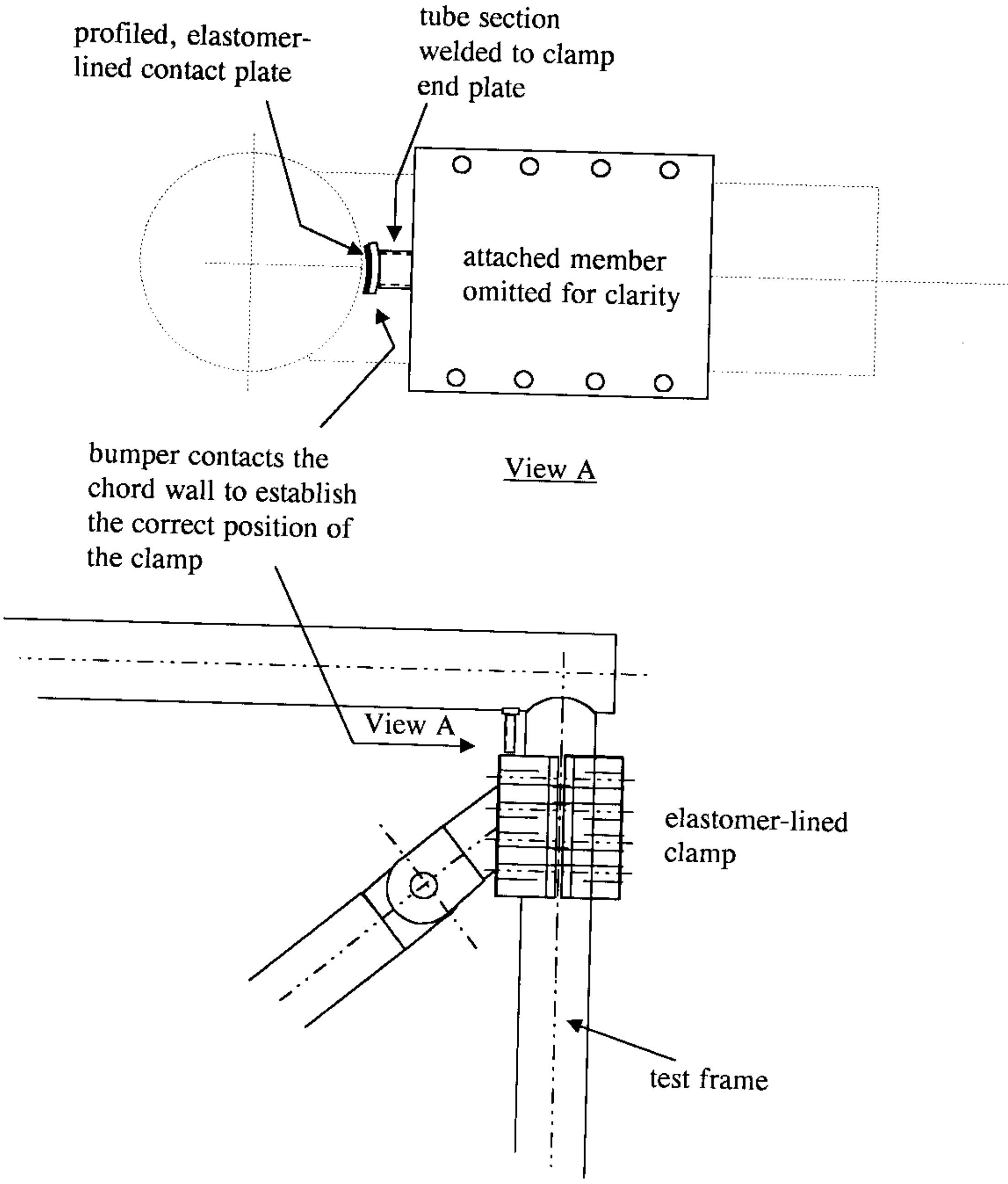
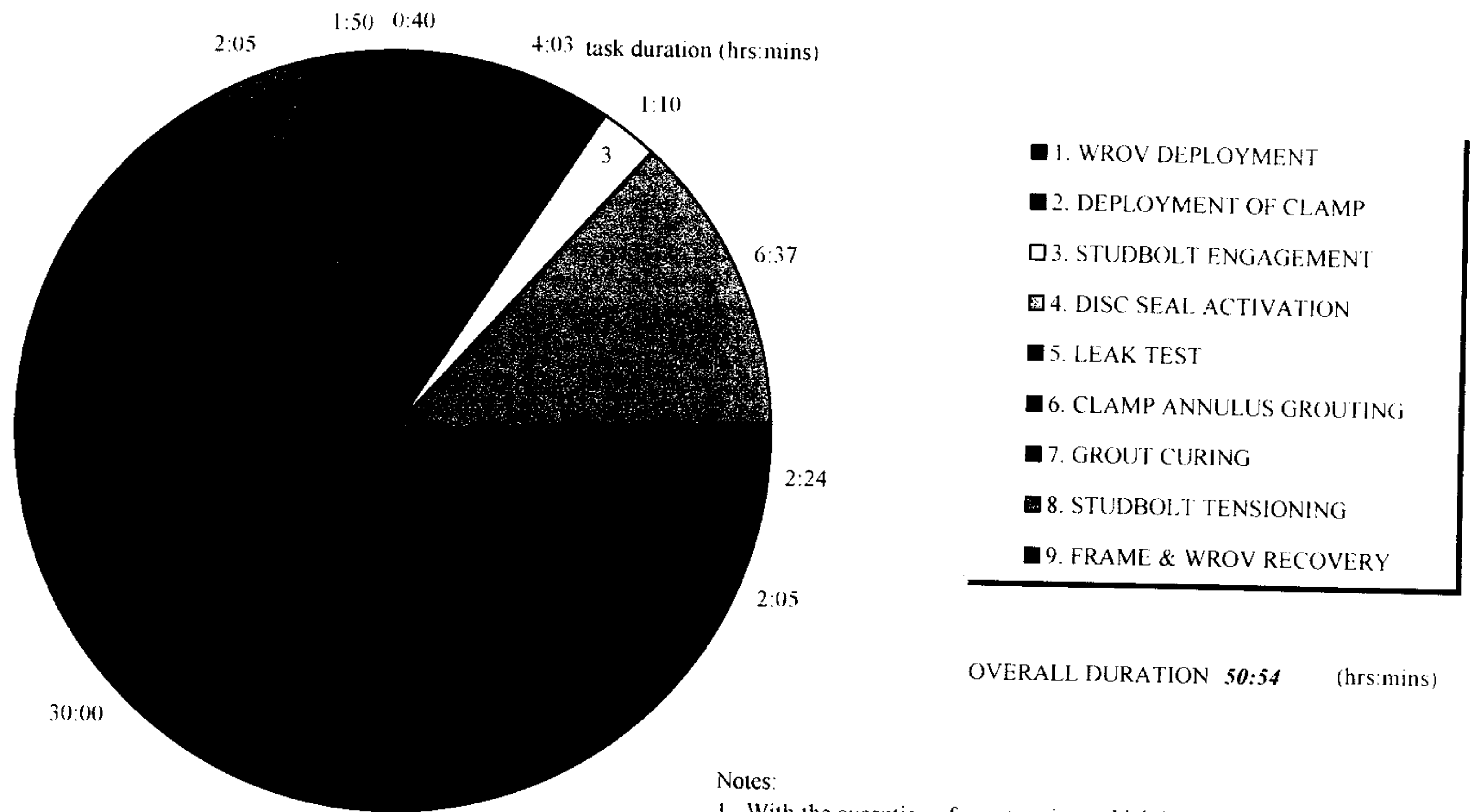


Figure 8.5: Installation Guide/Bumper for the Elastomer-Lined Clamp

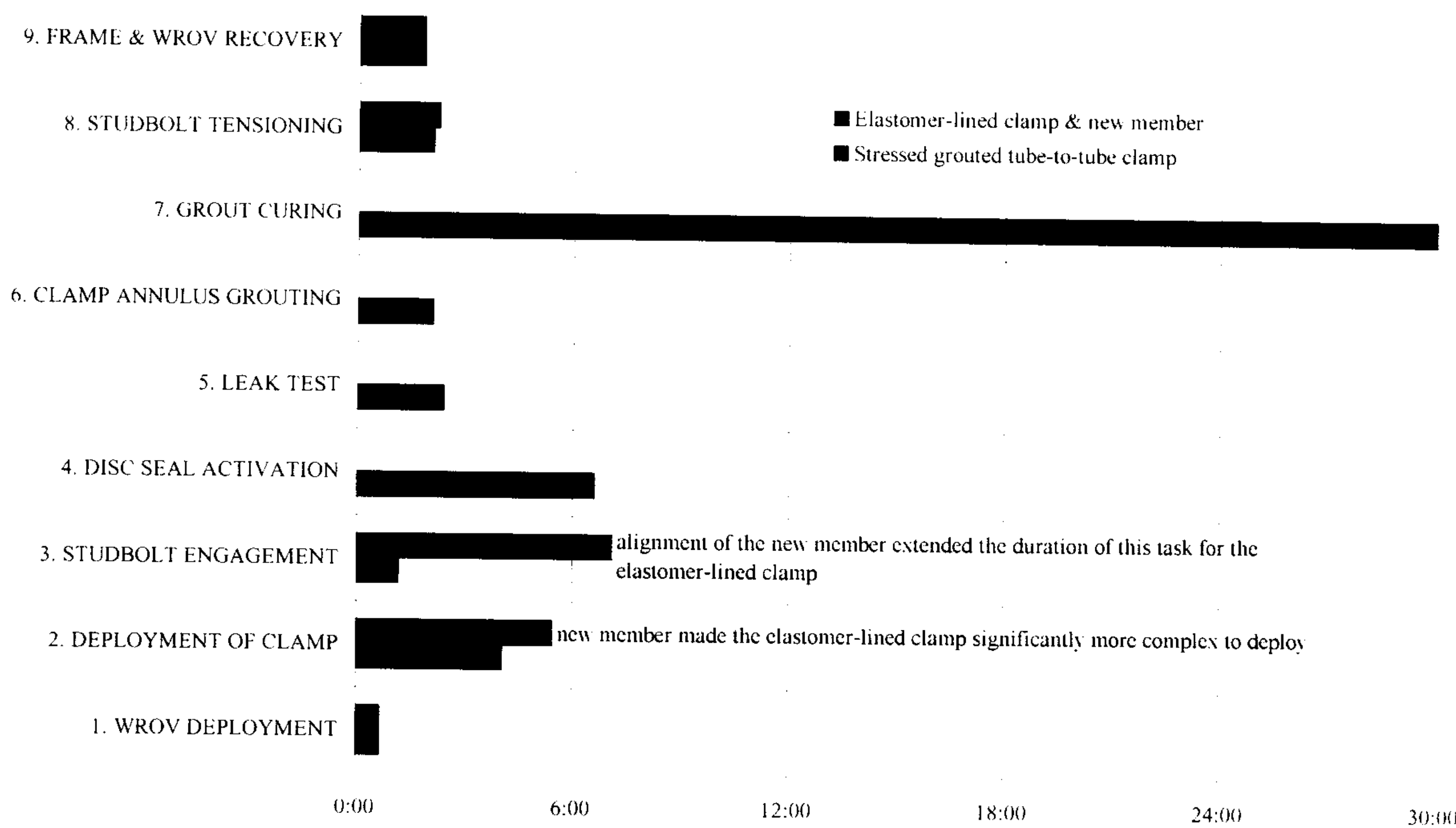


OVERALL DURATION ***50:54*** (hrs:mins)

Notes:

1. With the exception of grout curing, which includes non-working hours, task durations are based on operational times i.e. working hours including down-time.

Figure 8.6: Demonstration Trial of Tube-to-Tube Clamp Installation



Elastomer clamp overall duration: ***17:50*** (hrs:mins)
Grouted clamp overall duration: ***50:54*** (hrs:mins)
Grouted clamp duration (excl. curing): ***20:54*** (hrs:mins)

Figure 8.7: Grouted Clamp versus Elastomer-Lined Clamp Installation

9. VERIFICATION TESTING

9.1 Introduction

Following the completion of the in-water trials, and the shipment of the four clamp specimens to Karlsruhe University in Germany, a series of strength tests were conducted during Spring 1997. The four specimens are identified in Figure 9.1 and the tests were as follows:

- Specimen 1: the stressed grouted tube-to-tube (replacement member) clamp installed by WROV subjected to axial tensile loading along the joining member.

- Specimen 2: the stressed elastomer-lined clamp installed by WROV subjected to axial tensile loading along the new member (diagonal to the clamp). This specimen was tested twice to confirm results obtained in the first test. Following the first test, the bolts were de-tensioned and the strain gauge readings taken to determine bolt prestress applied by the WROV. Thereafter, the specimen was reassembled and the bolts were simultaneously re-tensioned by Hydra-Tight GmbH. The second test was then conducted.

- Specimen 3: the stressed grouted T-joint clamp installed by WROV subjected to out-of-plane bending (torsional moment on the chord member). This specimen was also de-tensioned to register the pre-tension in the bolts via strain gauges. The bolts were re-tensioned before commencing the test.

- Specimen 4: the stressed grouted T-joint clamp identical to Specimen 3 in all respects, expect that the underwater installation was by a NEWTSUIT ADS. The load and testing procedure were the same as for Specimen 3.

Detailed testing procedures were prepared beforehand, see Appendix G. The following pertinent aspects were common to all tests:

- Weld or bolt on connections to specimens to permit assembly into test rig.

- Attach instrumentation (strain gauges and LVDTs) and insert into test rig.

- Check operation of all instrumentation and data-logging equipment.

- Bed down specimen/rig assembly and strain gauges by applying a number of small load cycles.

- Application of three loading and unloading cycles, with the maximum load in each cycle being successively increased above the previous cycle, until failure occurs. Failure was defined when significant slippage between the clamp and member had occurred.

- Following failure, disassemble the specimen and individually calibrate the strain-gauged studbolts to estimate the initial studbolt tensions at the commencement of the tests.

9.2 Stressed Grouted Tube-to-Tube Clamp

9.2.1 Test Rig and Instrumentation

The stressed grouted tube-to-tube clamp was tested under axial tension in a Schenck 6000kN Universal Testing Machine. Figure 9.2 shows the specimen being assembled into the rig.

The specimen was instrumented as indicated in Figure 9.3. Each of the eight studbolts were provided with two strain gauges mounted on machined flat faces at opposite ends of a diameter located approximately at mid length. These gauges were used to estimate studbolt preload and the variation of studbolt load (about the preload) due to the tension load applied to the tubulars. Two strain gauges were also mounted on each tubular. These gauges were used, in conjunction with the tubular cross-sectional area and Young's modulus, to calculate the applied tension. Two additional strain gauges were used for laboratory temperature compensation purposes. Linear voltage displacement transducers (LVDTs) were provided at four positions to measure relative displacements, i.e. slip, between the clamp halves and the tubulars at either end of the clamp.

Measurements were recorded at 3 second intervals throughout the test. A low rate of displacement loading, 2mm per minute, was applied.

9.2.2 Results

Material Tests

Three coupons along the tubular axis were prepared from the tubular material subsequent to the slip test and the tensile results are summarised in the table below. The average Young's modulus was used to calculate the applied loading in the slip test.

Coupon No.	Yield Stress (N/mm^2)	Ultimate Strength (N/mm^2)	Young's Modulus (N/mm^2)
1	384.4	522.1	199400
2	392.3	532.7	199800
3	388.6	523.2	200078
Average	388.4	526.0	199760

Slip

The load/slip behaviours between the clamp and the lower and upper tubulars (as positioned in the test rig) are shown in Figure 9.4. As can be seen, the lower tubular started to slip at a load of around 65kN and completely failed at a load of 78kN. Thereafter, slippage occurred at a constant load. Only negligible slippage of the upper half was induced due to the benefit of the catcher plate, welded to the tubular, acting as a shear key.

Studbolt Load Variation

The variations in studbolt loads (from the preload) due to applied tension in the tubulars were small. Figure 9.5 shows a typical plot of studbolt load variation versus applied tension. Before slippage occurred at an applied tension of about 60kN, all studbolts saw a variation of 0.2kN or less, with only studbolts No 1 and No 5 seeing a relaxation of the preload thereafter. The maximum studbolt load variations (from the preload) are tabulated below, arranged according to studbolt pairs:

Studbolt Nos. (see Figure 9.5)	Load Variation (kN)
1, 5	-1.0, -0.8
2, 6	0.4, 0.8
3, 7	1.3, 1.2
4, 8	3.8, 2.5

Studbolt Preload

After the slip test, the strain gauge measurements were zeroed, the studbolts de-tensioned and the relaxation strains measured. The relaxation strains were then added to the difference of the strain measurements between the start and end of the slip test, to give the measured strain due to prestress in the studbolts at the start of the test.

The studbolts were then removed from the clamp and cut to 50 cm lengths to fit into a tensile testing machine, so that the strain in each studbolt could be calibrated against load. The studbolts cross-sectional area at the strain gauge positions as well as the modulus of elasticity were automatically included.

This calibration was used to convert all strain gauge readings on the studbolts into loads. The initial studbolt preload as well as load variation during the slip test could then be determined.

The studbolt preloads, so established, are recorded in Figure 9.6. The average of the measured preloads was 24kN, and this represents 15% of the intended value.

9.2.3 Assessment

Slip failure load is defined as the intercept of the line drawn through the initial load-displacement response with the line drawn through the data after the first change of gradient.

The measured slip load of 66kN is well below the expected value of 750kN (mean with factors of safety set to unity). This is primarily due to the low values of studbolt preload obtained (average 24kN compared an intended 155kN). An investigation was conducted as to why that might have occurred. The findings of the investigation are reported in Section 8. The most probable cause of preload failure was found to be, either a blocked hydraulic line, or an incomplete connection of the stab-in at the manifold.

Even though the preloads were small, the measured slip load is still less than that expected based on plain pipe bond alone, by a factor of 4.4. Detailed calculations are provided in Appendix H. Another significant observation made during the assessment calculations is that the effect of the (large) grout plug between the two tubulars should not be ignored in assessing the clamp strength. This is because a grout plug is relatively stiff, in the radial direction, compared to a tubular and therefore can attract a significant proportion of the bolt prestress. The calculations indicate that approximately 20% of the total studbolt load was attracted to the grout plug. This effect has not been formally recognised before.

9.3 Elastomer-Lined Clamp

The elastomer-lined clamp was tested twice. In the first test, a low coefficient of friction was obtained and it was suspected that the studbolt preload was less than the intended value, as was found in the tube-to-tube clamp (see above). Following the first test, the specimen was re-aligned and the studbolts re-tensioned before conducting the second test. It was subsequently established that the initial preloads were satisfactory and that the two tests gave very similar results. In the discussion below, attention is mainly directed at the second test as it was taken further, in terms of slip magnitudes, than the first one.

9.3.1 Test Rig and Instrumentation

The elastomer-lined clamp was tested in the Schenck 6000kN Universal Testing Machine with axial tension being applied in the direction of the addmember longitudinal axis, see Figures 9.7 and 9.8.

The specimen was instrumented as indicated in Figure 9.8. Each of the eight studbolts were provided with two strain gauges (strain gauge Nos. 0 to 15) to measure studbolt loads. Four strain gauges (Nos. 16 to 19) were mounted on the clamped member, and four more (Nos. 20 to 23) were mounted on the addmember. Three further gauges were used for temperature compensation purposes. Six linear voltage displacement transducers (LVDTs) were mounted on the specimen; four to measure the opening of the two clamp halves and two to detect slippage of either clamp half along the clamped tubular.

As for the tube-to-tube clamp test, displacement was applied at the low rate of 2mm per minute with the instrumentation being scanned every 3 seconds.

9.3.2 Results

Slip

The load/slip behaviour of the upper and lower clamp halves are shown in Figure 9.9. The upper clamp half is subjected to a component of axial tension in the direction of the studbolt, arising from resolving the applied force in the addmember, which is tending to lift the upper clamp half away from the clamped member. On the other hand, the lower clamp half is pressed more firmly against the clamped member. This causes the upper clamp to slip before the lower clamp (approximately at member loads of 180kN and 240kN, respectively). A ductile form of slip behaviour for both halves is indicated in the figure.

Studbolt Load Variation

The variations in studbolt loads (from the preload), due to the applied tensile test load, were similar for all studbolts. Figures 9.10 to 9.13 show the variations for the extreme pairs of studbolts (i.e. studbolt Nos. 1/5 and 4/8) throughout the test. Initially, up to the time of first slip of the upper clamp half at an applied load of about 180kN, the studbolt load variations are small, i.e. typically about 2kN. In most cases these variations tended to increase the preload although for studbolt Nos. 1 and 2, a relaxation of the preload occurred. This may be indicative of some slight twisting of the clamp due to minor misalignment within the test frame.

At the time of first slip, a small but consistent fall in the curves of Figures 9.10 to 9.13 may be noticed. This is clearly shown in Figure 9.12. A plausible explanation for this is that the effective coefficient of friction in the circumferential direction is very much reduced when sliding occurred in the longitudinal direction. (A useful analogy is that it is easier to pull out a cork from a wine bottle when the cork is also simultaneously twisted.) The reduced circumferential friction, in turn, allowed the elastomer liner to slide more easily in the circumferential direction and thereby for the clamp to hug the tubular more tightly (it should be noted that during initial tensioning of the studbolts, circumferential friction tended to keep the clamp halves apart). This hugging action caused the two halves to move towards each other and a small relaxation of the preload ensued.

After the initial slip, a marked increase of studbolt loads was evident, see Figures 9.10 to 9.13. This was due to two effects. Firstly, relative slip between the clamp halves caused a racking effect in the studbolts. This is a non-linear effect. Secondly, the applied load became largely resisted by the studbolts. The magnitude of the racking induced load variation can be estimated from the residual load in the studbolts illustrated on the curves shown in Figures 9.10 to 9.13.

Studbolt Preload

Studbolt preloads were established after the second slip test in the same manner as described in Section 9.2.2 for the tube-to-tube clamp. The following values were found.

Studbolt No	Preload in Test 1 (kN)	Preload in Test 2 (kN)
1	127	136
2	140	116
3	137	137
4	136	96
5	130	132
6	134	128
7	147	136
8	129	148
Average	135	129

As can be seen, the average preloads in the two tests are quite similar. The preloads achieved by the WROV installation (i.e. data for Test 1) are more uniform, though this may be no more than a fortuitous occurrence.

9.3.3 Assessment

The average studbolt preload of 135kN, as obtained by the WROV installation, is in accordance with the design assumption of a 10% transfer loss, see Appendix H.

Slip failure load is defined as the intercept of the line drawn through the initial load-displacement response with the line drawn through the data after the first change of gradient.

Coefficients of friction for the elastomer/steel interface can be back-calculated from the various measured slip loads. Care must be taken in the definition of the coefficient as this can be ambiguous. Here, two common definitions are used:

- global coefficient of friction (μ_g)

  $P = \mu_g F_n$

  where P = slip resistance of each clamp half

  F_n = total effective normal force on each clamp half

- local coefficient of friction (μ_l)

$$P = \mu_l \frac{\pi}{2} F_n$$

where P and F_n are defined above.

This definition is appropriate for calculations based on the unit area approach, i.e. μ_l can be directly associated with the ratio of slip stress to the radial pressure (due to preload) at the interface. The derivation of the above formula is given in Reference 5.

The coefficients of friction inferred from the slip tests are tabulated below. The calculations are detailed in Appendix H and take into account the effect of applied load in tending to lift off the upper clamp half but increasing the load in the lower clamp half.

Test No & Clamp Half	Global Coefficient of Friction	Local Coefficient of Friction
Test 1, upper clamp half	0.139	0.088
Test 2, upper clamp half	0.130	0.083
Test 2, lower clamp half	0.129	0.082
Average	0.133	0.084

For either given definition of the coefficient of friction, the calculated values are reasonably consistent, even though two slip surfaces are involved and different preload distributions apply in the two tests. It may thus be concluded that the above values are relevant and not apparent.

The current HSE Guidance Notes[7] state that for polychloroprene (elastomer) liners a value of 0.2 may be used for the friction coefficient. The Guidance Notes do not state whether $\mu = 0.2$ is to be interpreted as a global or local coefficient, but in either case the Notes would appear to be optimistic in the light of the measured values for this particular specimen. There does not appear to be any peculiar aspect of the clamp construction or of the loading applied to the clamp which would explain the 'low' measured values. It should be noted that there are no other reported slip tests on elastomer-lined clamps. Certainly, the HSE guidance value was not based on slip tests on clamps, but rather on flat elastomer/steel plate specimens.

Given that many elastomer-lined clamps have already been installed (mainly for the purpose of retrofitting risers), it is recommended that further tests should be conducted as a matter of urgency.

9.4 Stressed Grouted T-Joint Clamp (WROV Installed)

9.4.1 Test Rig and Instrumentation

A self-reacting test rig was designed and fabricated so as to apply an OPB moment to the joint, see Figures 9.14 and 9.15. This in turn results in forces tending to open the clamp at the brace end.

Figures 9.15 and 9.16 show the general arrangement and positions of strain gauges (indicated by circles) and transducers (indicated by a diamond sign and prefix W). The strain gauge pairs on the 4 studbolts around the brace (1a/b, 2a/b, 3a/b and 4a/b) had measurements taken independently, to measure any incidental large bending in these studbolts. The strain gauge pairs on the 9 studbolts around the chord (6, 7, 8, 9, 10, 11, 12, 13 and 14) had the strains automatically averaged throughout the test. Note, the studbolts numbering system used in the verification test differs from that used during the implementation trials. Strain gauges were mounted on the top and bottom faces of the brace, close to the clamp, to monitor bending stresses in the brace (to ensure that the yield stress was not exceeded). Two further gauges were used to compensate for temperature variations.

LVDTs were provided between the clamp halves, at 5 positions around the specimen to determine any separation of the clamp halves before failure. In the event, this did not happen. LVDTs were also provided at three positions between the chord and the free end of the brace (see Figure 9.15), to measure vertical displacement at these positions relative to the ground. Four LVDTs were provided at both ends of the chord at the top and bottom surfaces, to measure the rotation of the clamp (in torsion) about the chord.

Instrumentation was scanned at appropriate load increment levels (i.e. not continuously as in the earlier clamp tests.)

9.4.2 Results

To ensure the studbolts had been properly pretensioned, they were firstly de-tensioned, recording the as-installed strain and thereby their preload. Then the studbolts were re-tensioned. Thereafter, the OPB test was conducted and the test studbolt preloads were established in the manner described for the previous tests.

Slip

The eventual mode of failure consisted of the clamp undergoing significant rotational slippage about the chord member. The torsional moment/rotational slip behaviour is illustrated in Figure 9.17. To appreciate the magnitude of the slip, a rotation of 0.01 radians corresponds to a circumferential slip of about 3mm. The slippage, as may be expected, exhibits an almost horizontal plateau.

Studbolt Load Variation

The studbolts can be placed into four broad groups with respect to their behaviour under applied moment, depending on their distance from the chord centreline.

- Studbolts at the end of the brace (Nos. 1 and 3)

  These responded as shown in Figure 9.18. The loop in the curve near maximum applied load is associated with slippage of the clamp. The applied moment in this, and all similar figures, is that at the chord centreline. Two moment cycles were applied, the first to about 350kNm and the second to failure at about 700kNm. After removing the moment at the end of the test, the loads in the studbolts returned to nearly their initial preload values.

- Studbolts along the brace (Nos. 2 and 4)

  These responded in a similar manner to the end studbolts but had a higher level of residual tension at the end of the test, see Figure 9.19.

- Studbolts along chord on brace side (Nos. 6 to 9)

  Even higher residual tensions existed at the end of the test, see Figure 9.20. It is likely that the brace member moved relative to the chord at the unwelded intersections and jammed. Thus on unloading a degree of residual tension was locked into these studbolts by the jammed brace.

- Studbolts along chord opposite brace side (Nos. 10 to 14)

  These studbolts responded differently to all other studbolts, see Figure 9.21. This is because the action of applied moment was to move the flanges of the clamp halves towards each other at this side of the chord, thereby relieving a proportion of the studbolts' preloads.

A summary of the maximum studbolt load variations (about the preload) during the test, and the residual load variations remaining at the end of the test, is given in Figure 9.22.

Studbolt Preload

Studbolt preloads were established after the bending test in the same manner as described in Section 9.2.2 for the tube-to-tube clamp. The following values were found.

Studbolt No	Preload before retensioning (as installed) (kN)	Preload after retensioning but before testing (kN)
1	129	154
2	123	148
3	132	154
4	126	147
6	127	152
7	121	140
8	122	142
9	131	153
10	130	156
11	131	155
12	124	152
13	130	152
14	129	152
Average	127	151

9.4.3 Assessment

The original preloads before the studbolts were re-tensioned are consistently smaller than those after re-tensioning at the laboratory, by about 15%. This loss is in accordance with the design assumption of a 10% initial transfer loss and 10% longer term losses. The difference may, therefore, be attributed to a combination of:

- grout creep/studbolt relaxation
- different tensioner oil pressures being used at the wet trial site and at the laboratory.
- different transfer losses, as a result of differences between the two sites in the way the outer collars of the hydraulic nuts were adjusted immediately before load transfer was effected (one by WROV, one by laboratory technician).

The average studbolt preload of 151kN (at the beginning of the test) is close to the theoretical value of 158kN, based on applied oil pressure supplied to the tensioning tools. Furthermore, for both sets of data, a reasonably uniform distribution of preloads were obtained, indicating the manifold system and tensioning procedures were satisfactory. Before the clamp starts to slip (at, say, an applied chord moment of 350kNm), the load variations in the studbolts are all small, i.e. less than 4kN.

A design equation for estimating the studbolt load variation due to pure moment is given for T (or Y) clamps in reference 5. The equation is:

$P = \Gamma_i F_i P_{mi}$

where

Γ_i = Factor of safety (= 1.0 in the present case)

F_i = Calibration factor (= 0.05 for a stressed grouted clamp)

$P_{mi} = M_i (x/l)(l+l_1 - x)/2l_1$

in which M_i is the moment and all lengths are defined in Figure 9.23

The equation evaluates as:

$P = 0.011 M_i$ [P in kN, M_i in kNm)

For M_i = 350 kNm (i.e. a conservative value of the moment at the joint for fatigue calculation purposes), P = 3.9kN and this is considered quite adequate, especially since the contribution of brace shear to studbolt load variation has not been included in the above equation (which represents a proportionally greater contribution).

Slip failure load is defined as the intercept of the line drawn through the initial load-displacement response with the line drawn through the data after the first change of gradient.

A detailed appraisal of the slip load is given in Appendix H. Based upon the existing, axial slip, mean strength equation, contained in reference 5, with factors of safety set to unity, the OPB moment capacity of the clamp was predicted to be 691.8kNm. The observed failure load during the test was approximately 690kNm, as shown in Figure 9.17. Thus it was found that torsional slip ultimate load can be accurately estimated from existing axial slip equations. In general, the shear resistance (strength) at the interface is the same for the longitudinal (axial) direction or the circumferential (torsional) direction.

9.5 Stressed Grouted T-Joint Clamp (ADS Installed)

9.5.1 Test Rig and Instrumentation

The same test rig and instrumentation layout was used for both the WROV and the ADS installed clamps, see Section 9.4.1.

9.5.2 ADS Grouted Clamp Results

The ADS clamp, being structurally identical and subject to the same test loading, behaved in a similar manner to the WROV clamp. The studbolts were not subject to a detensioning operation before the test.

Slip

The eventual mode of failure again consisted of torsional slippage about the chord member. The torsional moment/rotational slip behaviour was as shown in Figure 9.24. A rotation of 0.01 radians corresponds to a circumferential slip of about 3mm. As for the WROV clamp, slip failure is associated with a horizontal plateau.

Studbolt Load Variation

The similarities with the ADS and WROV clamps continued with studbolt load behaviour in that four groups can be identified. Typical plots are given in Figures 9.25 to 9.28, and these may be compared to the WROV clamp data in Figures 9.18 to 9.21 respectively.

Studbolt Preload

The following studbolt preloads were established.

Studbolt No.	**Preload (kN)**
1	174
2	149
3	171
4	166
6	152
7	126
8	140
9	94
10	187
11	179
12	183
13	193
14	179
Average	161

9.5.3 Assessment

The studbolt preloads were generally higher but more variable in the ADS clamp compared to the WROV clamp. The minimum and maximum preload for the ADS clamp studbolts differed by a factor of two. Different tensioning systems were used for the two clamps, and the variability found for the ADS clamp preloads reflects the difficulty the operatives experienced in this part of the installation, see Section 8. It is to be noted that the factor of two is mainly as a result of the low preload in studbolt No. 9; this may be indicative of the captured nut not being sufficiently bedded.

Similar conclusions with respect to studbolt load variation under applied moment loading and slip behaviour apply here as well as for the WROV clamp, see Section 9.4.3. The predicted ultimate OPB moment capacity of the clamp based upon existing, axial slip, mean strength equations, contained in Reference 5, was found to be 712.5kNm compared to an observed failure load of 640kNm, a discrepancy of just 10%.

9.6 Summary of Verification Testing

The following main observations and conclusions have been made following the verification tests.

(i) Stressed grouted tube-to-tube clamp

- A failure in the studbolt tensioning system occurred at the time of installation. This led to a low slip strength. The cause of the failure is discussed in Section 8.
- The effect of a grout plug between the ends of the two enclosed tubulars should be taken into account in the design, as it is relatively stiff compared to the tubulars and will attract studbolt preload away from the (slip) interfaces.

(ii) Elastomer-lined clamp

- The studbolt preloading operations were executed satisfactorily.
- Consistently low coefficients of friction were obtained from the tests, well below current design values.
- In the light of the above, it is recommended that further slip tests are conducted.

(iii) Stressed grouted T-joint clamp (WROV installed)

- An even distribution of studbolt preloads was achieved.
- Studbolt load variations due to applied moment loading were small, and can be conservatively estimated by recent guidance[5] in this area.
- Torsional slip failure can be accurately estimated from existing axial slip equations.

(iv) Stressed grouted T-joint Clamp (ADS installed)

- A greater variability in preloads existed in the ADS clamp compared to the WROV clamp.

- In other respects, the ADS clamp confirmed the above findings for the WROV clamp.

With the single exception of the results for the grouted tube-to-tube clamp, the verification tests have shown that the in-water trials used appropriate procedures to achieve satisfactory installed repair systems. The verification tests have identified a number of issues, listed above, more associated with design issues than implementation philosophy.

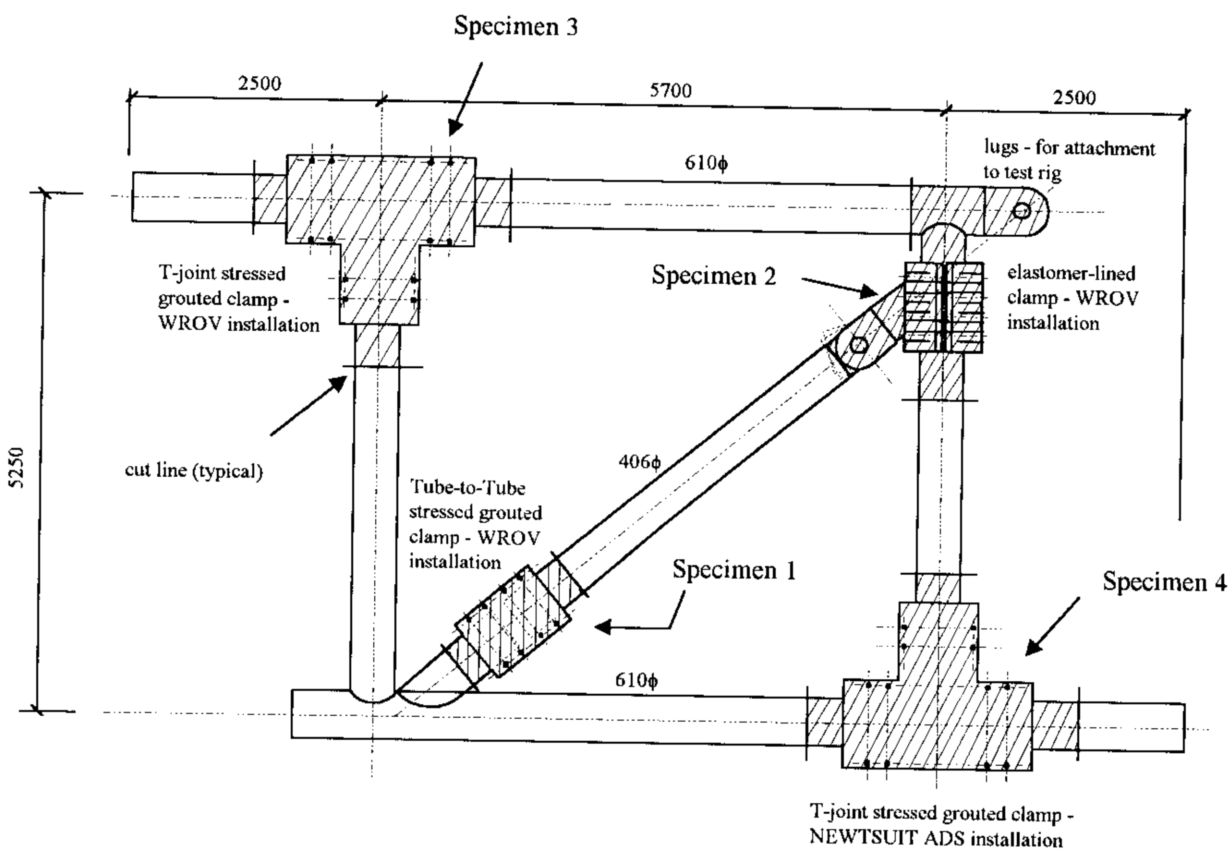


Figure 9.1: Plan View of Test Frame Identifying Specimens

Figure 9.2: Tube-to-Tube Clamp being Positioned in Test Rig

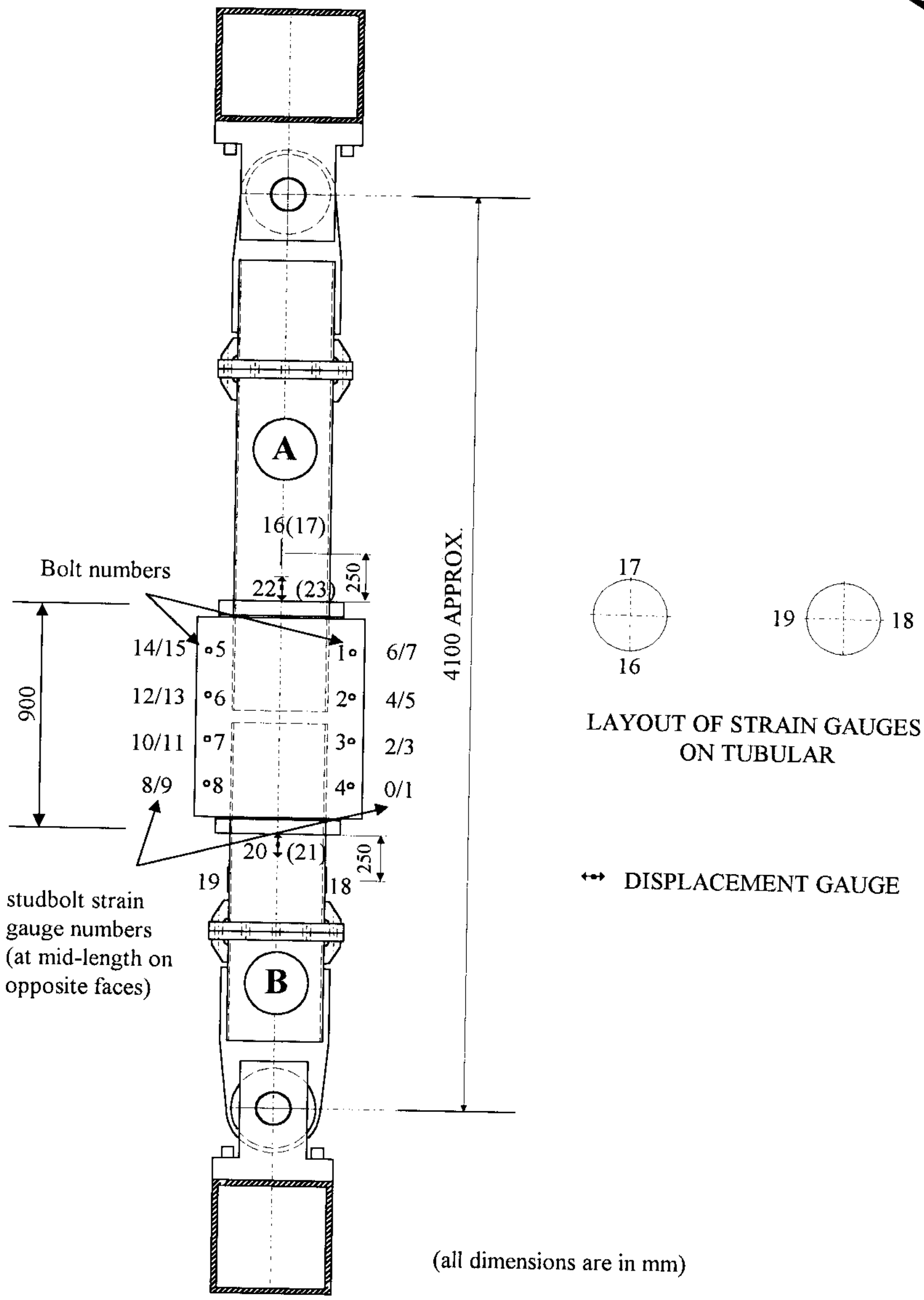


Figure 9.3: Static Test Arrangement (Tube-to-Tube Clamp) and Instrumentation

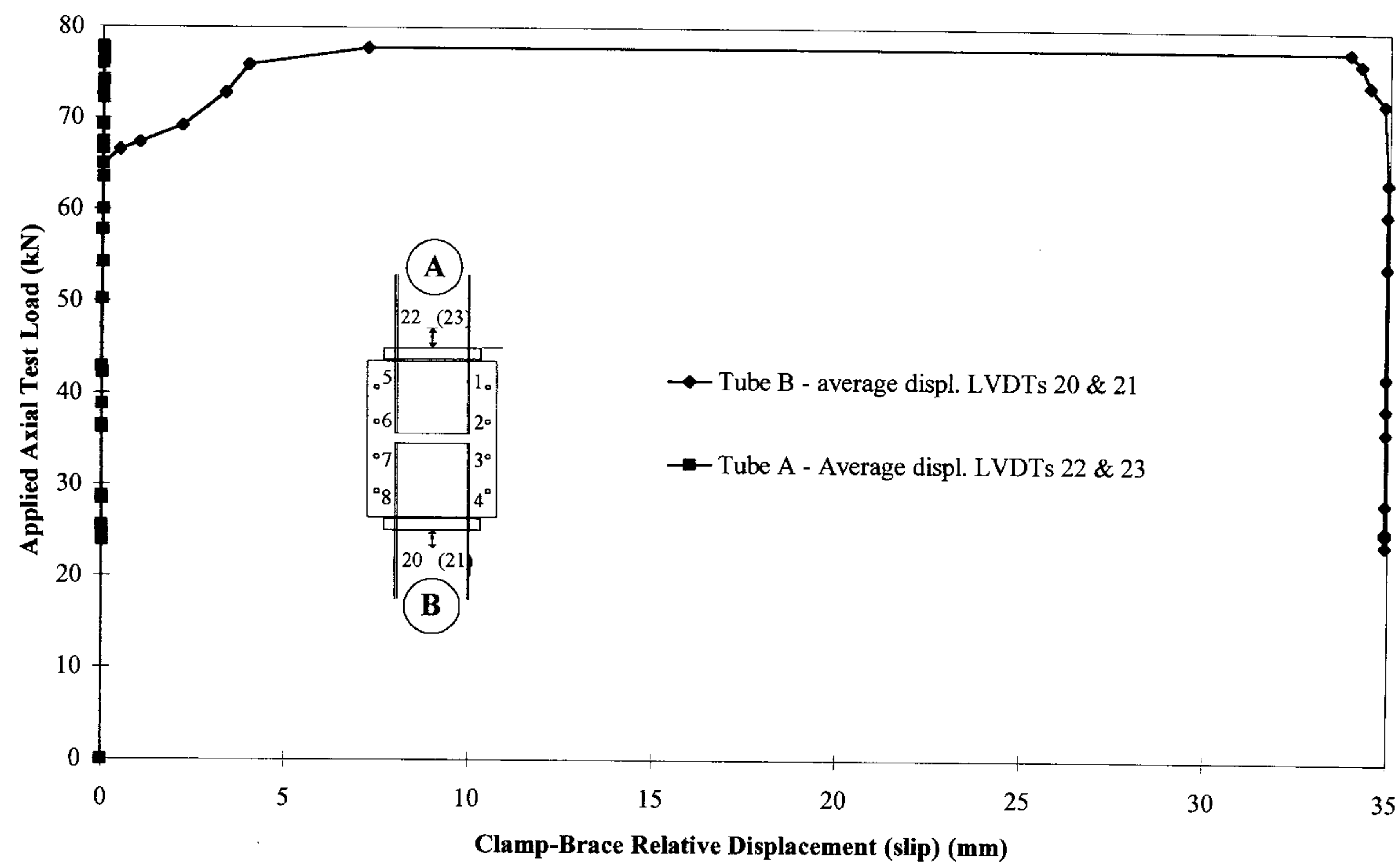


Figure 9.4: Load-Displacement Relationship Recording Slip of Lower and Upper Tubes from Clamp

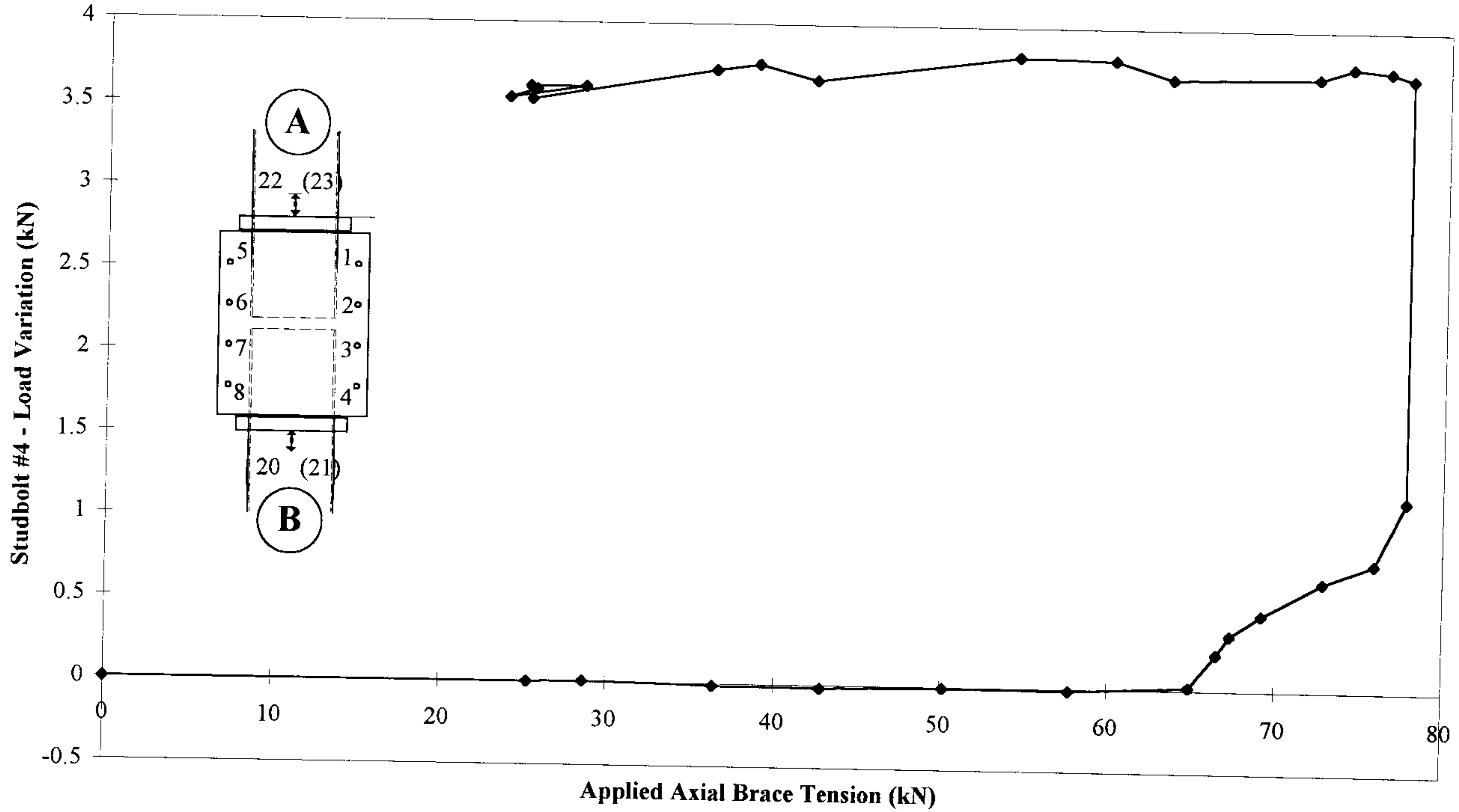
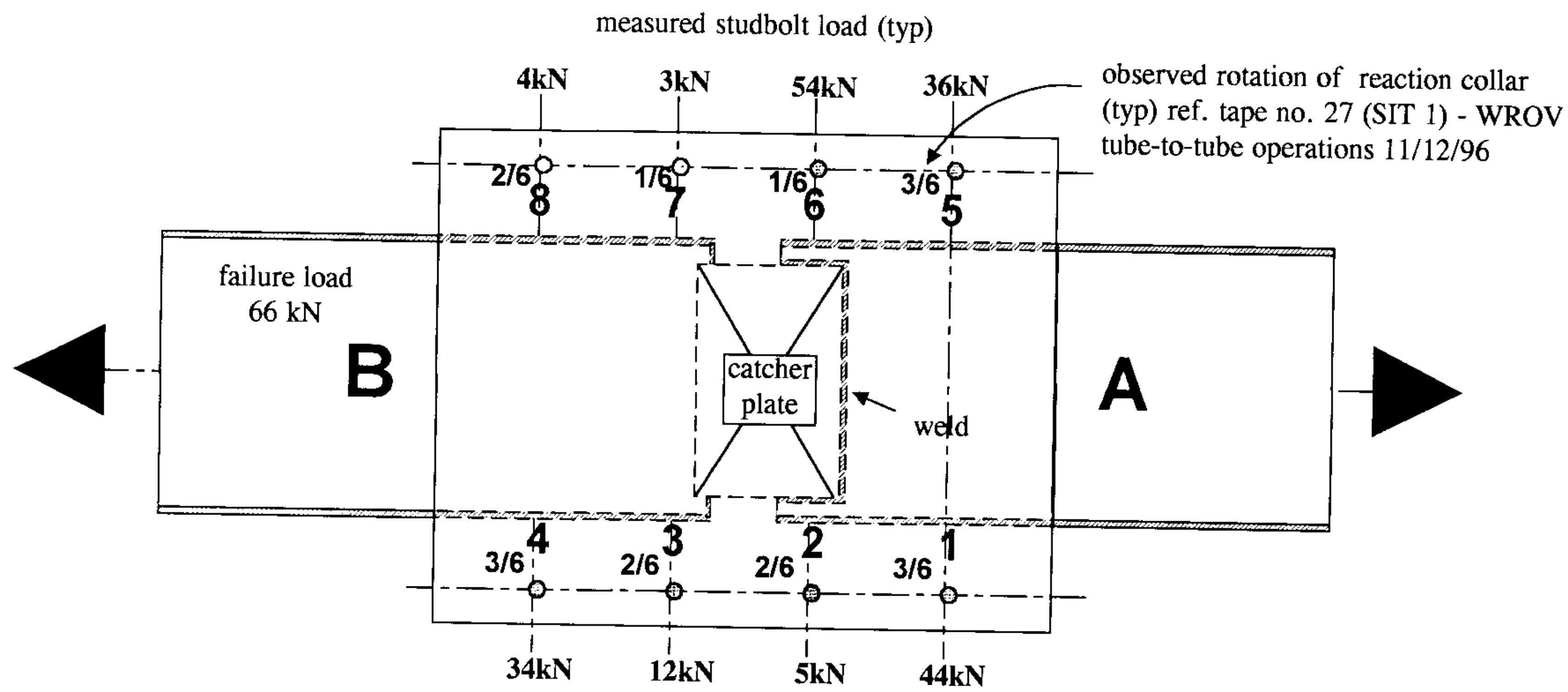


Figure 9.5: Bolt Load Variation (about Preload) in Bolt 4 with Applied Load in Specimen



studbolt loads:
overall = 24.0 kN
end A = 34.75 kN
end B = 13.25 kN

note: intended tension = 155 kN per bolt (62% of yield)

Figure 9.6: Tube-to-Tube Clamp - Studbolt Tensioning

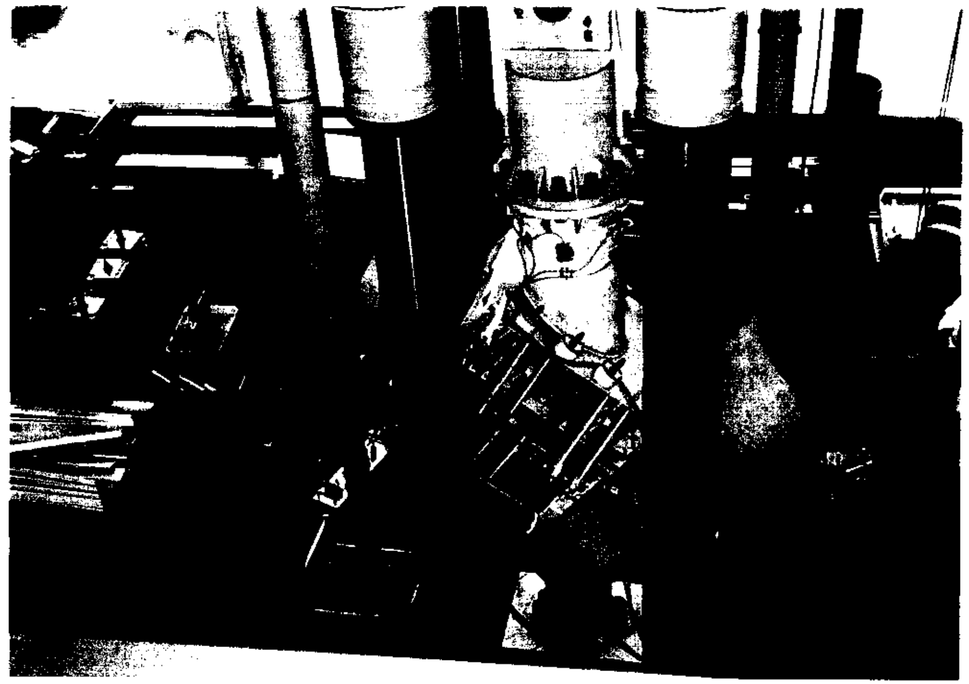
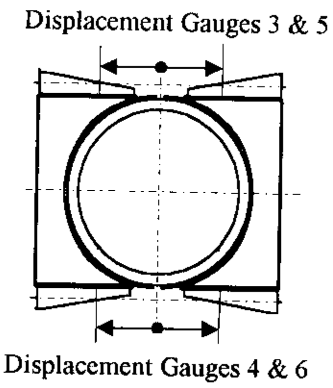


Figure 9.7: Elastomer-Lined Clamp in Test Rig



All 4 displacement gauges measure relative displacement (opening) of the upper and lower clamp halves

Bolt Number	*Strain gauge Nos.*
4	0/1
3	2/3
2	4/5
1	6/7
8	8/9
7	10/11
6	12/13
5	14/15

Note:
LVDT & strain gauge No's. in brackets indicate those on opposite side of clamp

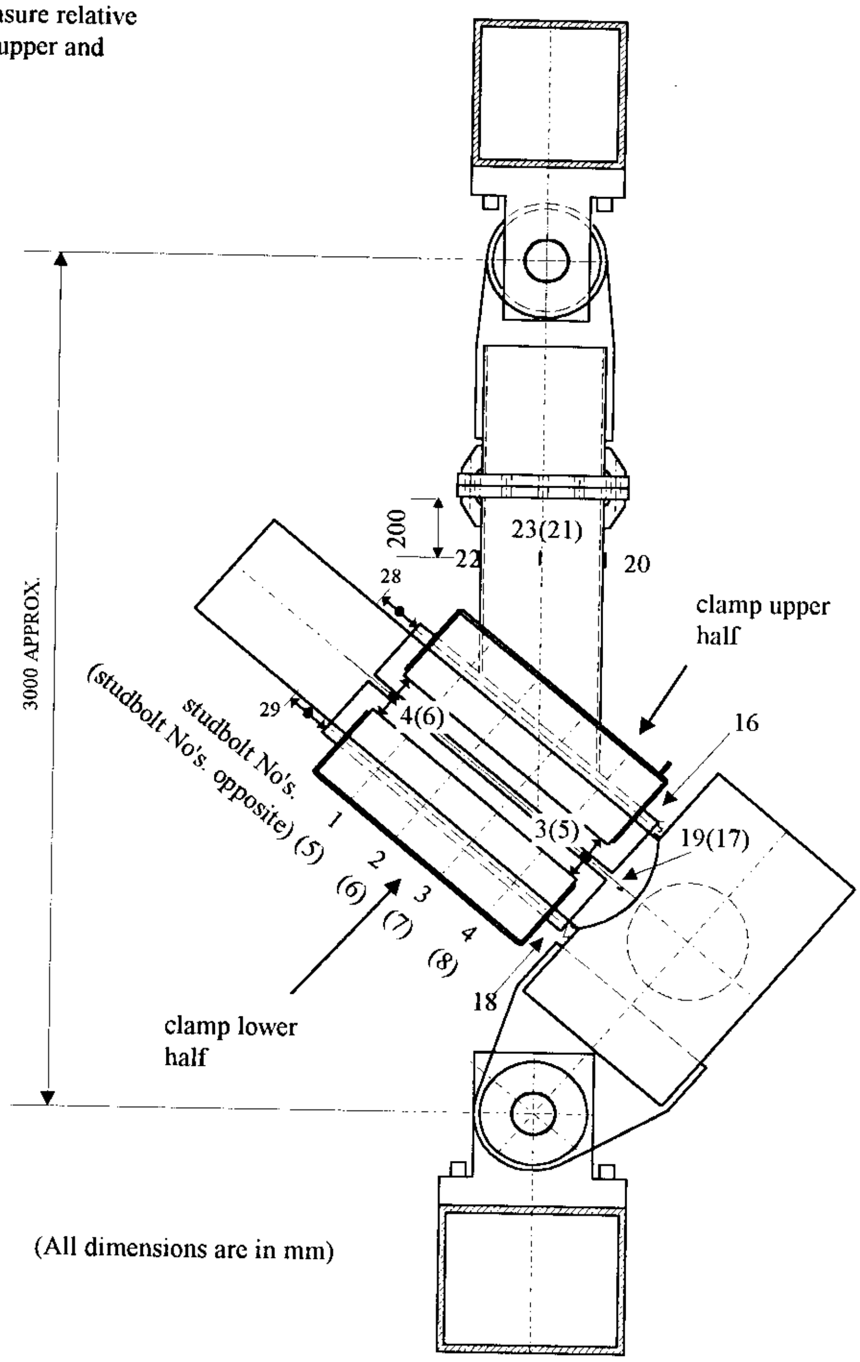


Figure 9.8: Static Test Arrangement (Elastomer-Lined Clamp) and Instrumentation

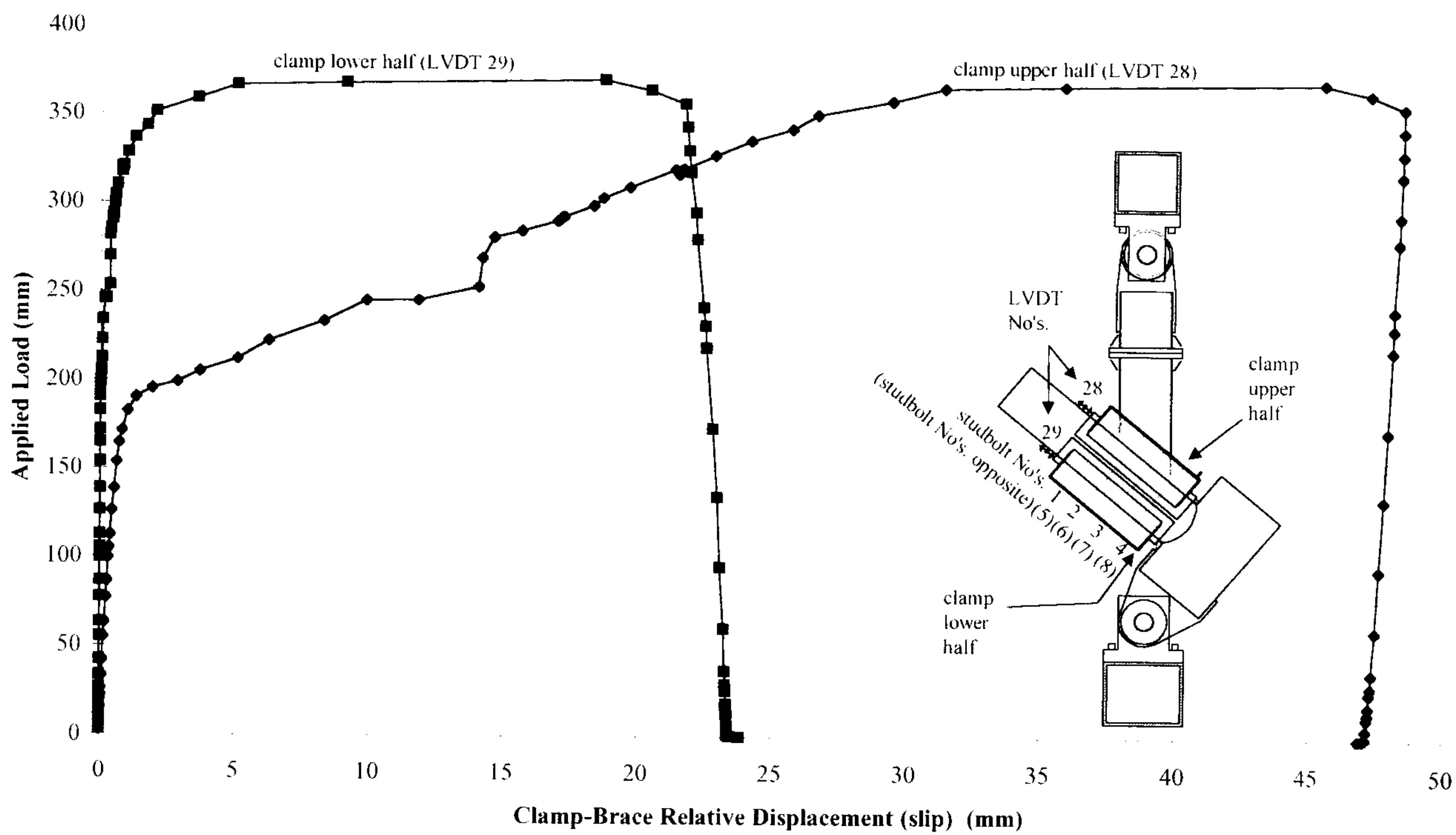


Figure 9.9: Load-Displacement Relationships for the Upper and Lower Clamp Halves

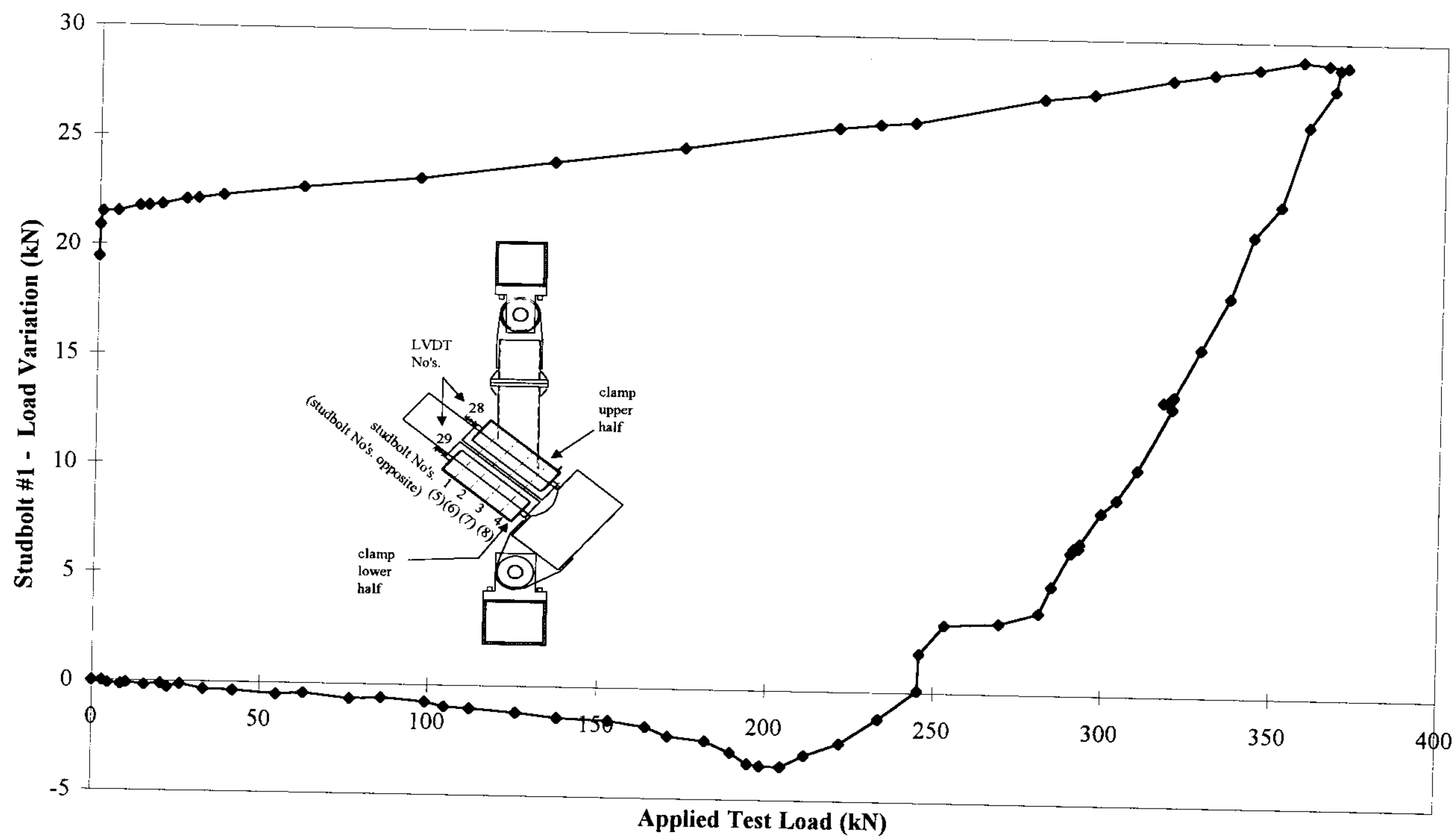


Figure 9.10: Bolt Load Variation with Applied Load for Bolt 1

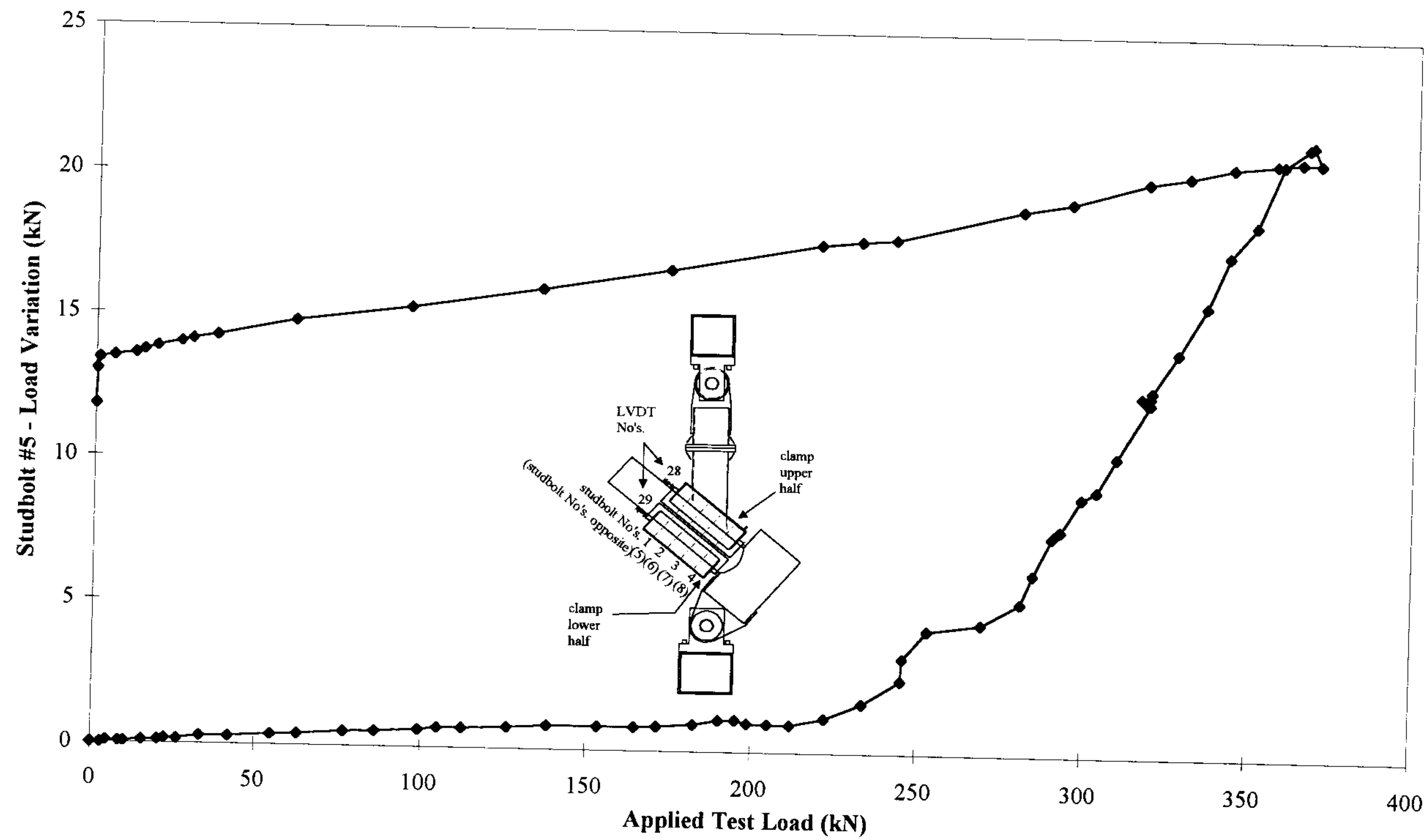


Figure 9.11: Bolt Load Variation with Applied Load for Bolt 5

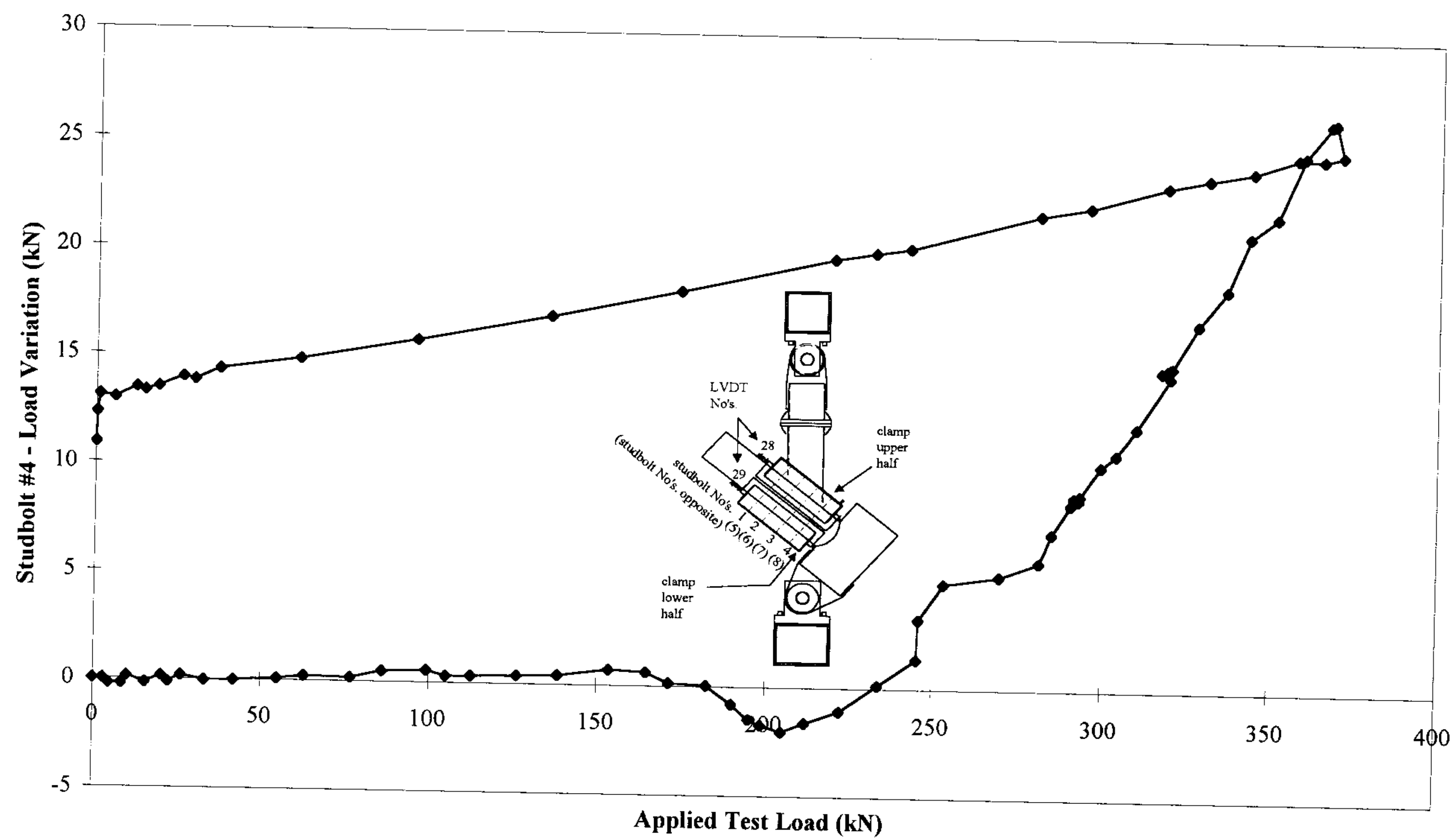


Figure 9.12: Bolt Load Variation with Applied Load for Bolt 4

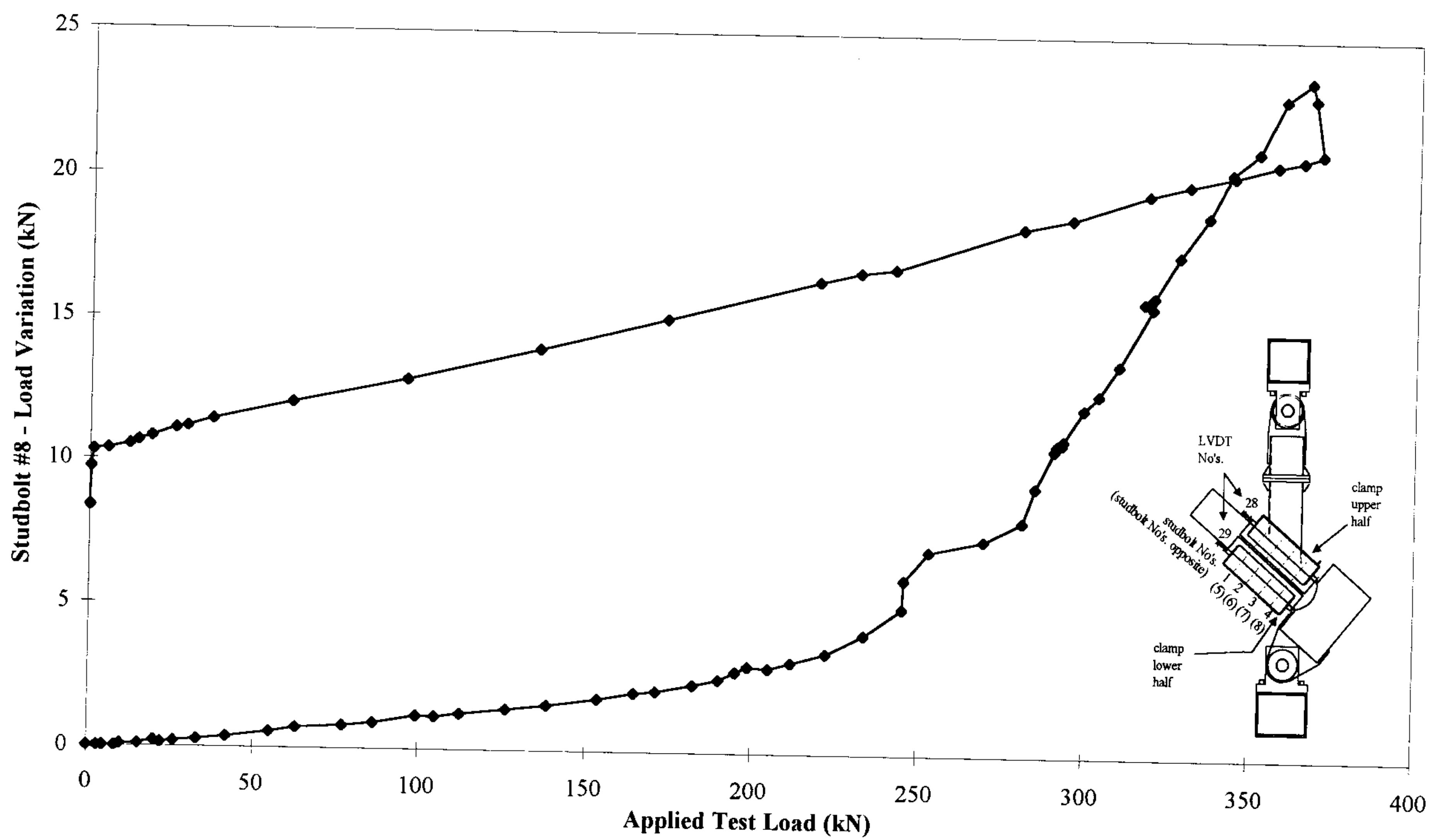


Figure 9.13: Bolt Load Variation with Applied Load for Bolt 8

Figure 9.14: Test Arrangement at Start of Test (WROV T-Joint Clamp)

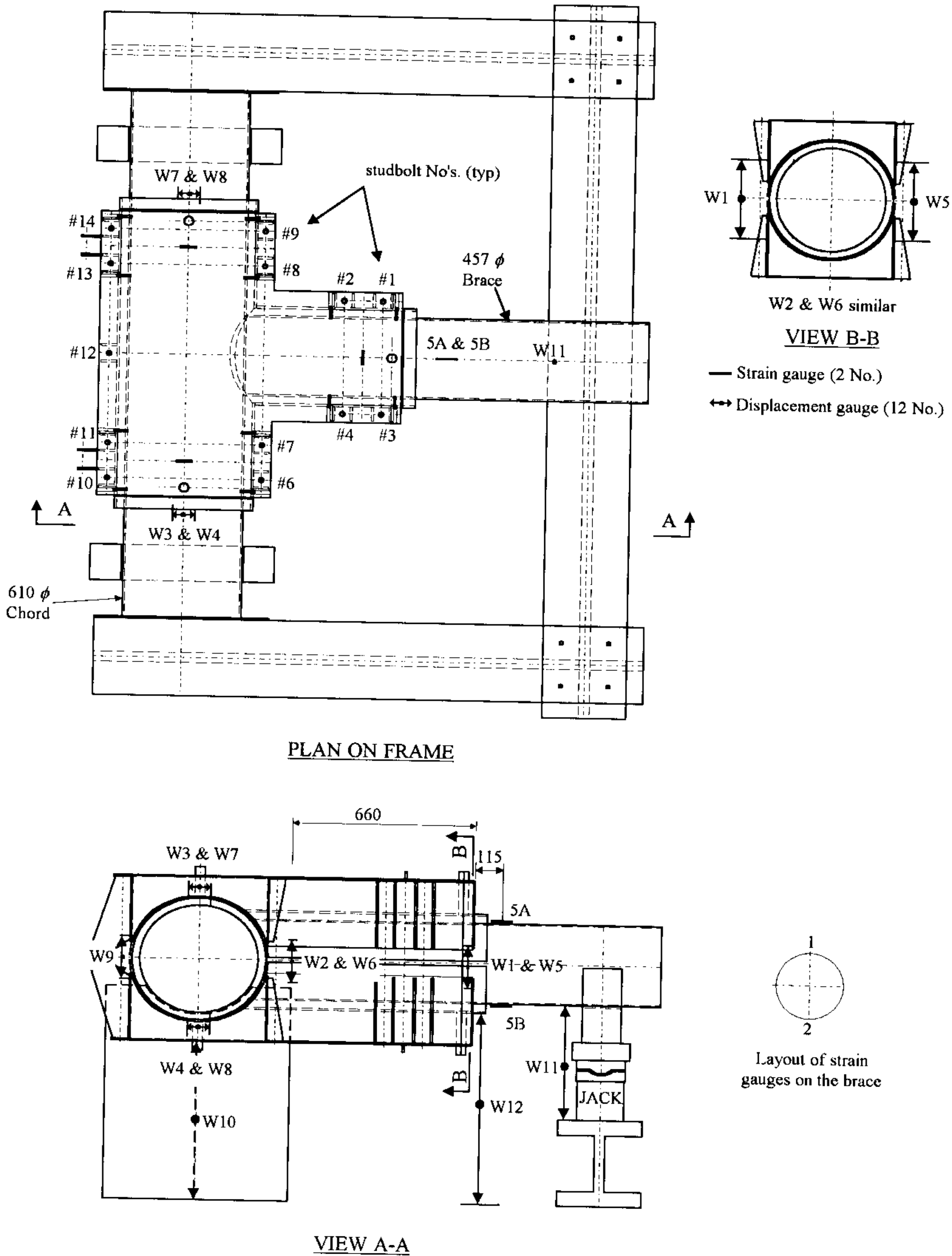


Figure 9.15: Static Test Arrangement (T-Joint Clamp)

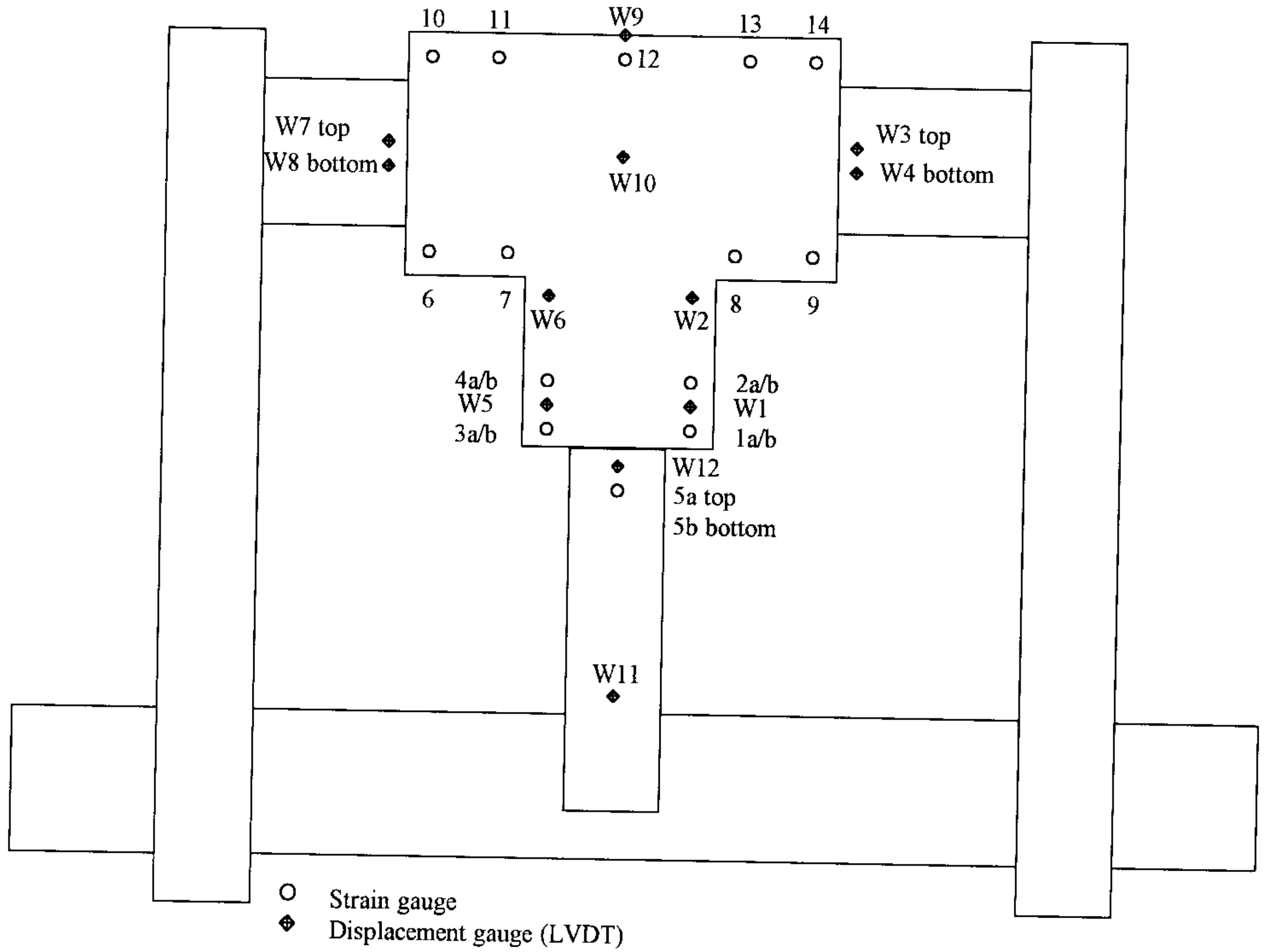


Figure 9.16: Positions of Strain Gauges and Displacement Gauges in Plan

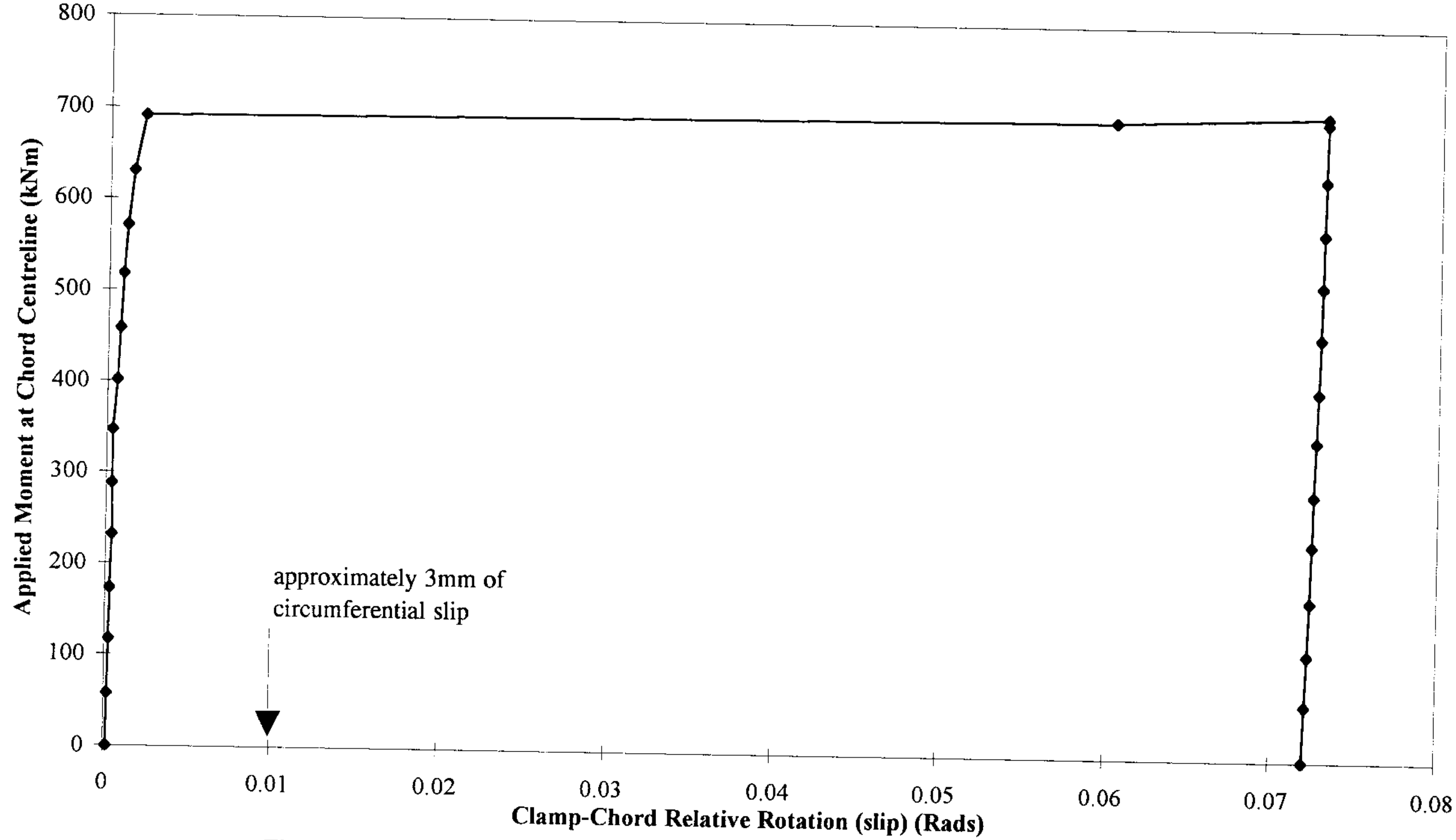


Figure 9.17: Torsional Moment versus Rotational Slip between Clamp and Chord Member (Average Readings from Displacement Gauges W3, W4, W7, W8)

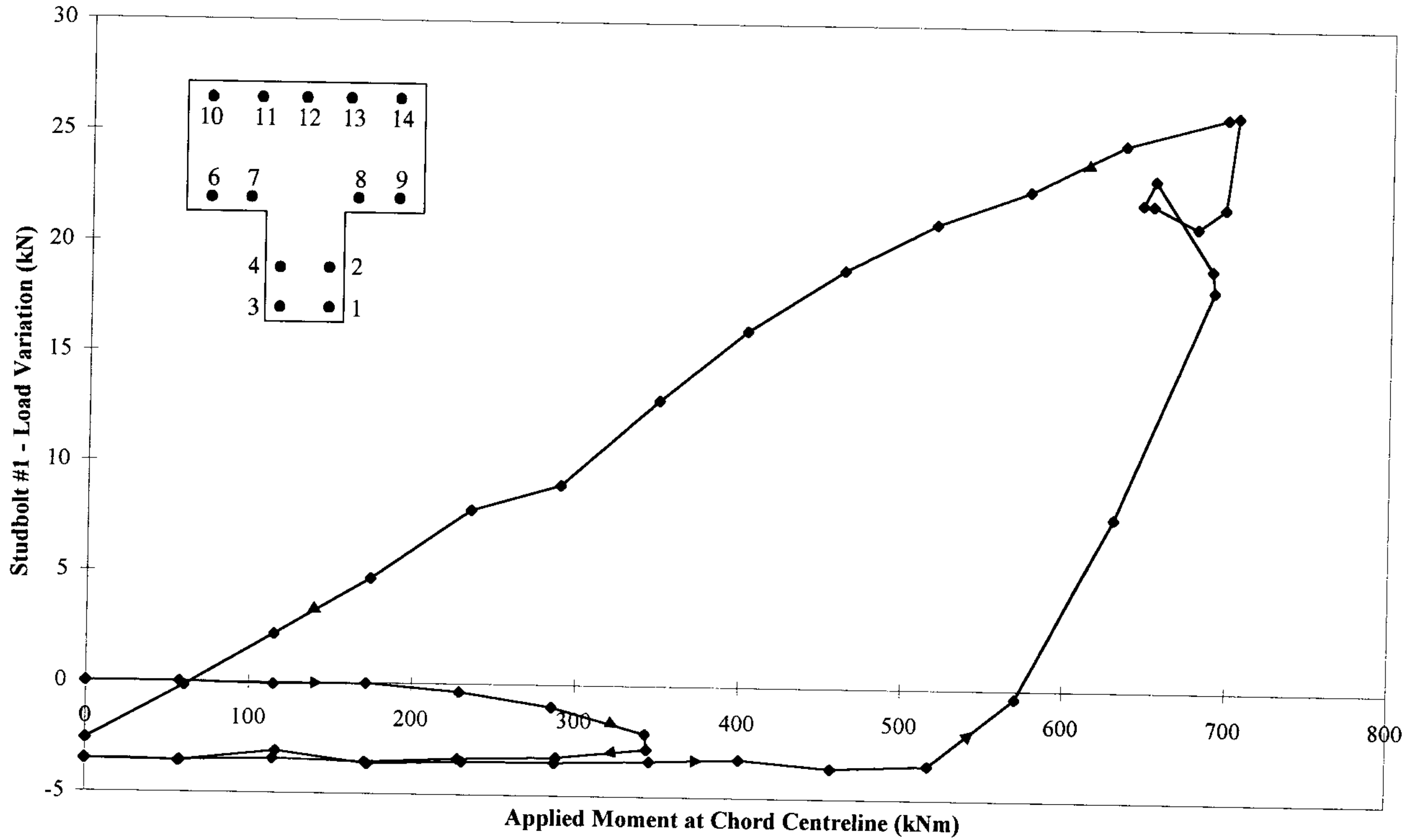


Figure 9.18: Bolt Load Variation with Applied Moment in Specimen for Bolt 1

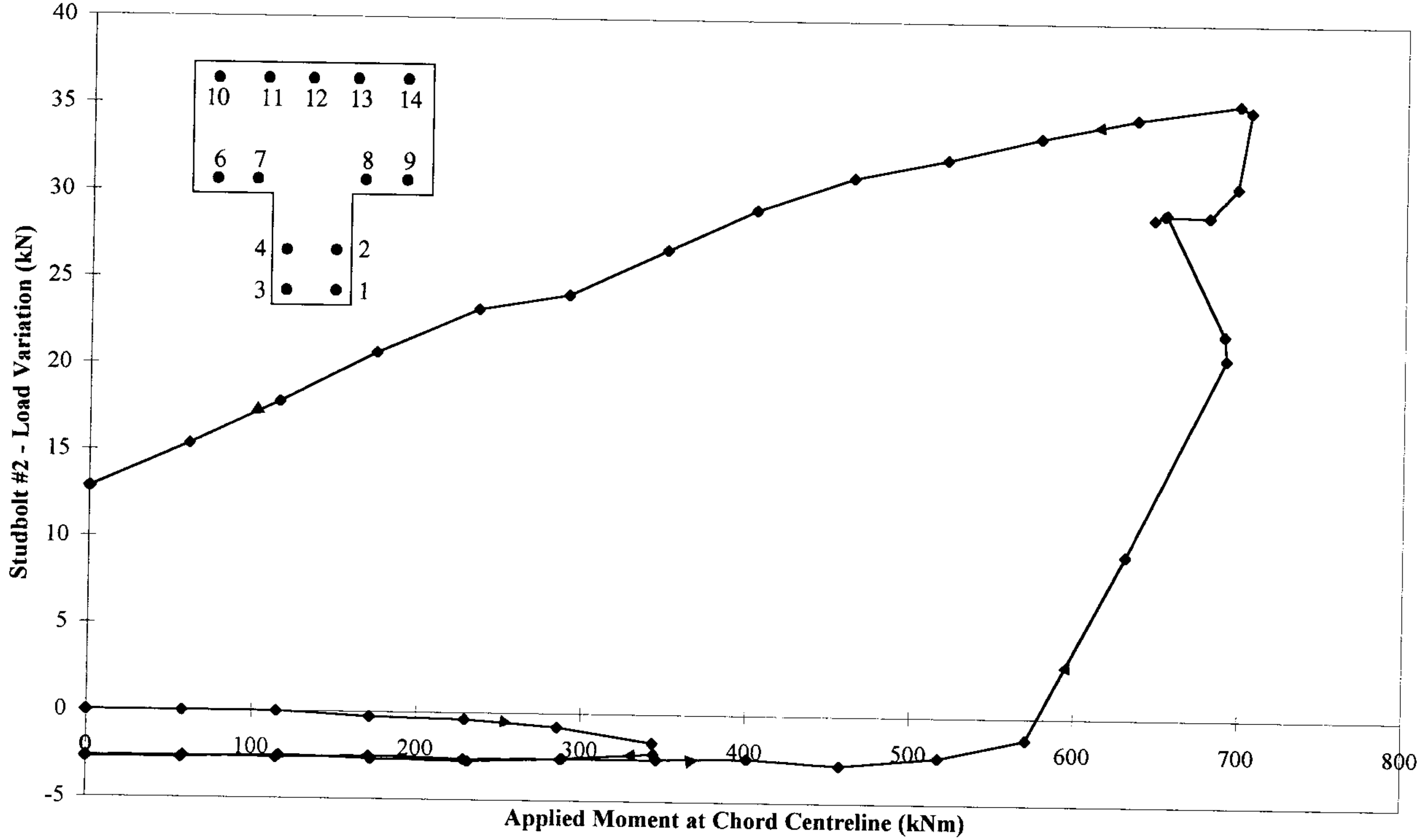


Figure 9.19: Bolt Load Variation with Applied Moment in Specimen for Bolt 2

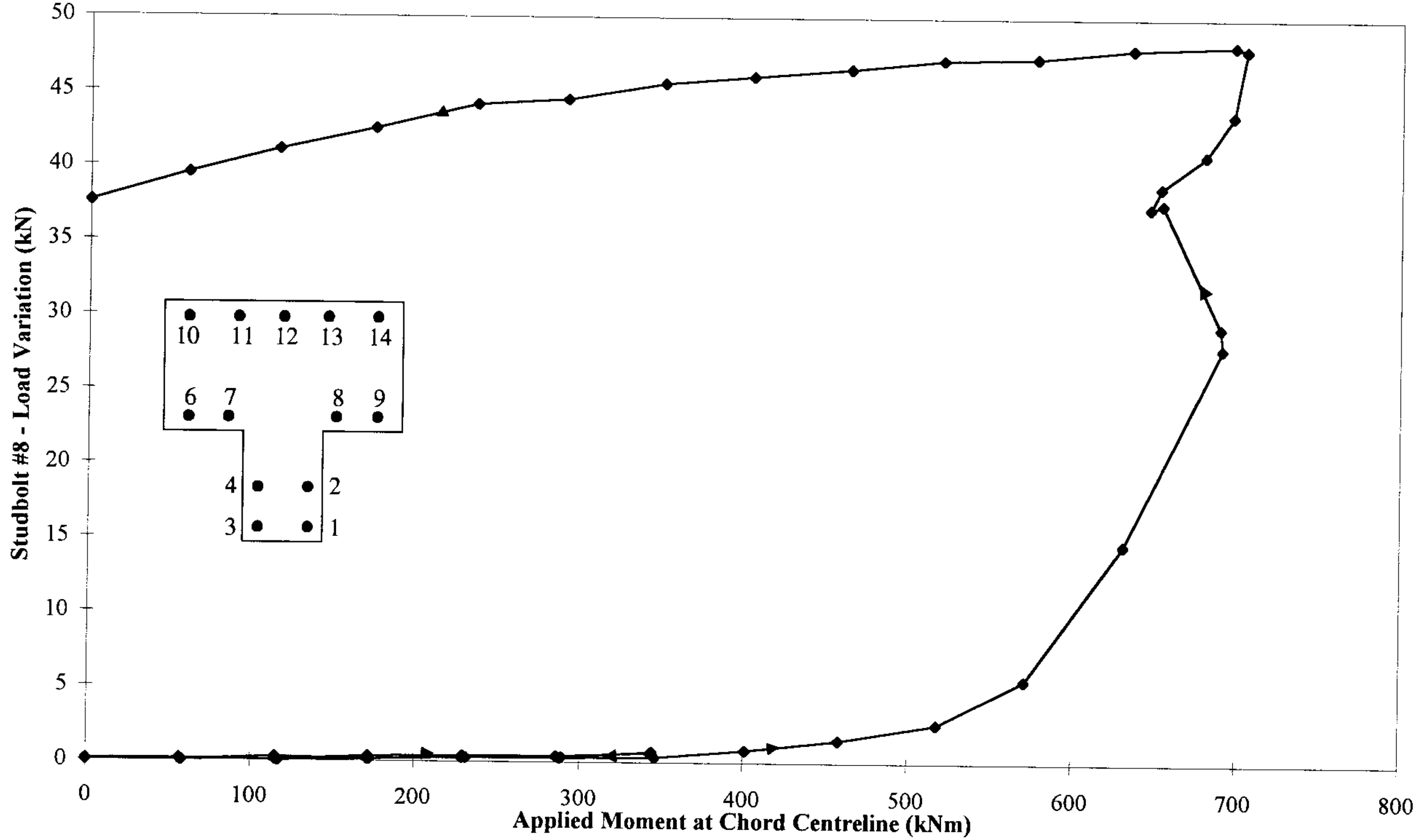


Figure 9.20: Bolt Load Variation with Applied Moment in Specimen for Bolt 8

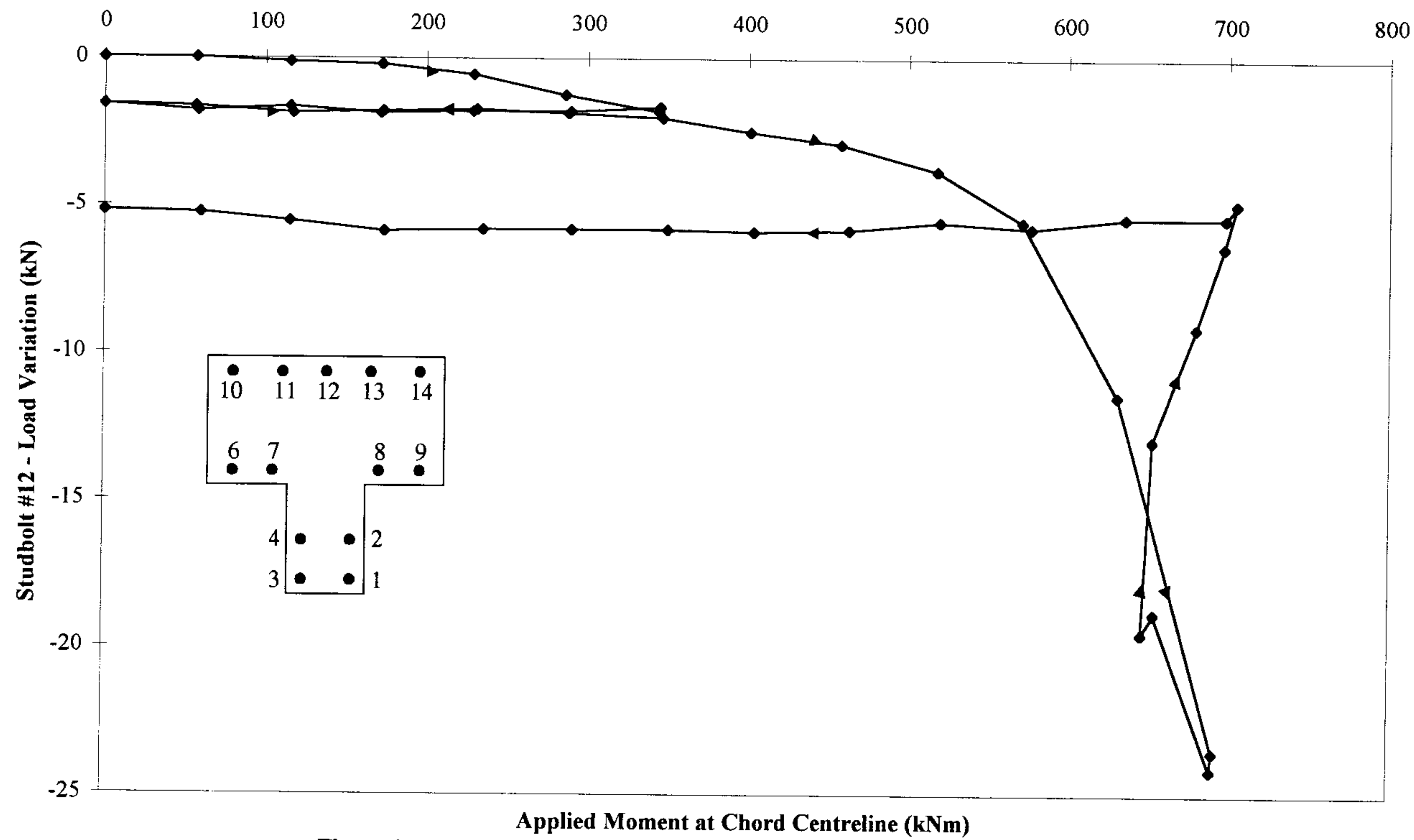
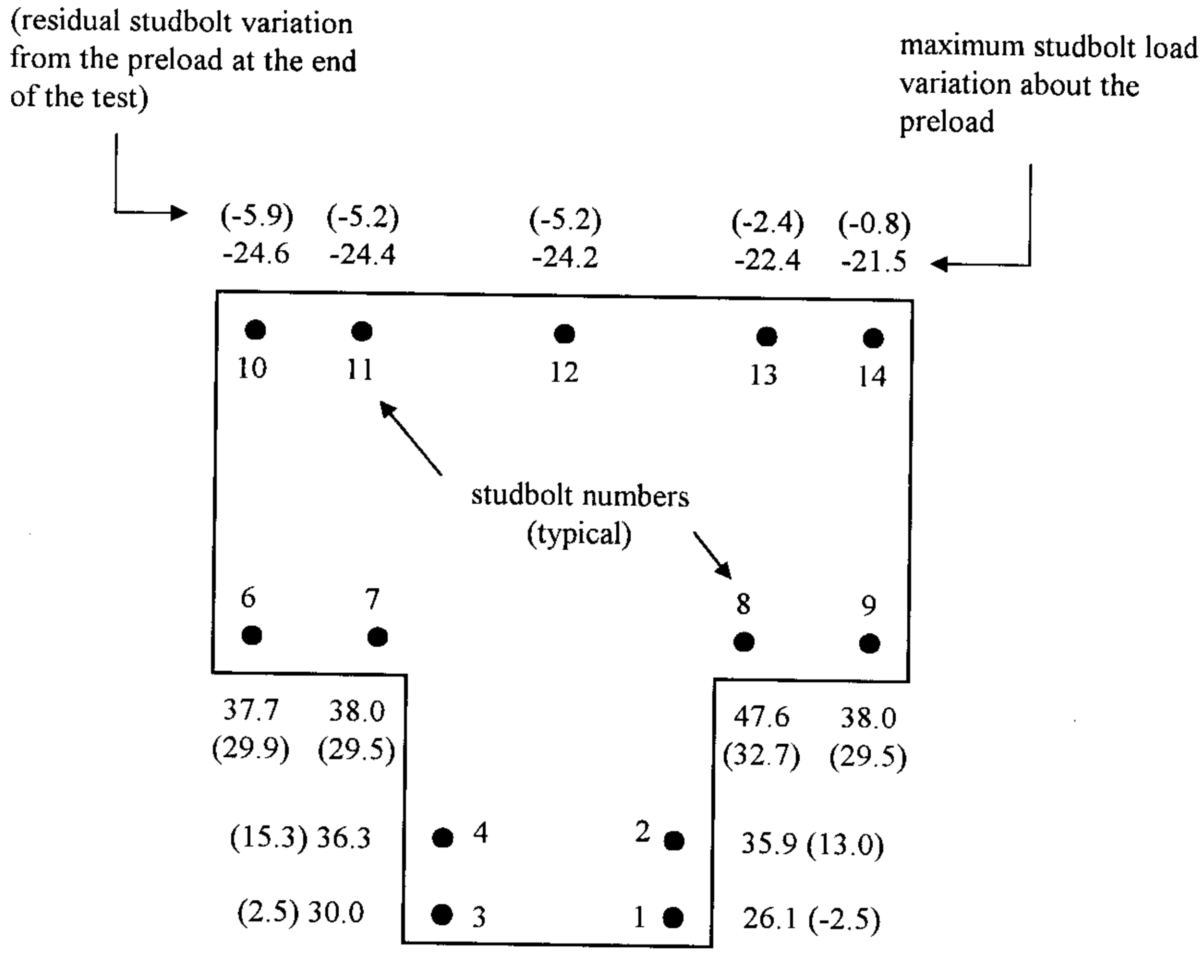
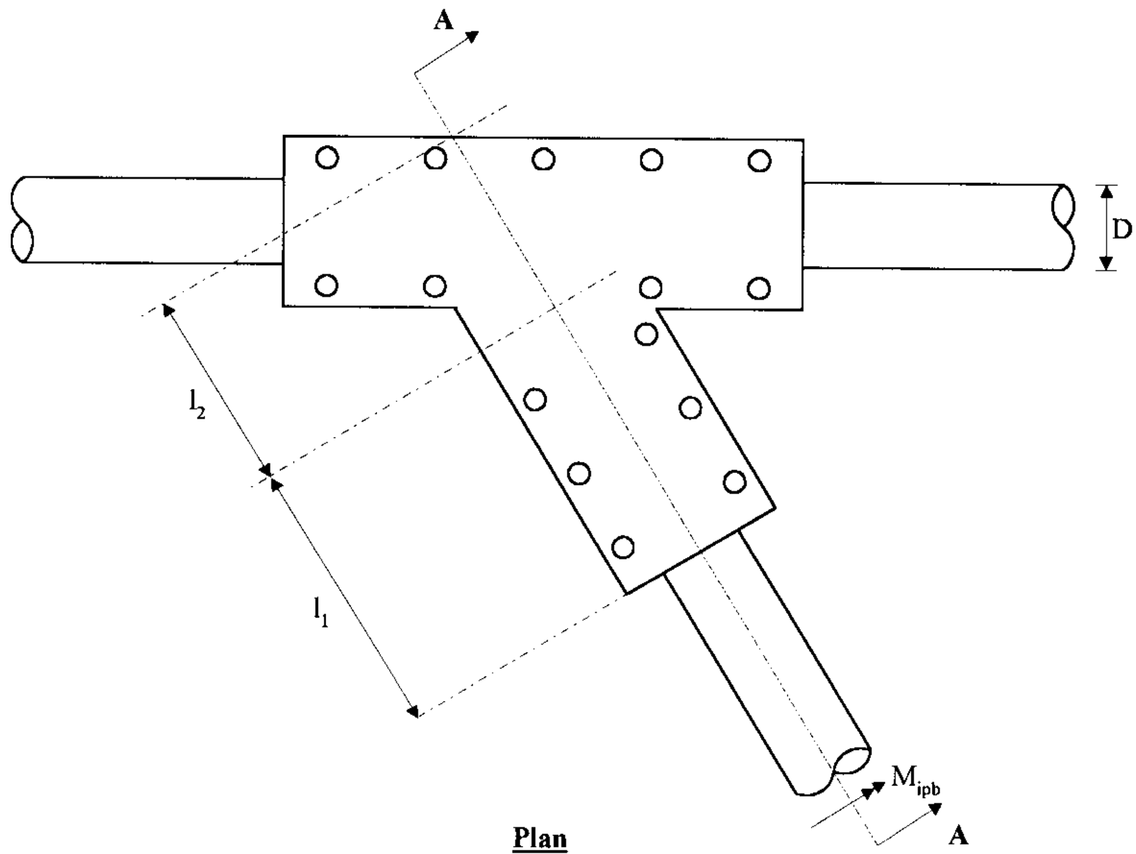


Figure 9.21: Bolt Load Variation with Applied Moment in Specimen for Bolt 12

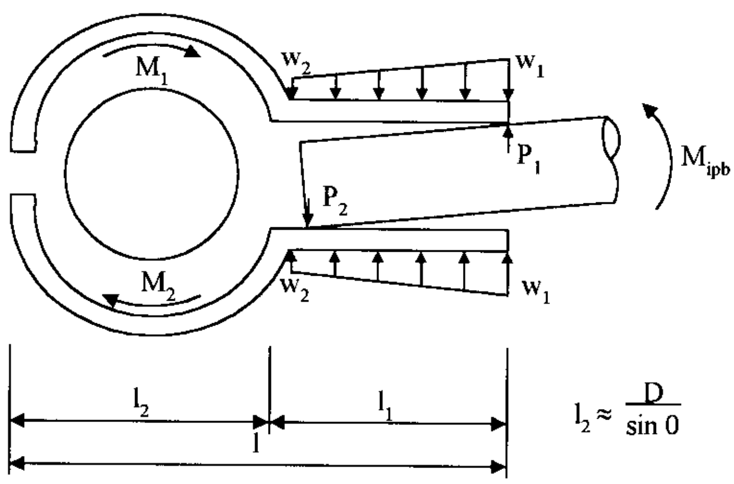


Note:
1. All loads are in kN

Figure 9.22: Maximum Studbolt Load Variations (and Residuals at end of Test) for WROV T-Clamp (about the preloads)



Plan



$l_2 \approx \frac{D}{\sin 0}$

View A-A

Figure 9.23: Rigid Clamp Model for Nodal Clamps

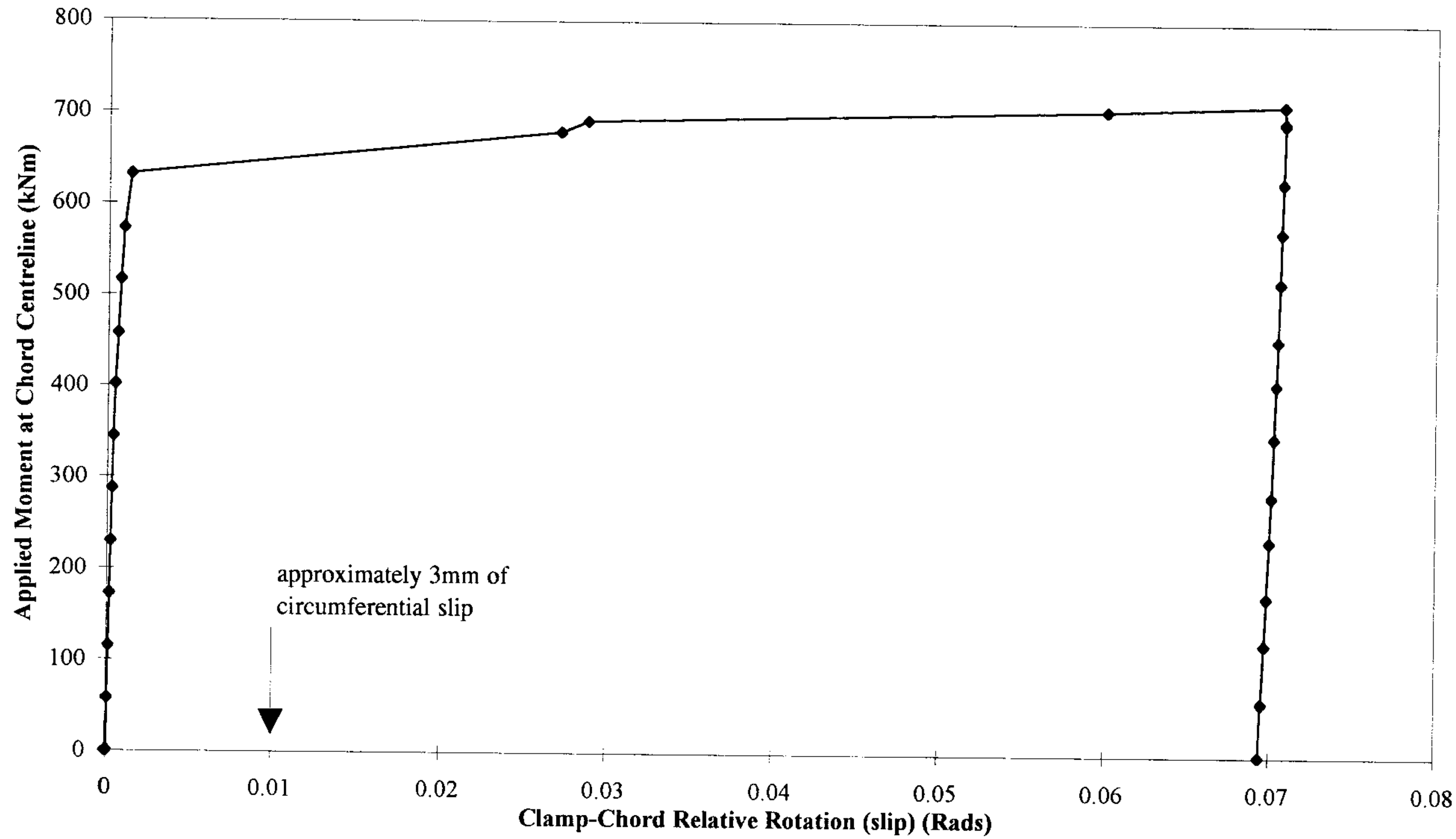


Figure 9.24: Torsional Moment versus Rotational Slip between Clamp and Chord Member (Average Readings from Displacement Gauges W3, W4, W7, W8)

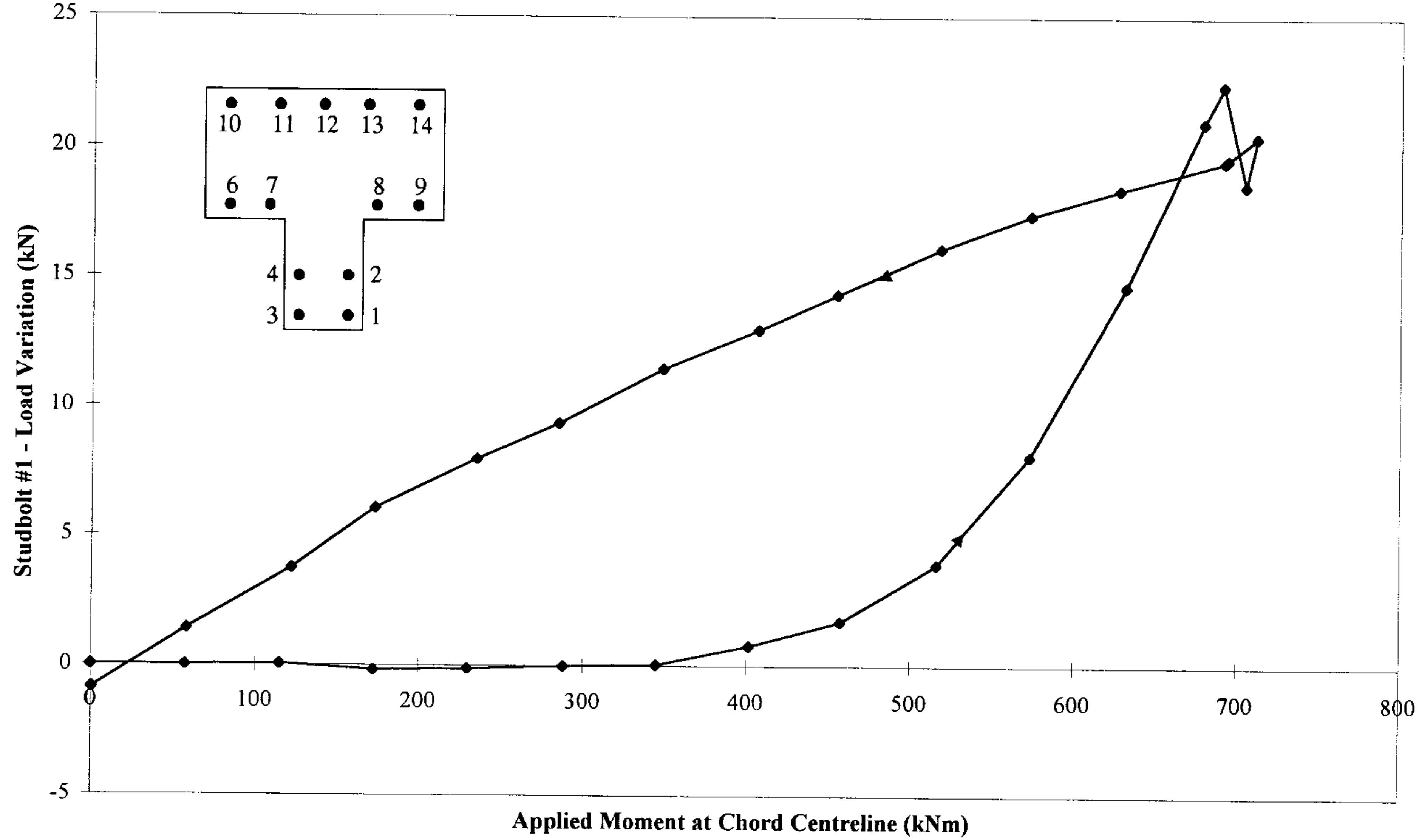


Figure 9.25: Bolt Load Variation with Applied Moment in Specimen for Bolt 1

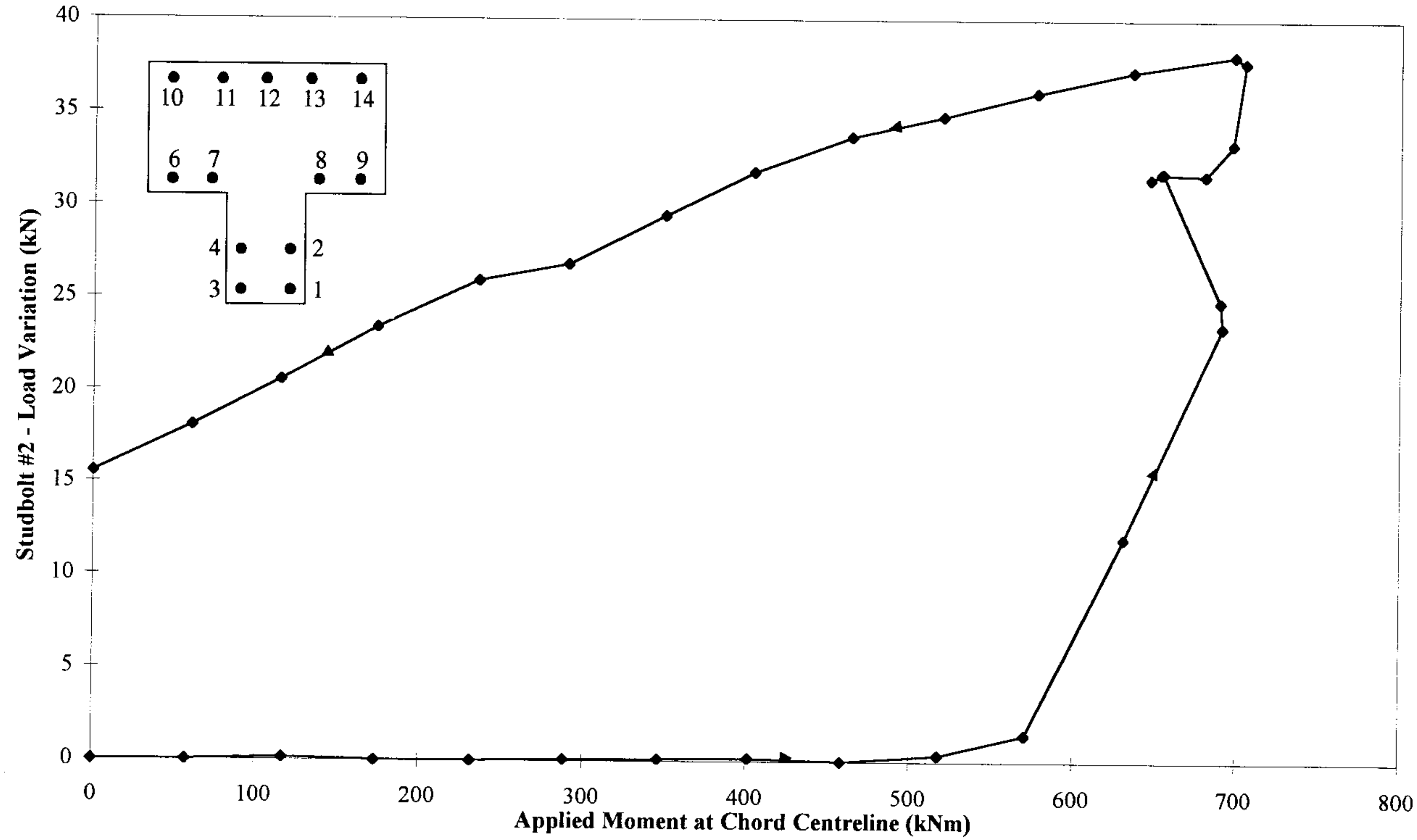


Figure 9.26: Bolt Load Variation with Applied Moment in Specimen for Bolt 2

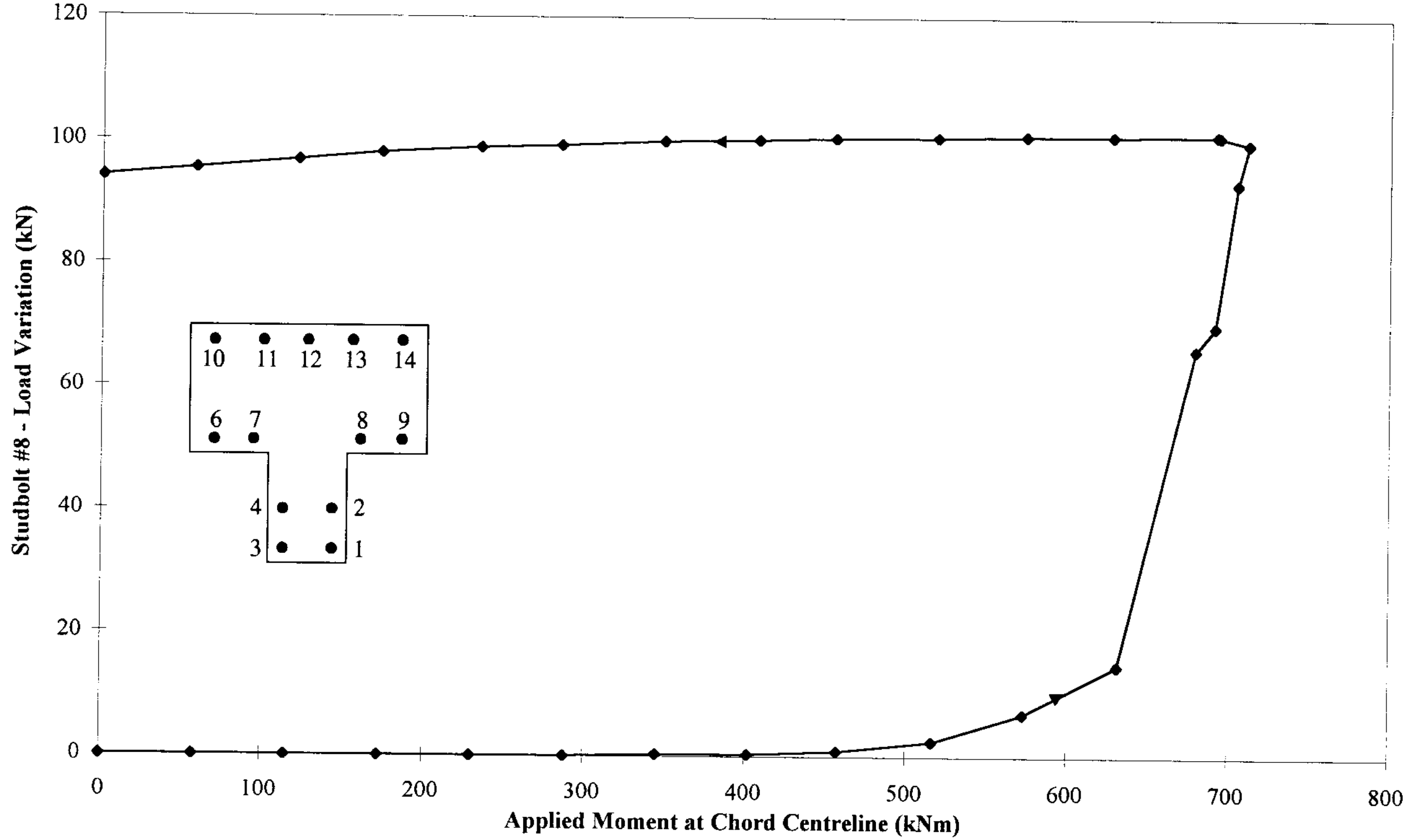


Figure 9.27: Bolt Load Variation with Applied Moment in Specimen for Bolt 8

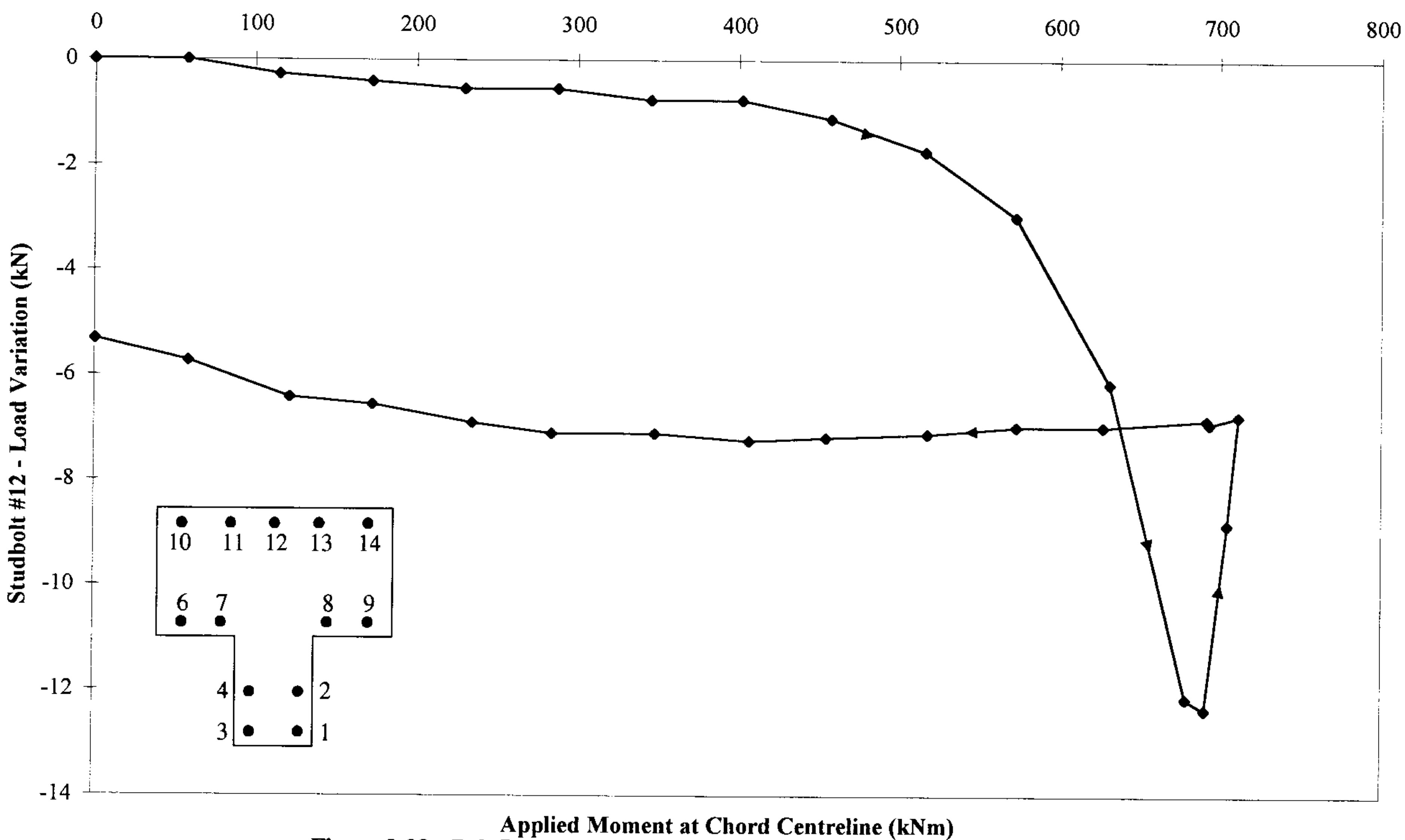


Figure 9.28: Bolt Load Variation with Applied Moment in Specimen for Bolt 12

REFERENCES

(1) Galbraith, D. N., Lalani, M. L., Sincock, P., Geddes, T.. 'Beryl Bravo: Diverless Structural Repairs'. OTC 7501, Offshore Technology Conference, Houston, May 1994.

(2) Offshore Engineer Magazine, January 1994, 'Beryl's Diverless Structural Clamps' pg 20-22.

(3) American Institute of Steel Construction. 'Manual of Steel Construction Allowable Stress Design'. Ninth Edition 1989.

(4) American Petroleum Institute. 'Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms'. API RP2A, Twentieth Edition 1993.

(5) MSL Engineering Limited. 'Strengthening, Modification and Repair of Offshore Installations. Final Report for a Joint Industry Project'. Document Ref. C11100R243, November 1995.

(6) The Engineering Equipment and Material Users Association. 'Construction Specification for Fixed Offshore Structures in the North Sea'. Publication No 158 1991.

(7) UK Health & Safety Executive. 'Offshore Installations. Guidance on Design, Construction and Certification'. Fourth Edition, HMSO, London 1990.

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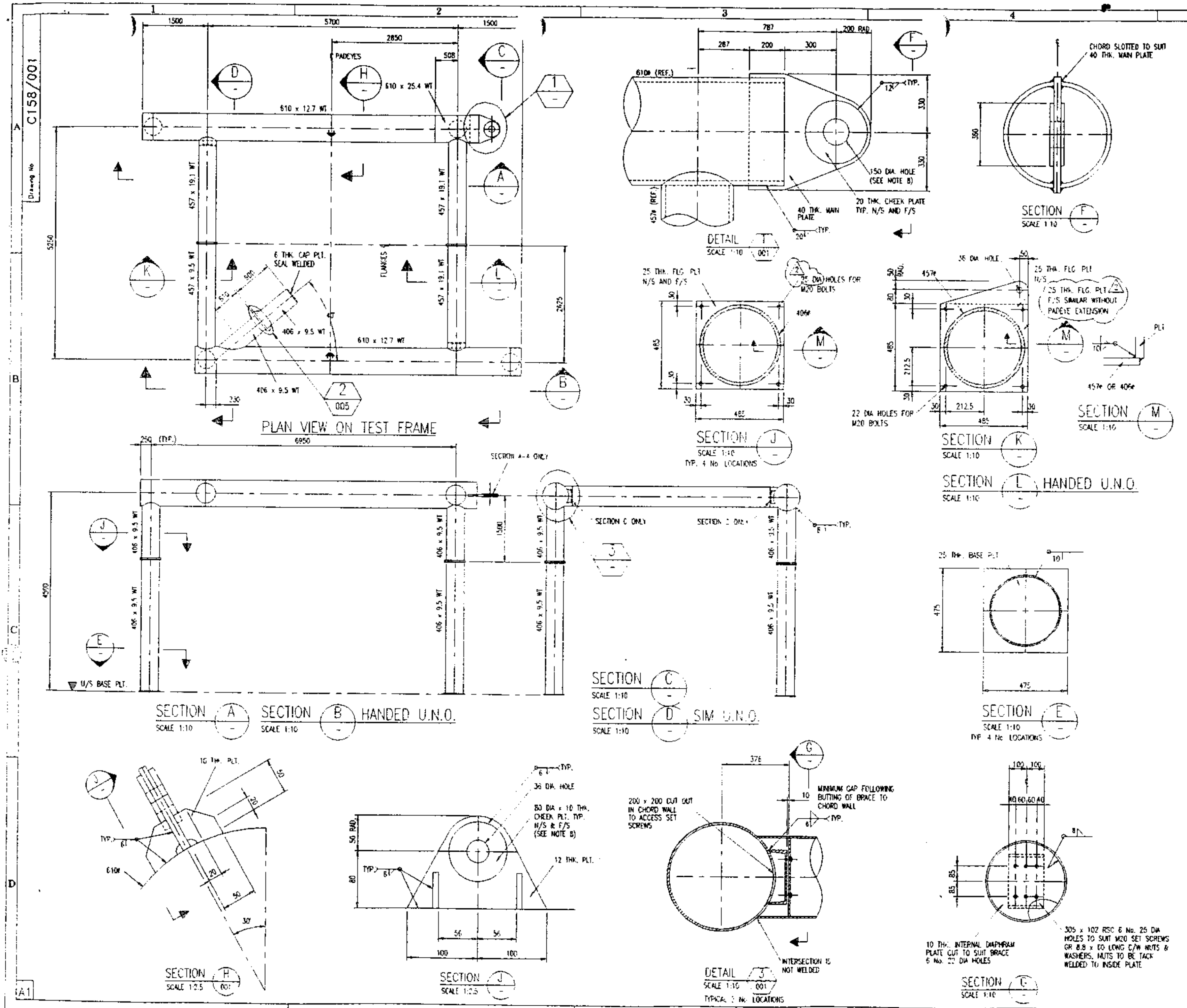

DO NOT S

NOTES.

1. ALL DIMENSIONS ARE IN MILLIMETRES UNLESS NOTED OTHERWISE.
2. ALL TUBULAR DIAMETERS ARE OUTSIDE DIAMETER
3. ALL STEEL PLATE SHALL BE SUPPLIED TO EEMUA FABRICATION No. 150 OR EQUIVALENT. CLAMP CIRCULAR SADDLE PLATE SHALL BE GRADE 275EZ. ALL OTHER STEEL PLATE SHALL BE 275D UNLESS NOTED OTHERWISE.
4. ALL TUBULAR SECTIONS SHALL BE SUPPLIED TO API 5L OR EQUIVALENT TUBULAR SECTIONS SHALL BE GRADE X52 UNLESS NOTED OTHERWISE.
5. ALL FABRICATION AND WELDING SHALL BE IN ACCORDANCE WITH EEMUA PUBLICATION No. 158(OR EQUIVALENT) AND PROJECT SPECIFIC ADDENDA GIVEN IN MSL ENGINEERING DOCUMENT No. C15800R020
6. INSIDE OF SADDLE PLATE SHALL NOT BE PAINTED.
7. ALL WELD TO BE FULL PENETRATION UNLESS NOTED OTHERWISE.
8. HOLE SHALL BE REAMED TO FINAL DIMENSION AFTER WELDING OF CHEEK PLATES
9. ALL TUBULARS TO INCLUDE 50φ DRAIN HOLE TOP AND BOTTOM DRAIN HOLES TO BE CLEAR OF CLAMP FOOT PRINT.

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
2	OCT 96	REVISED AS NOTED	RD	JB		
1	OCT 96	REVISED FOR CONSTRUCTION	RD	JB		
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PROJECT: DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES

TITLE: GENERAL ARRANGEMENT OF TEST FRAME

CLIENT APPROVAL AFC: | DATE:
APPROVED AFC: | DATE:
CHECKED AFC: | DATE:
DRAWN: RD | DATE: MAY 96
SCALE: 1:40 U.N.O.

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Ascot, Berkshire SL5 9NQ. United Kingdom.

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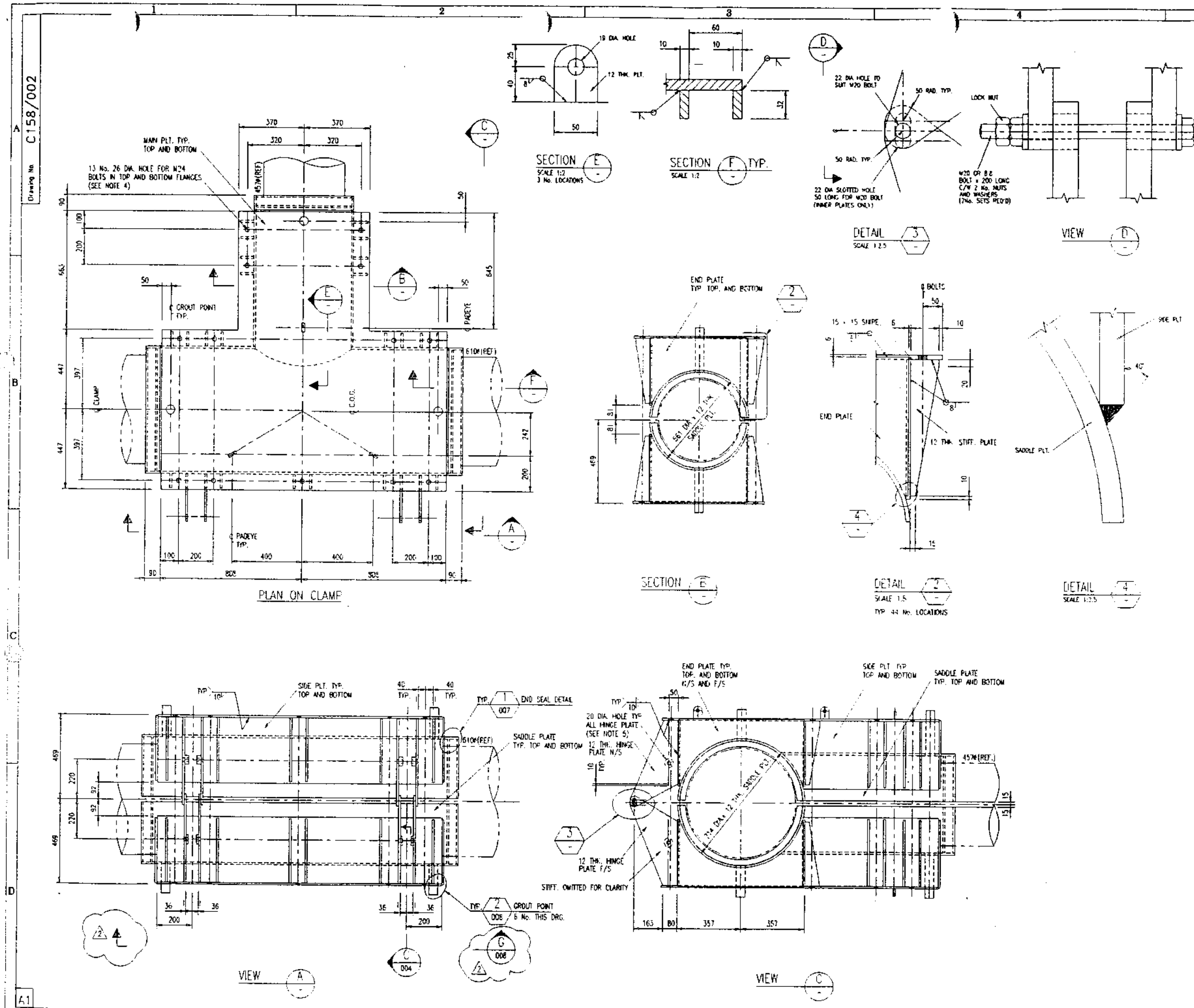

DO NOT SC

NOTES.

1. FOR GENERAL NOTES SEE DRG. No. C158/001
2. ALL PLATES ARE 12 THK. UNLESS NOTED OTHERWISE
3. FOR CLAMP SEAL DETAILS SEE DRAWING No. C158/007
4. FOR BOLT CONFIGURATION AND RETAINING DETAILS SEE DRG No. c158/009
5. HOLE SHALL BE REAMED TO FINAL DIMENSION AFTER WELDING OF CHECK PLATE.

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
2	OCT 96	REVISED AS NOTED	RO	JS		
1	OCT 96	REVISED FOR CONSTRUCTION	RO	JR		
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PROJECT: DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES

TITLE: GENERAL ARRANGEMENT OF T-JOINT CLAMP ROV INSTALLATION

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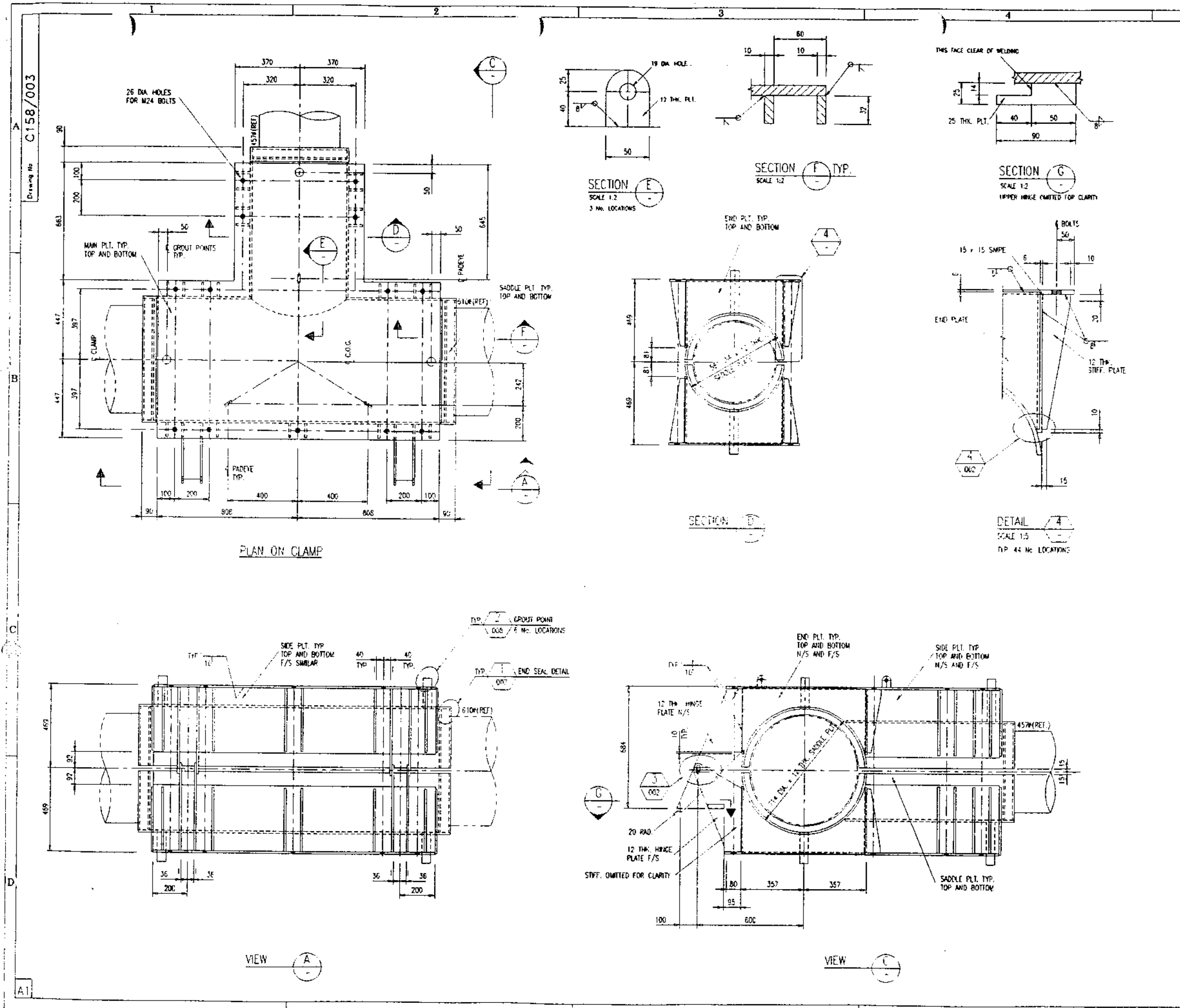

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2. ALL PLATES ARE 12 THK. UNLESS NOTED OTHERWISE
3. FOR CLAMP SEAL DETAILS SEE DRAWING No. c158007

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
1	OCT 96	REVISED FOR CONSTRUCTION	RC	JB		
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APPROVED AFC | DATE

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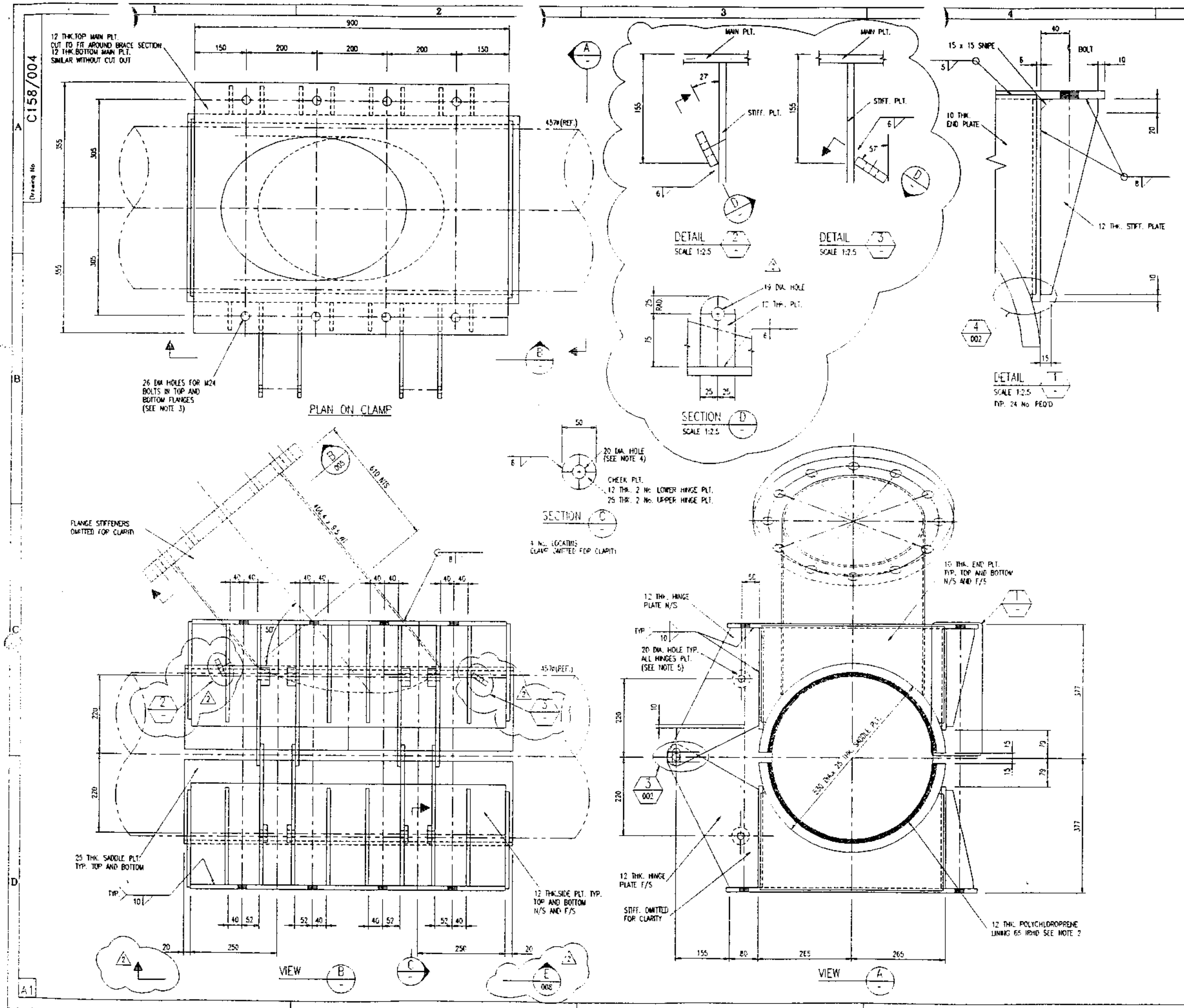
Drawing No C158/003



DO NOT SCALE

NOTES.

1. FOR GENERAL NOTES REFER TO DWG. NO. C158/001
2. CLAMP LINING TO BE HARDNESS VALUE 65 IRHD, SUPPLIED AND BONDED TO THE SADDLE IN ACCORDANCE WITH MSL ENGINEERING DOCUMENT No. C15800R008
3. FOR BOLT CONFIGURATION AND RETAINING DETAILS SEE DRG. No. C158/009
4. HOLES SHALL BE REAMED TO FINAL DIMENSIONS AFTER WELDING OF CHEEK PLATE

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
2	OCT 96	REVISED AS NOTED	RC	JB		
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PROJECT: DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES

TITLE: GENERAL ARRANGEMENT OF ADD-MEMBER CLAMP

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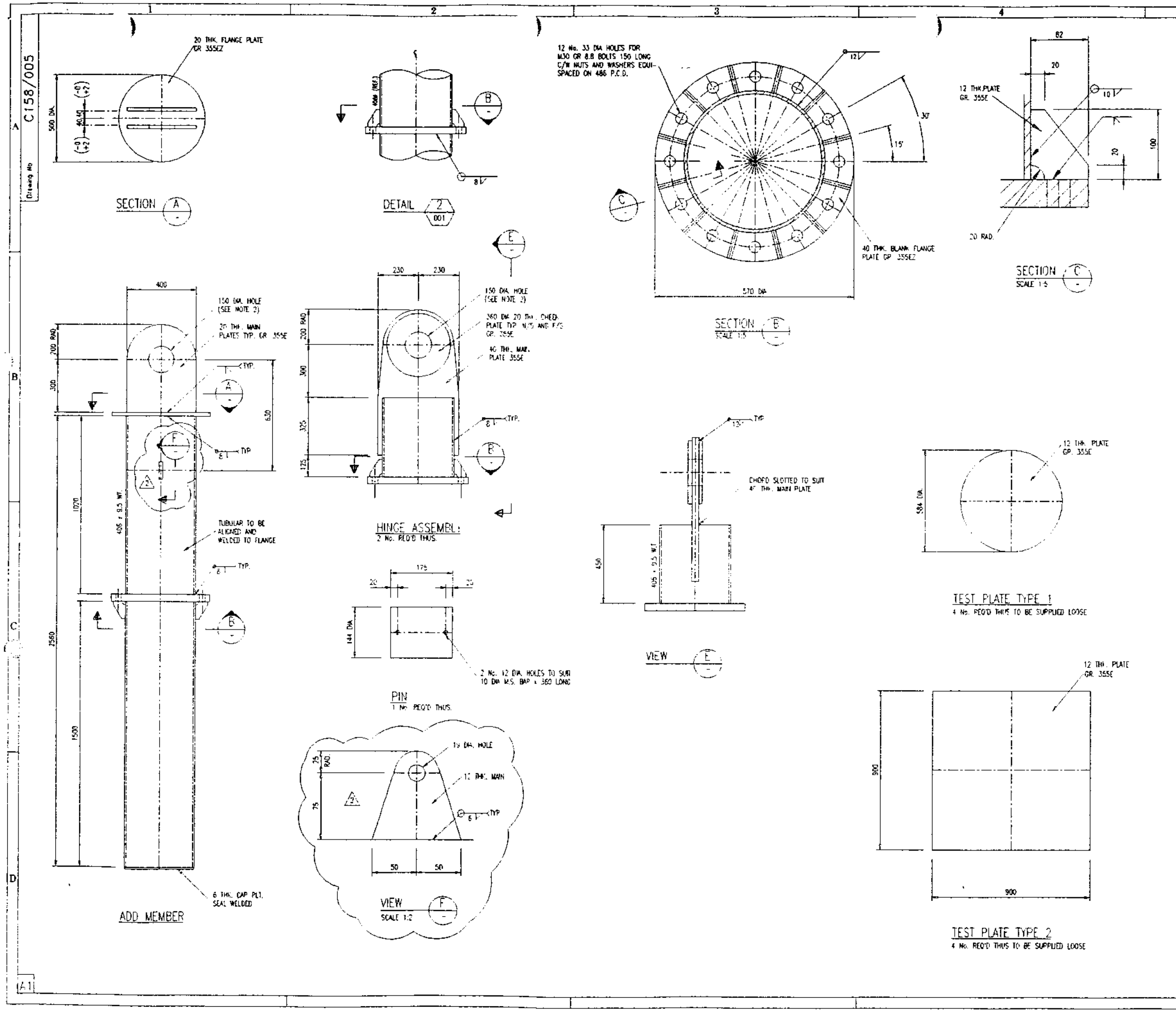

NOTES.

DO NOT S

1. FOR GENERAL NOTES SEE DWG. No. C158001
2. HOLES SHALL BE REAMED TO FINAL DIMENSION AFTER WELDING OF CHEEK PLATES AND DURING FIT-UP OF THE HINGE ASSEMBLY AND ADD-MEMBER COMPONENTS.

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
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[illegible]	SEPT 96	ISSUED FOR CONSTRUCTION	[illegible]	[illegible]		
[illegible]	SEPT 96	RE-ISSUED FOR COMMENT	[illegible]	[illegible]		
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TITLE: ADD-MEMBER DETAILS

DATE: MAY96
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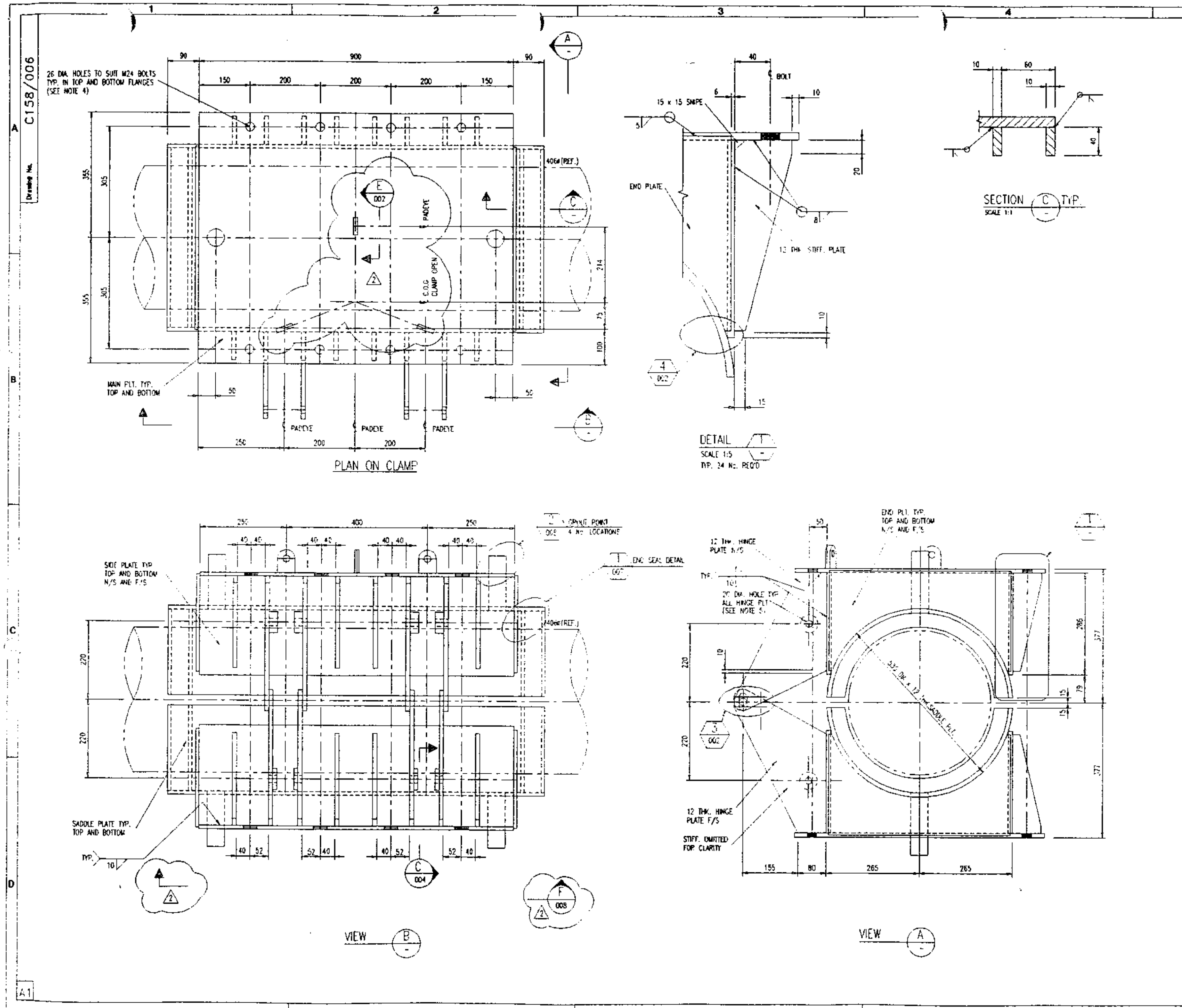

DO NOT S

NOTES.

1. FOR GENERAL NOTES SEE DWG. No. C158/001
2. ALL PLATES ARE 12 THICK UNLESS NOTED OTHERWISE
3. FOR CLAMP SEAL DETAILS SEE DRAWING No. C158/007
4. FOR BOLT CONFIGURATION AND RETAINING DETAILS SEE DRG. No C158/009
5. HOLE SHALL BE REAMED TO FINAL DIMENSION AFTER WELDING OF CHEEK PLATE

REV.	DATE	DESCRIPTION OF REVISION	ORIG. BY	CHK'D BY	APP'D BY	CLIENT APP'D
1	OCT 96	REVISED AS NOTED	RD	JB		
1	OCT 96	REVISED FOR CONSTRUCTION	RD	JB		
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CLIENT: JOINT INDUSTRY PROJECT

PROJECT: DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES

TITLE: GENERAL ARRANGEMENT OF TUBE TO TUBE CLAMP

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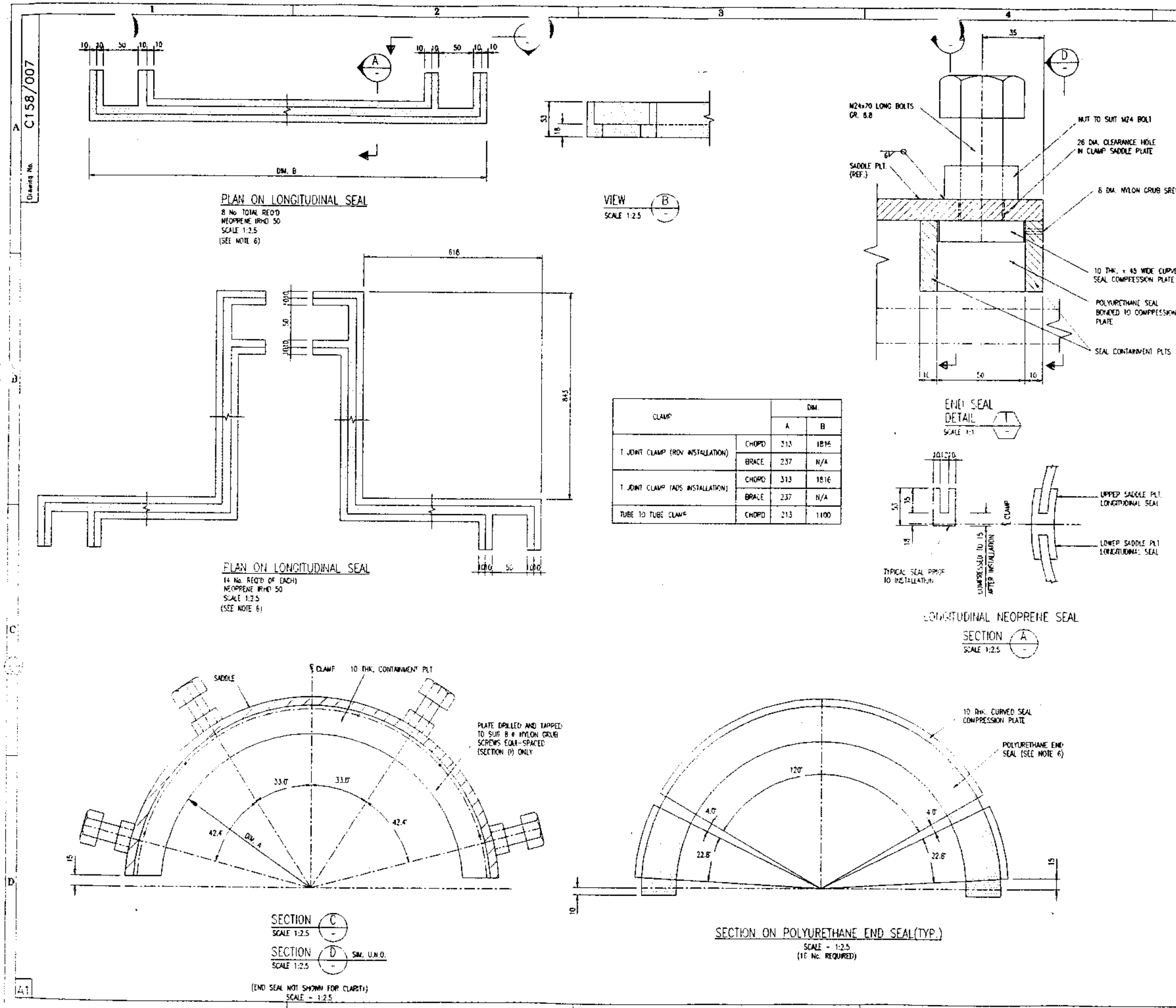
A1



CLAMP		DIM. A	DIM. B
T JOINT CLAMP (ROV INSTALLATION)	CHORD	313	1816
	BRACE	237	N/A
T JOINT CLAMP (ADS INSTALLATION)	CHORD	313	1816
	BRACE	237	N/A
TUBE TO TUBE CLAMP	CHORD	213	1100

DO NOT SCALE

NOTES.

1. FOR GENERAL NOTES SEE DRG No. C158/001
2. POLYURETHANE END SEALS ARE TO BE TRIMMED TO THEIR FINAL LENGTH DURING POST FABRICATION CLAMP COMPONENT FIT UP ASSEMBLY.
3. LONGITUDINAL NEOPRENE SEALS SHALL BE CONTINUOUSLY BONDED TO THE CLAMP STEELWORK ALONG EVERY INTERFACE IN ACCORDANCE WITH MSL ENGINEERING DOCUMENT No. C15800R007
4. POLYURETHANE END SEALS ARE BONDED ONLY TO THE CURVED SEAL COMPRESSION PLATES, IN ACCORDANCE WITH MSL ENGINEERING DOCUMENT No. C15800R007. THE REMAINING POLYURETHANE SEAL SURFACES ARE TO BE COATED WITH AN APPROPRIATE WATERPROOF GREASE PRIOR TO INSTALLATION BETWEEN THE SEAL CONTAINMENT PLATES AT EACH END OF THE CLAMP.
5. THE DISC END SEALING SYSTEM IS PATENT PENDING
6. MATERIAL FOR NOTED ITEMS TO BE FREE ISSUE SUPPLIED TO FABRICATOR

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
1	OCT 96	REVISED FOR CONSTRUCTION	RD	JB		
0	SEPT 96	ISSUED FOR CONSTRUCTION	RD	JB		
C	SEPT 96	ISSUED TO SUPPLIER	RD	JB		
B	SEPT 96	RE ISSUED FOR COMMENT.	RD	JB		
A	AUG 96	ISSUED FOR COMMENT.	RD	JB		

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CLIENT PROJECT NUMBER: ### | M.S.L. PROJECT NUMBER: C158 | ENGINEER: J BUCKNELL

CLIENT: JOINT INDUSTRY PROJECT

PROJECT: DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES

TITLE: CLAMP SEAL G.A. AND DETAILS

DRAWN: RD | DATE: MAR96 | SCALE: 1:10 U.N.

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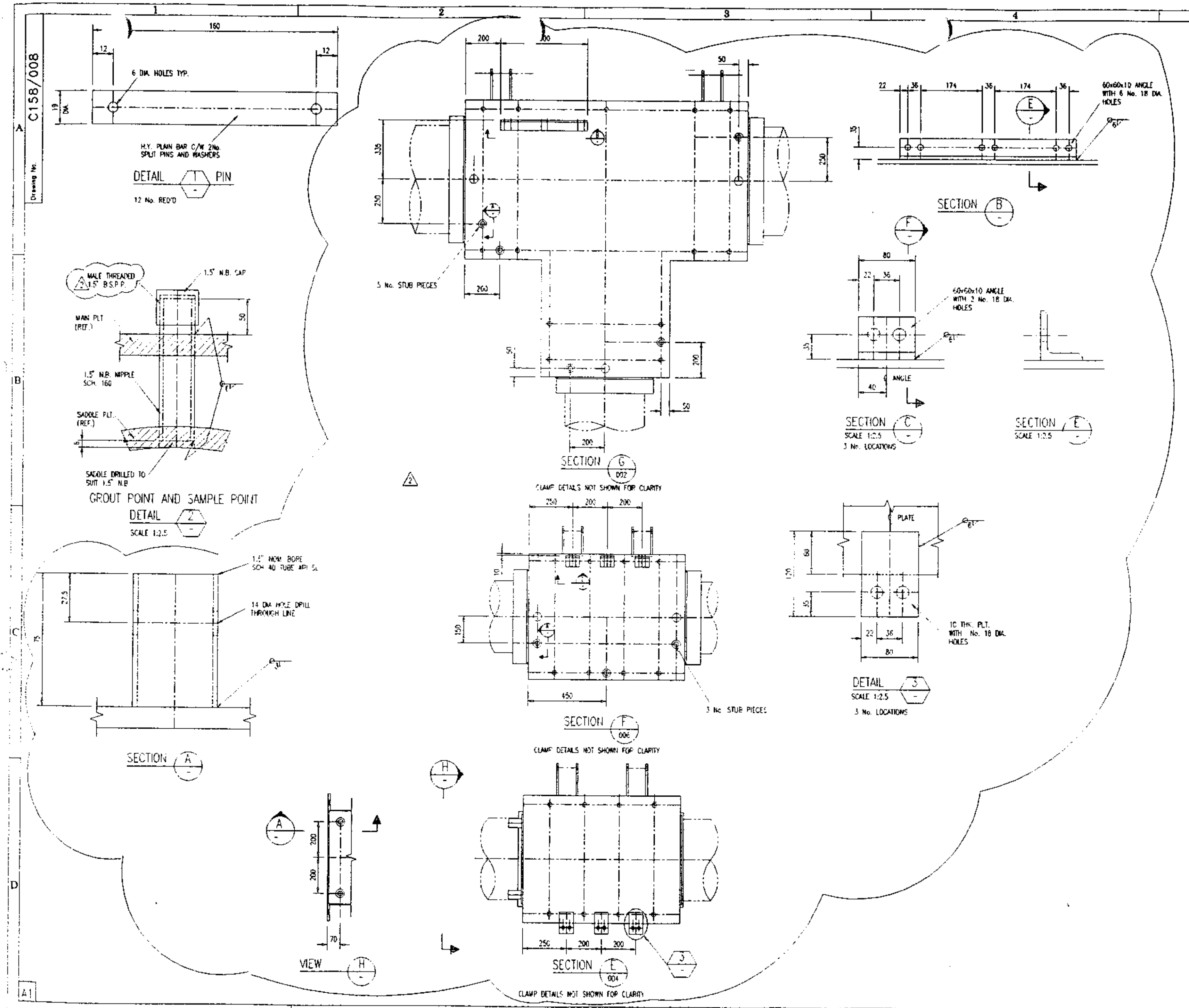
Ascot, Berkshire SL5 9NQ. United Kingdom.

DRAWING No. C158/007 REV. 1

A1



DO NOT S

NOTES.

1. FOR GENERAL NOTES SEE DRG No. C158/002.

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
2	OCT 96	REVISED AS NOTED	RD	JB		
1	OCT 96	REVISED FOR CONSTRUCTION	RD	JB		
0	SEPT 96	ISSUED FOR CONSTRUCTION	RD	JB		
B	SEPT 96	RE ISSUED FOR COMMENT.	RD	JB		
A	AUG 96	ISSUED FOR COMMENT	RD	JB		

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CLIENT PROJECT NUMBER	***
M.S.L. PROJECT NUMBER	C158
ENGINEER	J. BUCKNELL
CLIENT	JOINT INDUSTRY PROJECT
PROJECT	DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES
TITLE	GENERAL CLAMP DETAILS
DRAWN	RD
DATE	JUN96
SCALE	1:5 U.N.O.
CLIENT APPROVAL AFC / DATE	
APPROVED AFC / DATE	
CHECKED AFC / DATE	

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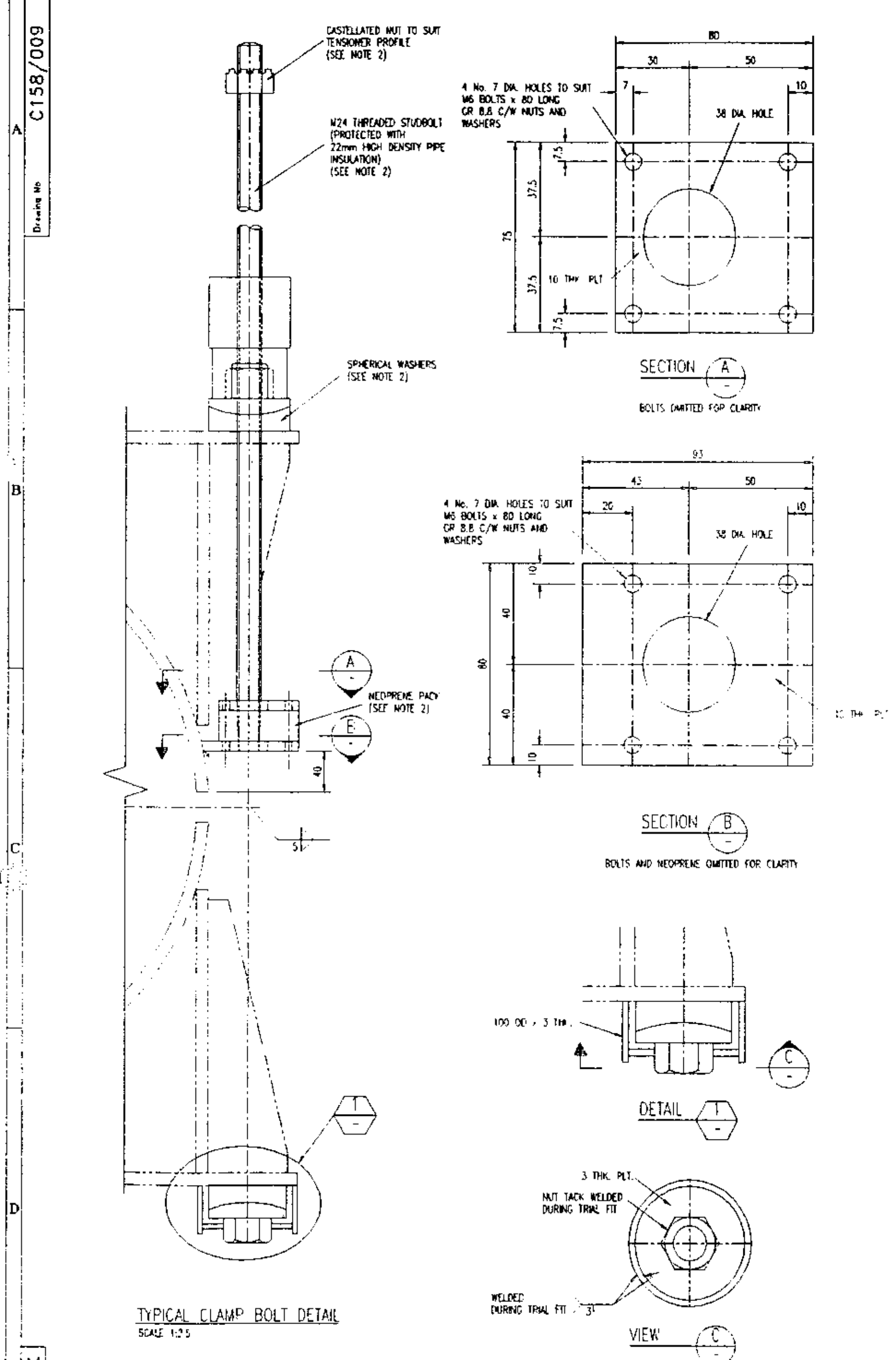
DRAWING No. C158/008 REV. 2



DO NOT S

NOTES.

1. FOR GENERAL NOTES SEE DRG No. C158/001
2. NOTED ITEMS WILL BE FREE ISSUE SUPPLIED TO FABRICATOR.

REV.	DATE	DESCRIPTION OF REVISION	DRN. BY	CHK'D BY	APP'D BY	CLIENT APP'D
1	OCT 96	REISSUED FOR CONSTRUCTION	RD	JB		
C	SEPT 96	ISSUED FOR CONSTRUCTION	RD	JB		
B	SEPT 96	ISSUED FOR COMMENT.	RD	JB		
A	AUG 96	ISSUED FOR COMMENT.	RD	JB		

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CLIENT PROJECT NUMBER	***
M.S.L. PROJECT NUMBER	C158
ENGINEER	J. BUCKNELL
CLIENT	JOINT INDUSTRY PROJECT
PROJECT	DEMONSTRATION TRIALS OF DIVERLESS STRENGTHENING AND REPAIR TECHNIQUES
TITLE	BOLT DETAILS AND SCHEDULE
DRAWN	RD
DATE	JUN96
SCALE	AS NOTED
DRAWING No.	C158/009
REV.	1

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A1

Drawing No C158/009