ESTIMATION OF THE TRANSVERSE CRUSH RESISTANCE OF A SECTION OF THE T23 FRIGATE

Dr. GS Kalsi
Royal Military College of Science, Cranfield University, UK

Introduction

Ocean-going vessels are very complex structures, and can have displacements ranging from hundreds to tens of thousands of tons. In the case of bulk carriers and tankers, this can be as much as half-a-million tons. When in motion, they can possess very large amounts of kinetic energy even if their velocities are small. They therefore have the potential to cause serious damage in case they are involved in a collision.

Ships moving in ports or harbours often move in limited space and there is always the possibility that an accidental collision may occur, albeit at a low velocity. If either the striking or struck ship carries sensitive or hazardous materials then the consequences of a collision may be far more serious than that consisting simply of structural damage to either ship. One way of reducing potential damage to ships carrying such cargo is to restrict the travel velocities of approaching ships to some limiting values. The reliable estimation of such velocities needs as a minimum a knowledge of the crush characteristics of at least the target vessel, and preferably that of the striking vessel too.

The situation addressed in this paper is one where a moored vessel, a T23 frigate, is struck normally by a similar moving vessel. It is required to estimate the crush characteristics of the struck vessel around the chosen impact location. A knowledge of the crush characteristics can then be used to derive limiting approach velocities in order to minimise damage, intrusion, etc. in the struck vessel. A three-dimensional mesh of the struck section of the moored ship has been modelled using finite elements. The implicit algorithms in LS-DYNA3D(1) were used to simulate the crushing of this ship section. The paper presents the method of analysis and the derived crush characteristic, which is then used to estimate limiting velocities for an approaching vessel

Aspects of Ship Collisions

A struck ship is subject to a wide range of loads depending on the size, shape and stiffness of a striking ship. Its own hull is a complex structural system consisting of plating attached through welding to longitudinal stiffeners, transverse frames, and bulkheads, and in the case of double-hull ships, web girders. Under the collision forces, each component of its hull deforms and fails in its own way, whilst also interacting with its neighbouring elements. This whole process of progressive deformations makes for a very complex structural response problem. Numerical studies (2) tend to show that the largest part of the absorbed energy is consumed by the side shell plating, although its energy absorption per weight is smaller than for the transverse web members. Material and weld characteristics have also been found to be important parameters with regard to damage resistance of the side structure. In this regard it was found (3) that in side shells built from higher strength steel without reducing the original plate thickness, the energy absorbed is some 25% greater than that absorbed by a side shell made from mild steel.

A similarly complex structural problem can be posed by the deformations occurring in the striking ship. Hull-to-hull contact may give rise to a pattern of structural deformations similar to those of the struck ship, depending on relative strengths. But for collisions involving a bow strike, the possible crushing of the bow presents a complicated structural problem. In the case of a normal impact between a hull and a bow, the damage developed depends on the structural arrangement of the ship side and the location of the strike relative to the transverse web frames and bulkheads, and on the strength of a striking bow compared with the strength of the struck side.

Generally, a stiff bow absorbs very little energy so that most of the kinetic energy lost during impact is absorbed by the side of the struck ship. On the other hand, a weak bow generally absorbs most of the kinetic energy lost during a collision, leaving the side of the struck ship essentially undamaged.

The primary factor which controls the extent of damage which may develop during ship collisions is the kinetic energy which the ships posses. The more this can be reduced, the lesser the damage which will be developed. For an acceptable kinetic energy envelope, it is clear that the larger the mass of the ship the lower must be its velocity. Any impact between vessels must consider a number of factors, the most important of which are the relative velocity at impact, the mutual attitudes at impact, and the relative stiffnesses of the vessels, both local and remote from the impact site. Other factors that are significant are the displacements and draughts of the ships, the shape of the attacking bow, etc.

Brief Review of Modelling Approaches

Consider the case of a bow impact onto the side of a stationary ship. Assuming that the bow and hull both crush, then a very complicated problem exists wherein the contact area between the struck and the striking ships is changing with time, where very large plastic strains and deformations are occurring, possibly accompanied by buckling and rupture of the interacting structural members. In case the target ship can move under the impact, then further complications arise due to the ship motions occurring during collision. A realistic solution under these circumstances would require the calculation of the motions of both the ships in the analysis loop, including the effects of the surrounding water. To obtain the complete reaction forces between the striking and struck ships, a ship motion analysis and calculation of the hydrodynamic forces are needed.

Due to the earlier lack of advanced computer codes which could treat such problems, various simplified approaches have been used in the industry for many years. Clearly a large number of simplifying assumptions have had to be made in order to derive a usable approach. Even though these are labelled ‘simplified’, models based on rigid-plastic methods are still fairly complicated.

Minorsky's Method

Minorsky's approach (4) used rigid body mechanics together with the conservation of energy and momentum principles to estimate the kinetic energy lost during a collision between two vessels. Based on available accident data, Minorsky was able to develop a straight-line relationship between the kinetic energy dissipated and the volume of material damaged during a collision as shown in Figure 1. This 'global approach' relationship has been used over many years to derive estimates of the likely damage which could occur during ship collisions. However for better insight the behaviour of detailed components such as side shells, bottom shells, bulkheads, decks, girders, and transverse members is required. Also work has shown that consideration of material failure modes is important.

Rigid-Plastic Methods

In the bulk of the work done on ship collisions using these methods the assumption has been made that the attacking bow is rigid (5), and absorbs no energy. Alternatively, an arbitrary percentage (6) of the incident kinetic energy, e.g. 25%, is assumed to be absorbed in crushing the bow, but in the analysis the bow is still represented as rigid. This simplifies the collision problem significantly as the evolution of the ships' contacting surfaces is totally ignored. One is then left with the problem of assessing the load-deformation characteristics of the struck hull. The way this is done is to take a representative section of the ship consisting of hull plate, transverse frames, bulkheads, decking, webs, etc. To keep the model simple it is usually assumed that the material behaves in a rigid-plastic manner, and any dynamic strain-rate enhancement is often neglected as it complicates the models.

The plastic energy absorption characteristics of each of the structural members that can deform during collision is then estimated using plasticity theory and any available load-deflection relations. Essentially this consists of a load-deformation curve, and the area under the curve represents the energy absorbing capacity of the member. A global model for the response of the struck side can then be produced by assembling such sub-models together. If sufficient numbers of contributing elements are used then such a model can grow to considerable complexity. A total load-deflection curve for the complete model then gives an estimate of the energy absorbing capacity of the side of the ship. Comparing this with the incident energy of collision can provide an estimate of the likely damage to the struck ship.

Finite Element Methods

Finite element computer programs have been used in engineering analysis for nearly forty years. The early approaches based on the 'stiffness method' were developed for use in the aerospace industry. A number of codes have been developed to simulate material behaviour in the non-linear range, so that plastic effects can be studied. Problems involving very large plastic strains and gross deformations fall into a class of their own, and require specialist codes to treat them. Usually these problems also involve buckling and collapse of components, and the failure of structural fabrication materials. Another common feature is that contact between bodies such as during collision is usually involved in such problems and robust, automated contact logic algorithms are required in order to track the development of evolving contact surfaces and the transfer of momentum between the bodies.

A small number of computer programs is available which have the capability of performing such analyses. The earliest and probably the best known of these, DYNA3D (7) and NIKE3D (8), were originally developed for military applications where problems having the characteristics described above are common and urgent.

In ship collision situations the kinetic energy of impact is mostly dissipated by doing plastic work in deforming and possibly tearing metal plates and other structures. So it is important that the fabrication materials are accurately represented in any finite element models developed for use with codes such as those described. This means that the constitutive behaviour of the materials, e.g. the yield stress and the post-yield behaviour, must be well known. Equally care must be taken when generating finite element models to represent the correct volumes of materials, particularly at locations close to the impact sites.

Unlike simplified and rigid-plastic methods, finite element methods can give greater insight by providing information on time histories of impact forces, deformations, and stress/strain distributions, etc., throughout the duration of analysis. A fuller review of modelling approaches is given in (9).

Postulated Impact Scenario and Related Considerations

This paper is concerned with collision between a moving and a berthed vessel, both of which are assumed to be T23 frigates. A normal collision is assumed to occur close to the location of the 4.5" magazine aboard the berthed T23 frigate. Assuming a rigid jetty, the struck ship cannot move and so it does not dissipate any energy in acquiring a velocity. Therefore the bulk of the impact energy has to be dissipated in the crushing of the two vessels, with the attacking ship ultimately retaining perhaps some kinetic energy depending on the attitude at impact and the degree of damage inflicted. In a normal collision between the side of the struck ship and the bow of the striking ship it is unlikely that much of the incident energy will remain as kinetic energy at the end of the collision event due to the intensity and extent of the impact damage. For oblique or glancing blows the structural damage will naturally be less severe, all other factors remaining constant. In this scenario one can largely neglect the effects of added mass and drag forces on the struck ship.

Figure 2 shows an elevation view of a T23. The area of interest is that shown as unit 22, since the 4.5” magazine lies within this unit. A strong gun-ring bulkhead and stiffened deck structures also exist in and near this unit, which helps to stiffen the ship structure locally. The magazine store itself is situated fairly low in the ship, below deck 2. Therefore before any direct contact can occur between the magazine hull and the striking vessel, the upper structures of the struck T23 will have to be crushed and pushed inwards. This process will consume a large amount of the kinetic energy which the striking ship possesses. Whether or not the magazine hull is damaged by the striking vessel depends on the crush capability of the struck T23 in the vicinity of the magazine, and on the kinetic energy of the striking vessel. Hence the need to evaluate the crush characteristics of this section of the T23.

Particularly when considering normal or near-normal impacts, the characteristics of the bow of the striking ship become an important factor. If the bow is sharp and very stiff then in near-normal impacts it is very likely to pierce through the hull of the struck ship, and the latter can provide very little resistance to the impact and might even be sliced in two. Partly for reasons of simplification, in the work reported here it has been assumed that this situation does not apply. The bow of the T23 is likely to crush to some degree under the impact, and so spread the load over a wider area of the struck hull. It has been assumed that the T23 becomes ‘hard’ and uncrushable a short distance ahead of the location of the 4.5” gun, where this width is approximately 5m. So in near-normal impacts one could assume that the impact loads would be spread over roughly this width.

On examining the elevations of the T23, it becomes clear that first contact between similar ships will be at the top deck level. Only once the top deck, its transverse stiffening beams, and the hull main frames have been pushed sufficiently far sideways will contact occur at the next deck level, and so forth towards the lower decks. So as the impact develops more and more of the struck ship’s structure will interact with the striking ship and help dissipate the imposed kinetic energy. These and other relevant considerations have been taken into account in developing the analysis model described below

The Finite Element Model

In terms of the T23’s structure, unit 22 is situated between frames 17.5 and 26.5, as indicated in Figure 3, which shows frame and deck locations. Unit 22 spanning between frames 18 through to frame 26 has been modelled with finite elements using INGRID (10), which is a pre-processor developed to generate models for the DYNA and NIKE family of codes. The distance between the centre-lines of these two frames is 5.6m.

All the primary structural and load-bearing features present in unit 22 have been represented in the finite element model. Figure 4 shows a view of the finite element model looking forward. In order to reduce the model size the hull frame has not been modelled right down to the bottom of the ship, but it has been taken sufficiently far to not affect the response of the model at the loaded regions. The various decks and some of the bulkheads which have been modelled can be seen in this Figure, as well as the representation of the gun-ring bulkhead, which is the cylindrical structure. The latter plays an important role in stiffening decks 1 and 1A against premature buckling. Similarly to the gun-ring bulkhead, other transverse and longitudinal bulkheads also enhance the crush resistance of the ship section. However not all these bulkheads are symmetrically located in unit 22. In reality the postulated impact can occur on either side of the ship, but in the model it has been assumed that the impact occurs on the starboard side. In order to provide conservatism in the analysis, no unsymmetric bulkheads have been included in the model.

The structural arrangement in unit 22 is typical of ship structures, i.e. steel plating stiffened with various kinds of beams, e.g. T-beams, obp.s’, etc. The plating has been modelled using shell elements, whilst the various stiffeners have been represented with beam elements. The major resistance to transverse crushing is provided by the (deck) transverse beams and the main frames that support the hull. For clarity, these are shown in Figure 5, without displaying the main longitudinal beams or the attached sheeting.

With regard to the mesh discretisation used in the finite element model, a finer mesh has been used on the impacting side than on the port side. The element sizes used are quite small on the impacting side, the smallest being of the order of 30cm. The purpose of this analysis is to obtain a first estimate of the crush behaviour of unit 22, and not to provide a detailed stress analysis of the various structural components.

Boundary Conditions

At the base of the model the nodes have been fixed against all movement. Thus the port and starboard hulls and their attached frames are rigidly constrained against all movement at this level. On the port side, the model is allowed no movement in the horizontal direction. As the ship is assumed to be berthed tight against the quayside in reality, it will be unable to translate laterally but will probably rotate under impact, dissipating some of the incident energy in motion. This rotation has been prevented in order to maximise the loading on the structural components, so that a conservative solution will be calculated.

Sliding planes exist at the front and rear of the model, transverse to the longitudinal axis of the model. This constrains nodes lying at the locations of frames 18 and 26 to move in these planes and they cannot depart from them. As any finite element model has to be restricted in size, conditions such as these are imposed to approximate the continuity of the structure.

The load has been applied on the starboard side of the model using a moving stonewall. At the beginning of the analysis this stonewall has been positioned to be in touch with the ship at top deck level, frame 26, and it is parallel to the vertical plane passing through the (longitudinal) centre-line of the ship. During analysis it maintains this attitude whilst it continues to move inwards towards the centre-line of the ship, its motion being resisted by the ship's modelled structure. As the top deck deforms lower parts of the hull around frame 26 come into contact with the stonewall, adding to the resistance. As these get crushed the stonewall progressively makes contact at top deck level with frames 25, 24, etc. in the direction of frame 18. Contact progressively also develops towards the lower decks at these frames as the ship section buckles.

Material Modelling

Steel is the only material model that has been represented in the finite element model, as only mild and high strength steels have been used in the construction of unit 22. The behaviour of both types of steel has been represented in the model with an elasto-plastic linear-hardening constitutive law. The appropriate material constants have been used to define the characteristics of mild and high strength steels. No material failure through rupture is allowed in the model. The inclusion of this refinement would have complicated the analysis needlessly without probably adding much to the information that has been obtained by neglecting material rupture. It is likely that material rupture will be considered in future studies.

Results and Discussion

The analysis was somewhat arbitrarily terminated when the lateral displacement of the stonewall had reached just over 1.9m.

The initial deformations occur near frame 26 as the stonewall pushes against the hull. With increased displacement of the stonewall the transverse beams and deck1 plating around frame 26 buckle, and permit frame 26 to bend inwards. As the upper part of frame 26 does so, its lower part comes into contact with the stonewall, and eventually contact is made between the stonewall and structure at deck1A level and below.

At the same time as the stonewall develops contact downwards along the hull, it also progressively makes contact with frames 25, 24,... etc. at the top deck level. Once the top deck and transverse beams buckle at these frames the stonewall pushes against the lower part of the hull, towards deck1A and below. So with time an increasing extent of unit 22 undergoes buckling and bending deformations. These progressive deformations are shown in Figure 6.

The amount of energy absorbed in the plastic deformations which develop in unit 22 is given by the area under the curve shown in Figure 7. In this Figure the horizontal axis represents the displacement of the stonewall, or that of the top deck at frame 26. This curve provides an estimate of the transverse crush resistance of unit 22. It may be used to calculate the extent of damage to be expected when a T23 is impacted in the vicinity of unit 22 by a vessel of mass m_o moving at a velocity of v_o. This is based on the premise that the magnitudes and patterns of plastic deformations likely to be produced during such an impact are similar to those caused by the moving stonewall. Clearly where the deformations are going to be significantly different then care will be needed in using the relationship presented in this Figure. However, the generation of this relationship is an improvement over the existing state of affairs as it provides a basis upon which to make reasonable assessments.

Application of Crush Characteristic

Consider an impact which takes place with a T23 moving at velocity v_o as shown in Figure 8. The velocity v_o is directed at an angle θ to a plane sited at the initial location of the stonewall. It is further assumed that the only component of velocity that causes damage to unit 22 is that normal to the plane A-A. Then the damage-causing component of the kinetic energy of the moving vessel is given by

$$\frac{1}{2}(m_o + m_a)(v_o \sin\theta)^2 \tag{1}$$

where m_a is the added mass of water associated with the moving ship.

If one assumes that the total crush resistance is denoted by the area under the curve, then

$$\frac{1}{2}(m_o + m_a)(v_o \sin\theta)^2 = \text{area under the load-deformation curve}$$

$$= Z \text{ MN-m, say} \tag{2}$$

Taking the mass of a moving T23 to be 2500T, and the associated added mass to be 50% of this value, Equation (2) can be reduced to

$$v_o = cosec\theta \;\; \text{x } 0.730\text{x}Z^{0.5} \text{ m/s} \tag{3}$$

In these calculations it is implicitly assumed that all the damage-causing kinetic energy of the moving vessel is imparted to the target. In reality some of it will be dissipated in the crushing which can be expected to develop in the striking vessel. This should be borne in mind when calculations such as shown here are made.

On the basis that the area under the curve in Figure 7 represents the maximum damage that can be sustained by unit 22, then equation (3) gives limiting velocities at which the moving T23 could in theory be allowed to travel at the moment of impact. Note that no ‘factors of safety’ have been applied to these velocities thus far. Fuller details of the analysis described here are given in (11).

Discussion

The limiting velocities calculated as indicated will be based on the assumption that the crush characteristic applies equally to impacts at various angles. This is not necessarily true in all cases. For example if a near-normal impact occurs nearer frame 18 then a weaker response can be expected since the longitudinal bulkhead which exists near frame 26 is not present near frame 18. Hence deck1 can be expected to buckle at lower impact loads than calculated here. However the crush characteristic produced herein has a great deal of value because it can be used as a guide to calculate approximate limiting velocities. What is needed is a little care and some knowledge of the important structural features of unit 22. Further, where a different pattern of deformations is expected to occur, a corresponding factor of safety (or factor for ‘ignorance’) can be applied to the estimated values to arrive at a reasonable approximation.

The load-deformation curve presented in Figure 7 shows the oscillatory behaviour which is typically exhibited by structures which undergo buckling deformations. At analysis termination the curve appears to have flattened off but this is unlikely to be the case: as the stonewall makes contact with a larger area of the ship it will encounter increased resistance, leading to an increase in load, followed by a drop-off as buckling deformations develop. By the time the top deck has buckled inwards by about 1.95m at frame 26, at the level of deck2 there has been no contact with the stonewall. The latter still needs to travel some distance before this contact can occur, and allow the magazine to come under impact loads. Hence an increase in the crush resistance can be expected if the analysis were to be continued further, to some point at which no additional resistance is available.

The crush characteristic has been derived assuming possible contact along the length of the hull between frames 26 and 18. If this contact distance were to be reduced then clearly a greater indentation into unit 22 would occur for similar impact loads. Conversely, a reduced crush resistance would exist for the same displacement of the stonewall.

In Equation (3), the added mass has been taken to be 50% of the mass of the moving T23. This added mass is a function of the attitude of a moving vessel and so this 50% value could possibly be reduced, if justified, to give higher velocities.

Conclusions

The work reported here is a first assessment of the crush capability of unit 22. The results of this work have demonstrated that advanced finite element methods can be used to derive the crush characteristics of ship sections, and these can then be used to relatively quickly calculate limiting impact velocities. To provide greater realism, the manner in which the impact loads (and the area over which they) are applied could be improved. In the limit one could model a part of the striking vessel as well, although this would make for a computationally large and complex but ‘do-able’ problem. If the crush characteristics for a variety of striking vessels were derived in a similar manner as in this work it would simplify future calculations and reduce the time required to produce reasonable approximations.

As mentioned earlier the finite element model is of limited extent. This model could in future be extended beyond current boundaries in order to provide a better approximation of the continuity of this or any other ship section. Future work should investigate the influence of material rupture on the crush characteristic and also attempt to model both the plate and weld failures realistically in order to predict the energy absorption with greater accuracy. It is worth mentioning that the element size influences the choice of rupture strain when modelling plate failure in such idealisations.

Acknowledgements

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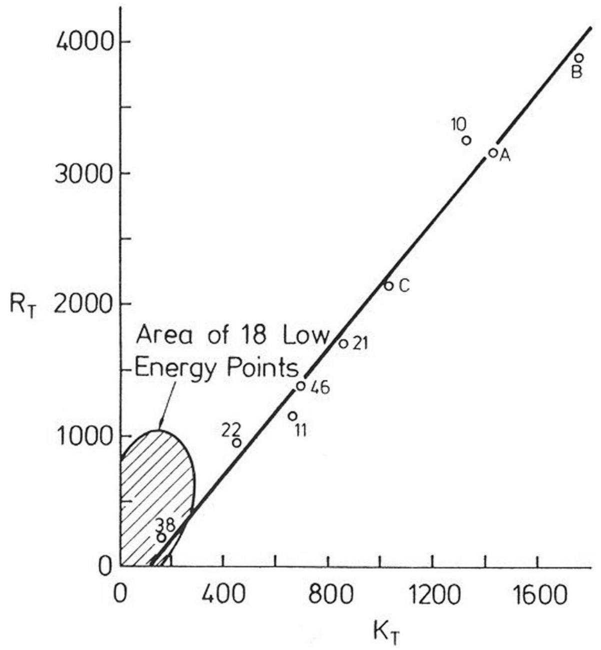

Figure 1: Minorsky's Empirical Correlation Between Resistance Factor (RT) and Kinetic Energy(KT) Absorbed During a Collision

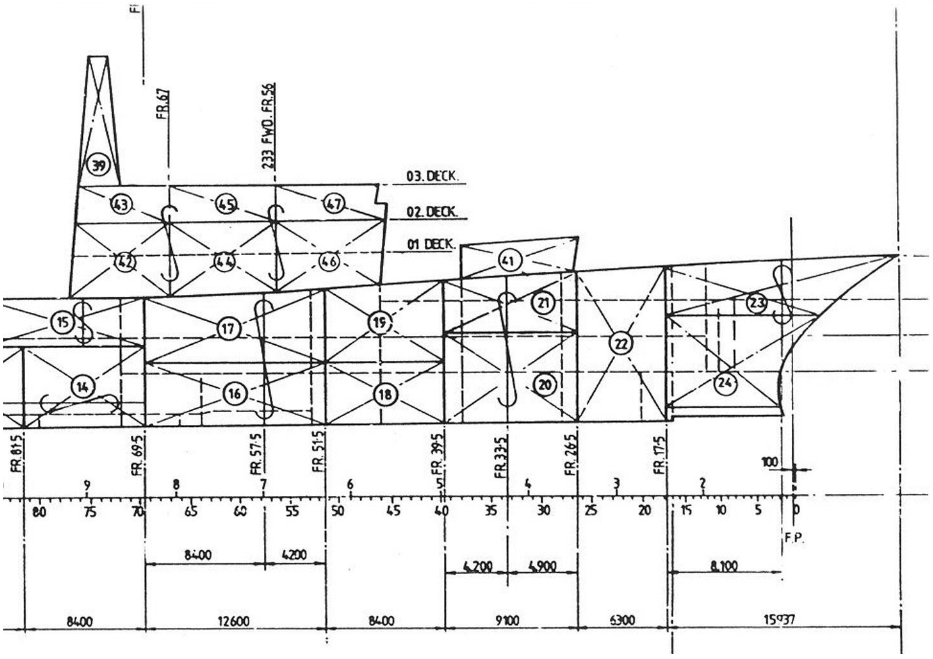

Figure 2: Elevation View Showing Location of Unit 22 within T23 Frigate

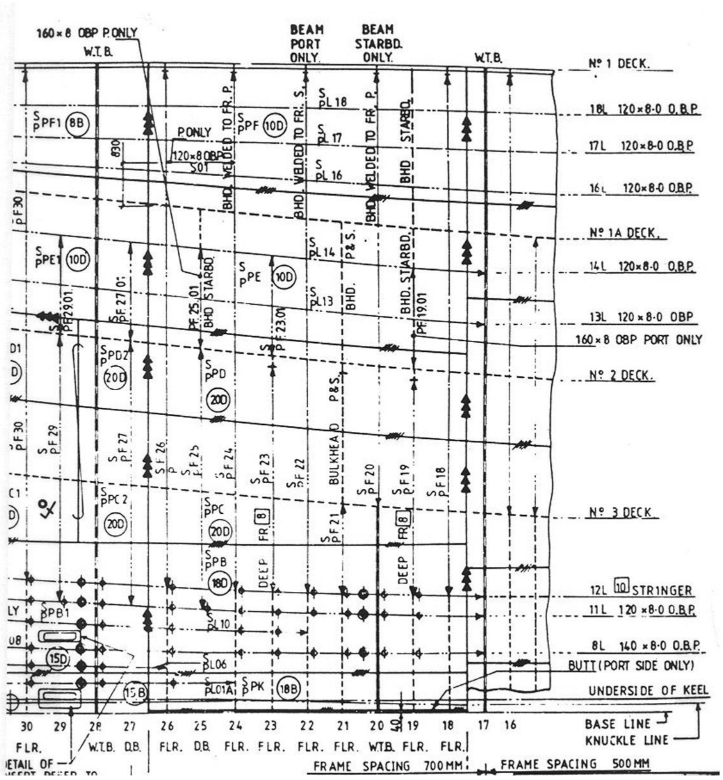

Figure 3: Mainframe and Deck Numbering within Unit 22

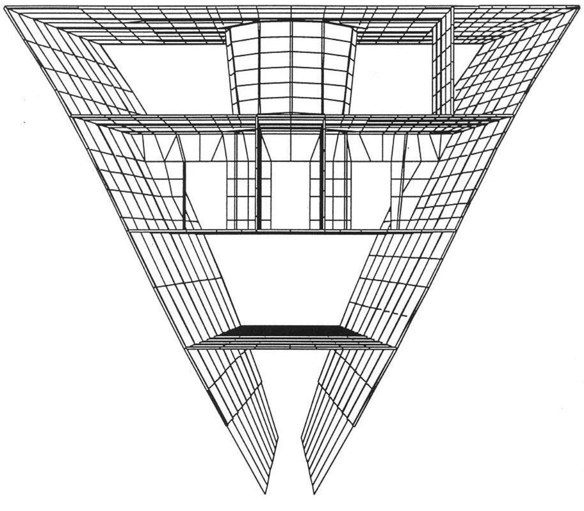

Figure 4: Finite Element Model of Unit 22

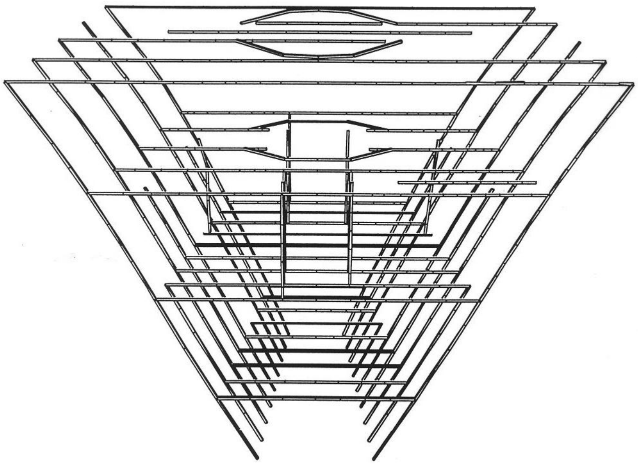

Figure 5: A view of the Main Frames and Transverse Beams (Longitudinal Beams not shown)

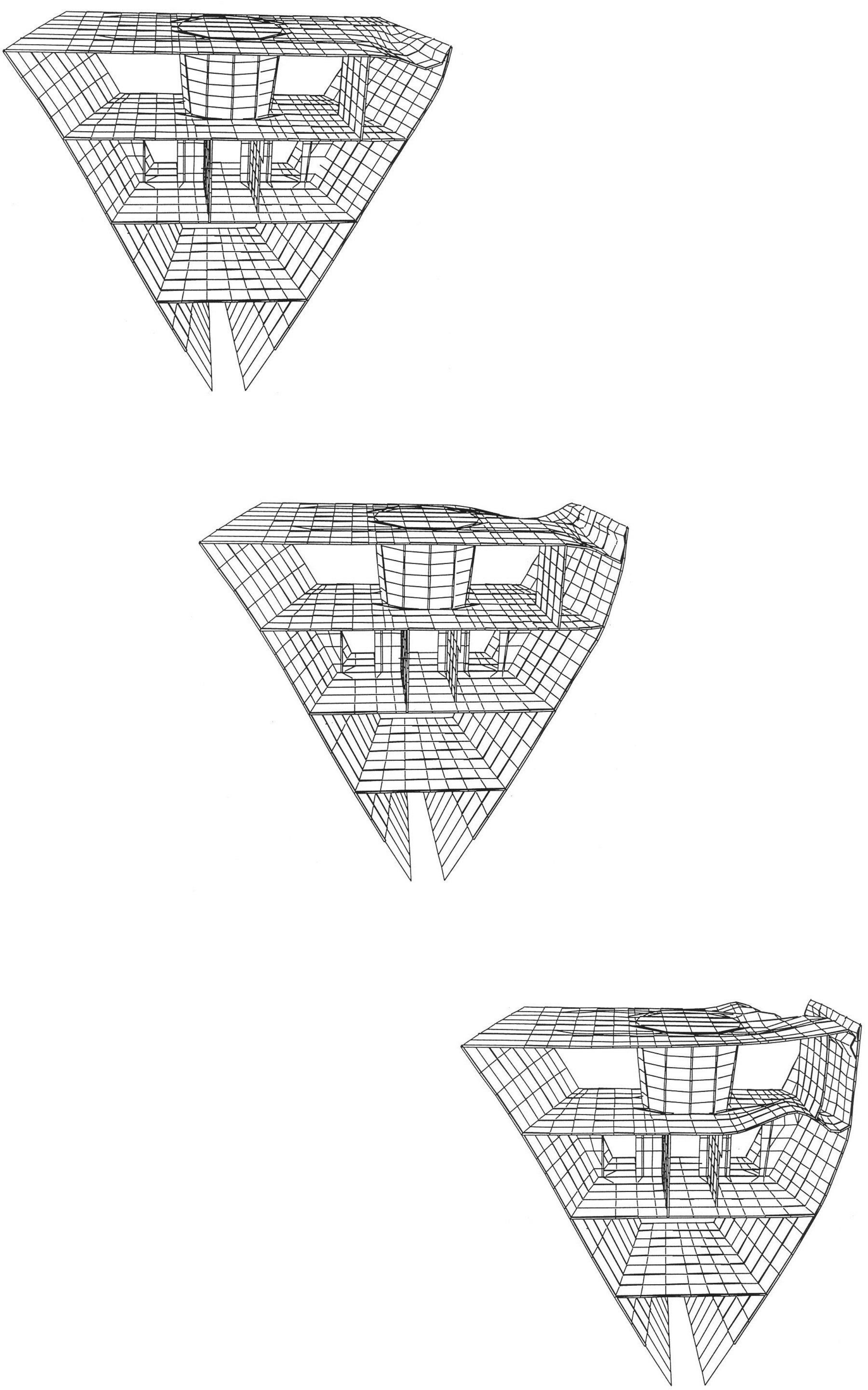

Figure 6: Views of the Progressive Crushing of the Structure of Unit 22

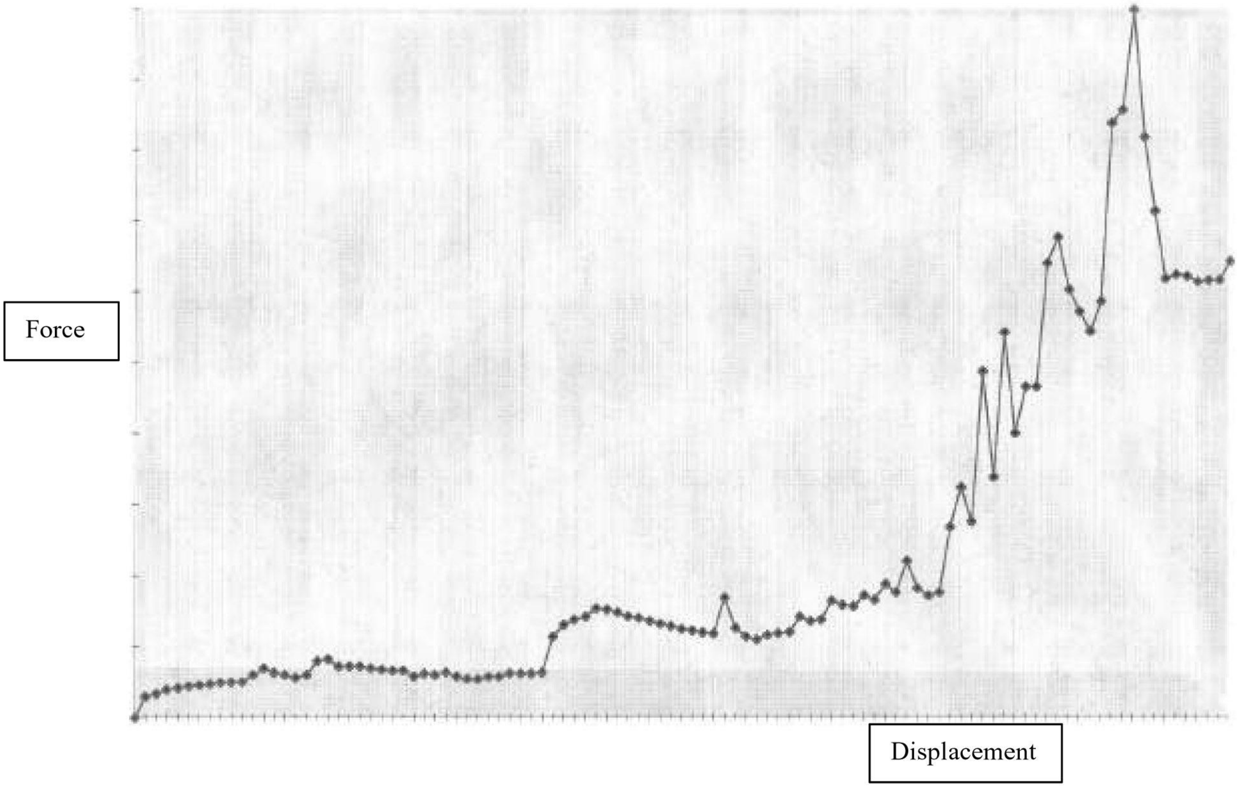

Figure 7: Calculated Load-Deformation Characteristic

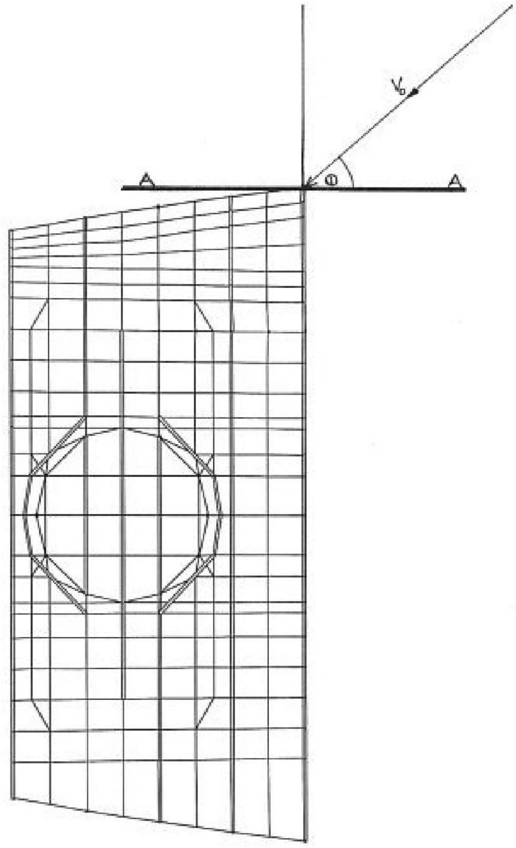

Figure 8: Relative Orientations at Impact