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Evaluation of forearm fixation plate design using finite element methods

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Abstract

The purpose of this paper is firstly to review the performance of the existing fracture plates in terms of suitability of the design as well as the choice of materials and secondly to evaluate stress distribution in two different forearm fixation plate designs using FEA techniques. Internal fixation plates are subjected to cyclic stresses which occasionally result in the failure of the device. An ideal fracture plate must be very strong so that secure fixation can be achieved and have a sufficient flexibility to allow movement at the fracture site to generate the formation of external callus which is essential to accelerate the healing process time. The two fracture plates investigated were made from carbon fibre reinforced plastic (CFRP) composites. The lower stiffness of CFRP plates compared with traditional metal plates can result in greater movement at the fracture. In order to improve or optimise the implant geometry and the stress/strain and displacement conditions the different designs were modelled and the loading conditions, including static and dynamic bending and torsion, were simulated and analysed using a three-dimensional, linear finite element analysis Package. The results also include consideration for detailed deformation and stress concentrations as a result of screw tightening and contact stresses between the plate and the screws. It has been found that the inside regions of the plate were subjected to elevated stress levels with the inner screws carrying higher loads.

1 Introduction

The healing of a fracture in the forearm can be assisted by screwing a fracture plate across the fracture site. The early devices of the Orthopaedic Industry were made from 306 or 316 stainless steel due to their good corrosion resistance. However, orthopaedic industry has closely followed the aerospace industry in utilising high performance metal alloys, based on Cobalt-Chromium and Titanium alloys, with an elastic modulus 10 times that of bone, for superior implant performance and might be on the road to repeating this with advanced composite materials.

These high performance metal alloys have distinct disadvantages as follows:

a) The metal ions can be released, over the years, into the body which could lead to the development of Carcinogenic tissue reaction (1).

b) Metal implants are usually stiffer than the living bone, therefore external callus formation is inhibited by the absence of mechanical stimulation at the fracture site (3,11,12).

The density of the living bone is always controlled by the stress conditions applied to the bone; thus if a higher stress is applied to the bone, the density of the region increases (2). So if the metal plate, with high modulus of elasticity, is attached to the bone, the stress will be transmitted by the plate to the bone directly beneath the plate leading to a high stress concentration region. Hence the possibility of re-fracture of the bone after loading or unloading of the bone.

The ideal material which will satisfy the numerous conflicting loading performance needed has yet to be found. Therefore an ideal internal fixation device should :

- allow adequate fracture fixation without loosening over a period of time
- reduce vascular impairment and retain more physiological strain fields
- be produced from a material with a Young's Modulus similar to the living bone, around 20 GPa
- withstand complex loading, have good mechanical strength similar to the metal alloys, as well as high impact damage tolerance
- have a sufficient bending stiffness above the fracture site, but the overall axial stiffness and the bending of the plate ends should be reduced to prevent stress protection of the bone
- have fatigue strength many times higher than that of bone, if materials with an elastic modulus less than that of bone are to be used
- have a high strain to yield so that the material can deform without breaking

Numerous studies (11-13) have shown that rigid metal plates interfere with normal bone physiology by stress shielding the bone beneath the plates. This causes osteopenia of cortex beneath the plate, alters the diameter of the bone and inhibits normal bone remodelling as evidenced by the persistence of immature woven bone. This alteration in bone physiology can result in the refracture of long bones after removal of plates.

About 40 different polymers, copolymers and composites have been developed in order to substitute the metal implants for internal fixation plates. In responding to the above complex demands on fracture plates, the use of advance composite materials potentially would enable designs that can seek optimal mechanical characteristics through modifications of fibre types, orientation and ply-stacking sequences, as well as implant geometry (4).

The experimental and clinical results have so far demonstrated some limitations of these new materials (3). Disadvantages of carbon fibres embedded in epoxy, polyester or PMMA include; a) long term reduction in properties sometimes before bone healing has been completed, interaction of body fluids with the matrix material may degrade the properties, b) the release of carbon fibre fragments that can migrate into other tissues (8), c) lack of ductility that prevents reshaping in the operating room in the manner of metal implants (9). The latter problem can be overcome by selecting an alternative matrix polymer such as polysulphone, which can be reshaped to the required size, under moderate heat, in the operating room (5).

The first commercial application of carbon fibre composite, in the orthopaedic industry, was for bearing surface in tibia knee prosthesis and acetabular cups for hip implant. The material was carbon fibre reinforced ultra high molecular weight Polyethylene (UHMWPE). The incorporation of carbon fibre into (UHMWPE) has a marked effect on the stiffness (modulus) and creep resistance of the materials. (5-7).

In a recent investigation (4) to compare deformation behaviour of composite fracture plates made from aramid-epoxy and carbon-epoxy composites, in which 4-hole test specimens were used, it was shown that the aramid composites appeared to be less subject to catastrophic failure than carbon fibre composites. Also when the specimens

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were fastened to a plastic tube, simulating bone, the strain shielding was significantly reduced by the aramid composites relative to carbon fibre composites. Claes (10) conducted an extensive study of fracture behaviour of 6-hole plate design made from carbon fibre reinforced carbon composite. It was concluded that bending and torsional rigidities of the plate over the fracture zone must be sufficient to prevent gross motion at the fracture site, however the axial stiffness, bending and torsional rigidities must be reduced to minimise stress protection.

1.1 Failure of Forearm - Fracture Plate

When failures of fracture plates occur, they most commonly occur within the first 10 to 13 weeks, with a mode of failure of fatigue (18). Assuming a patient will walk between 1/2 h and 1h per day on average during this time a fracture plate used to stabilise the fracture will be loaded between approximately 162,000 and 325,000 times (15).

Various investigators have studied the affect of different loading conditions on the screws holding the fracture plates onto the bone (14-17). Screw loosening has been shown to be possible in vivo and has been attributed to cyclic mechanical loading (14,15). All screws undergo mixed modes of loosening with those near the fracture site experiencing the largest loads and the greatest amount of loosening.

Other studies have involved assessment of refracture of the forearm after removal of the fracture plate (19-20). Hidaka and Gustilo (19) reported seven refractures in 23 patients with 3 refractures occurring at the site of the original fracture, three through a screw hole adjacent to fracture site and one through a screw hole distant from the fracture site.

2 Fracture Plates Considered

In this study two different six-hole fracture plate designs were investigated, namely straight edge and waisted edge. The waisted edge design was intended to provide more movement at the point of bone fracture. These plates were assumed to have isotropic properties with short carbon fibre reinforced thermoplastic composite materials. These plates were designed and manufactured by Orthodesign Ltd.

3 Finite Element Models

FEA was performed to examine the mechanical performance of the fracture plates under two different loading conditions, namely bending and torsion. The I-DEAS (Integrated Design Engineering Analysis Software) software package from SDRC running on a SGI (Silicon Graphics), Iris Indigo graphics workstation was used to define implant geometry, to generate the finite element model and to evaluate the stress distribution. This was achieved by first constructing three dimensional solid models within the CAD Solid Modeller, then the geometric information was used by the Finite Element Mesh Generation task to create mesh areas and mesh volumes. Nodes and elements were then generated from the mesh volume.

The input consisted of the discretized mesh with elemental properties specifying the stiffness matrix components (elasticity tensor) in addition to the boundary conditions and loading history. The output of this program in addition to nodal displacements gave the stress state at any location of the fracture plate. The element distribution was controlled by setting global and local element sizes. In the regions of interest, i.e. the upper edge of the inner screw holes, the number of elements was increased to reduce the step between nodes and thus decrease errors associated with discretized models.

4 Results and Discussion

Two separate load boundary conditions were performed to analyse the stress concentration in the two different designs. First the effect of applying a pure bending load was examined by specifying a load of 100 N at the plate end. The second loading condition involved a twisting moment of 1.2 Nm at the plate end. In both cases the plate was fixed across the middle cross section. Also to simulate the effect of screws a uniform radial stress of 19 kNm^{-2} was specified in all the screw holes. The load boundary conditions specified are described in Fig. 1.

Finite element models of the two designs symmetric about the longitudinal mid-plane including the innermost screw hole and the adjacent regions up to the next hole position were constructed and shown in Figs 2 and 3. These show the Von Mises stress distribution for both fracture plate designs under the two specified loading conditions. Von Mises stress is used as a fatigue criterion, since fatigue is the expected mode of failure. It should be noted that in all the models considered no portion of the model appeared to be yielding. Utilising Von Mises yield criterion showed that finite element analyses were within the elastic range. If loads were increased due to dynamic effects, then analyses including plasticity may be appropriate.

When pure three point bending is specified the two models react differently, the maximum stress occurs at different locations. For straight edge model the stress levels tend to be lower with the innermost screw holes carrying increased stresses, with the highest stress of 245 MPa. For the waisted edge model the highest stress concentration occurs around the middle of the span with the stress of 322 MPa. This is an increase of 31% over the straight edge model. However the next highest stress in the waisted edge design is around the inner screw holes with a value of 225 MPa. A similar trend was also present for torsional load case. Thus the inner screw hole regions are the most likely areas for plate failure.

Therefore the waisted profile can be optimised further by increasing the radius to reduce the local stress in the mid span to match the stress around the inner holes. It is believed that once the waisted edge design is optimised it will eventually prove more satisfactory for general use. Although it does not appear to be as strong as the straight edge plate but as it is less rigid it can result in a better fracture fixation.

5 Conclusions

It is important to tailor make the stress/ stiffness distribution of fracture plates. The highest stresses occur in the inner screw hole regions. To optimise the stress/ stiffness the plate can be waisted to yield a more uniform stress distribution.

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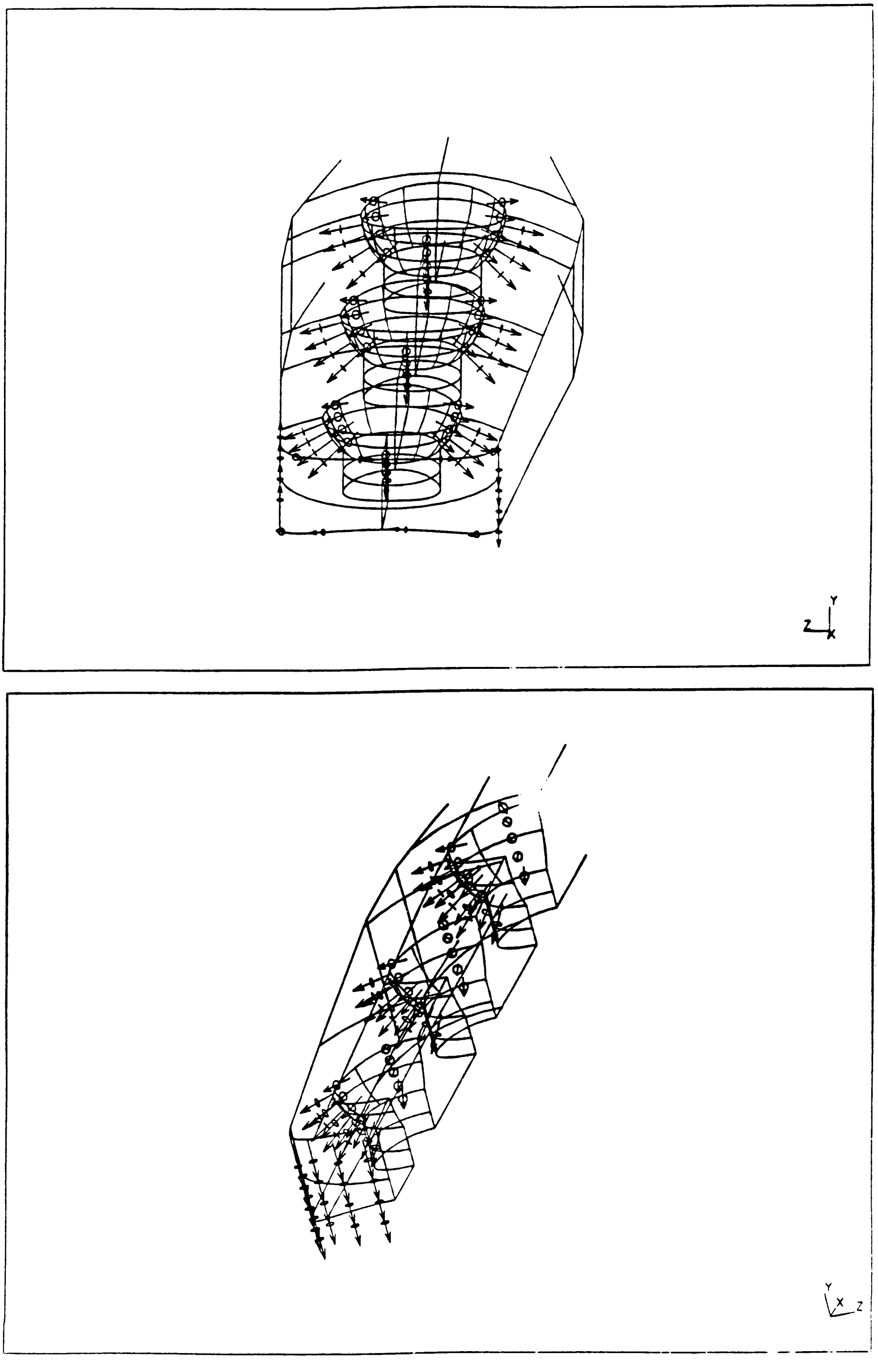

Fig. 1 Load boundary conditions applied on the two fracture plate models

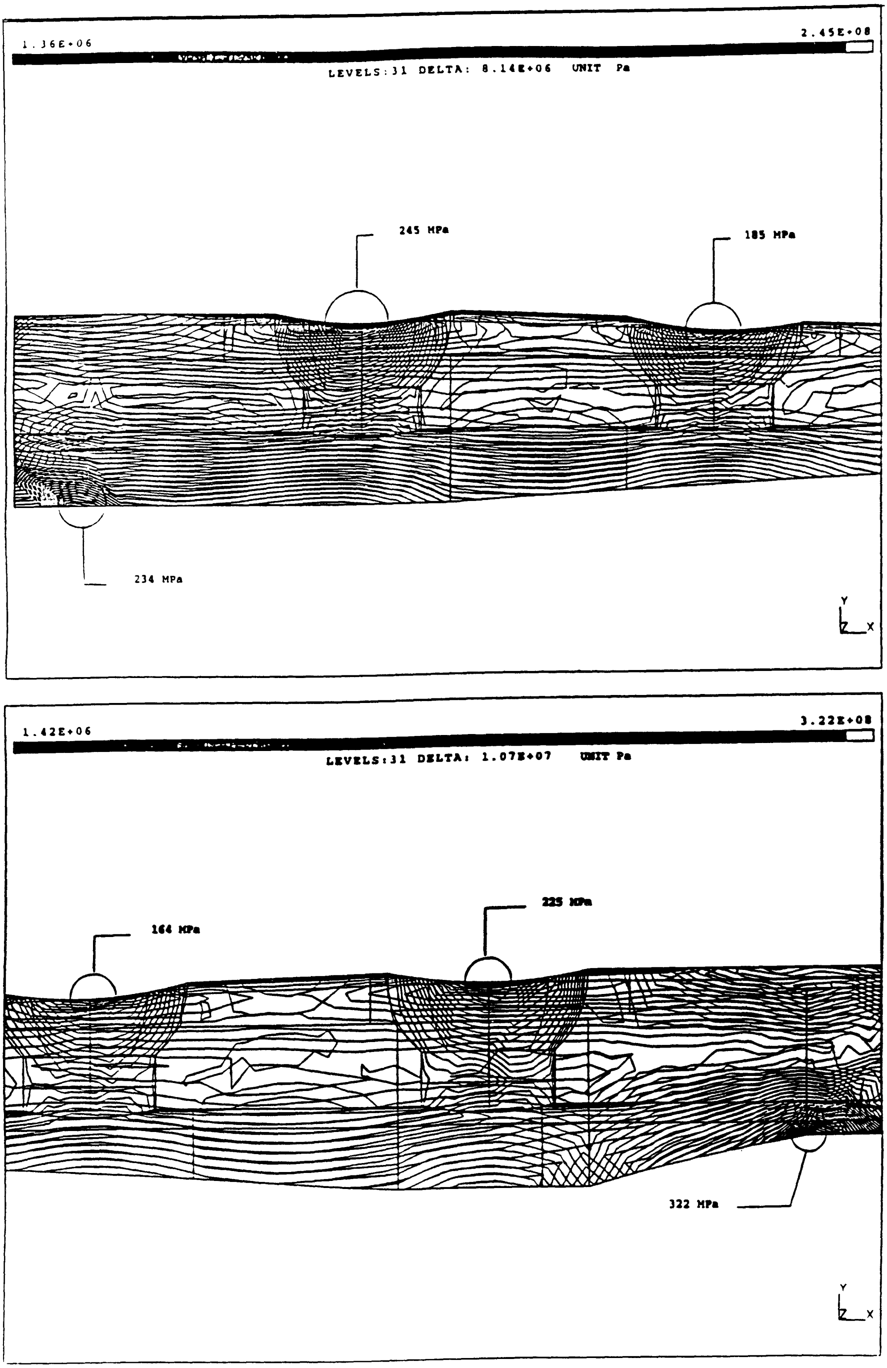

Fig. 2 Von Mises stress distribution on straight edge and waisted fracture plate models loaded in pure bending

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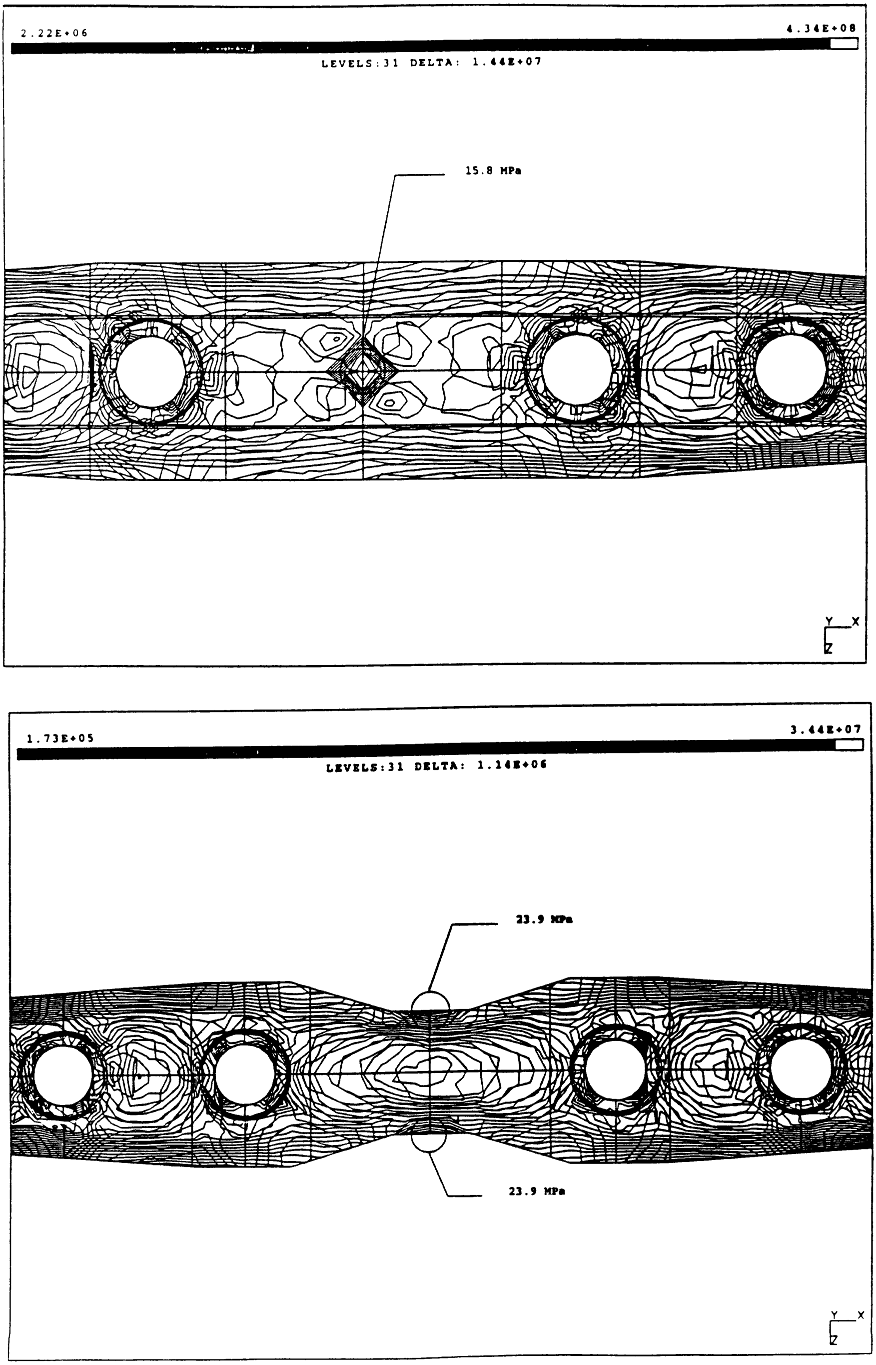

Fig. 3 Von Mises stress distribution on straight edge and waisted fracture plate models loaded in torsion

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