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13 ABSTRACT(MAX 200 WORDS) A LARGE-DEFLECTION DESIGN TECHNIQUE IS PRESENTED FOR THE THIN-WALLED TUBULAR FRAMES WHICH FORM THE SUPERSTRUCTURE OF PASSENGER BUSES. THIS PROCEDURE COULD BE USED AT THE EARLY STAGES OF BUS DESIGN SO THAT POTENTIAL DESIGNS CAN BE QUICKLY EVALUATED TO ASCERTAIN WHETHER THEY MEET THE LEGISLATED OCCUPANT PROTECTION REQUIREMENTS FOR ROLL-OVER ACCIDENTS. THE FAILURE OF SUCH THIN-WALLED FRAMES CAN BE QUITE SUDDEN, THE MAXIMUM LOAD-CARRYING CAPACITY NOT BEING SUSTAINED AND A DROOPING LOAD-DEFLECTION CURVE CHARACTERISTICALLY BEING EXHIBITED ONCE THE MAXIMUM LOAD IS PASSED. CONSEQUENTLY THIS DESIGN TECHNIQUE DETERMINES THE COMPLETE LOAD-DEFLECTION BEHAVIOUR OF A FRAME. THIS IS BECAUSE PROPER CRASHWORTHY DESIGN REQUIRES A DETERMINATION OF A BUS FRAME'S ENERGY ABSORPTION CAPABILITY AND SUDDENNESS OF COLLAPSE, NOT JUST ITS ULTIMATE STRENGTH. THE LOAD-DEFLECTION BEHAVIOUR OF A TWO-DIMENSIONAL FRAME WAS SUCCESSFULLY MODELLED.

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A Large-Deflection Design Technique for Modelling the Collapse of Bus Frames Constructed from Thin-Walled Tubes in Roll-Over Accidents

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SUMMARY

A large-deflection design technique is presented for the thin-walled tubular frames which form the superstructure of passenger buses. This procedure could be used at the early stages of bus design so that potential designs can be quickly evaluated to ascertain whether they meet the legislated occupant protection requirements for roll-over accidents. The failure of such thin-walled frames can be quite sudden, the maximum load-carrying capacity not being sustained and a drooping load-deflection curve characteristically being exhibited once the maximum load is passed. Consequently this design technique determines the complete load-deflection behaviour of a frame. This is because proper crashworthy design requires a determination of a bus frame's energy absorption capability and suddenness of collapse, not just its ultimate strength. The load-deflection behaviour of a two-dimensional frame was successfully modelled.

1. INTRODUCTION

While the behaviour of thin-walled tubes is generally predictable up to the elastic limit, their behaviour in the large-deflection range must also be able to be determined. The upper body-work or superstructure of passenger buses is an example of a thin-walled tubular framework that requires an accurate large-deflection design technique. This is because this framework must protect the occupants of such vehicles in roll-over accidents.

In roll-over accidents bus frames generally fail in bending in a collapse mode involving lateral sway of their side walls. A frame will collapse when a sufficient number of plastic hinges have formed in its component members. Clearly then, a bus structure should be strengthened and even braced to prevent bending and lateral sway. However, bracing may not be possible because of inconvenience to the passengers. Furthermore, a design priority is to maximise the window area for clear unobstructed vision. Because these demands severely limit the options available for designers, the bending strength of the bus frames themselves must be maximised while minimising the weight of the bus for good fuel efficiency. This requires accurate methods for determining the response of such bus frames to the loads encountered in bus roll-over accidents. The collapse of such frames can be quite sudden, the maximum load-carrying capacity not being sustained and a drooping load-deflection curve characteristically being exhibited once the maximum load is passed. While a prediction of the ultimate strength of such frames is useful, proper crashworthy design also requires a determination of the energy absorption capability of a bus frame as well as its suddenness of collapse. This requires a determination of its complete load-deflection behaviour. Possible intrusion of the side-members of the frame into the passenger survival space can also then be modelled.

Unfortunately the gross plastic deformation and geometric distortion that accompanies the formation of plastic hinges in thin-walled sections makes the analysis of collapsing frames particularly difficult by conventional methods. However, their load-deflection behaviour can be predicted to large deflections simply by superimposing separate elastic and rigid-plastic analyses as has been demonstrated in the past for many types of thin-walled sections (1). This paper applies this approach to thin-walled tubular frames.

While bus roll-over accidents are not common in Australia such tragedies still occur from time to time (2),(3). Because of the serious nature of such accidents an Australian Design Rule, ADR 59/00 (4), which is concerned with the roll-over protection of passenger buses, has come into effect as of 1 July 1992. This Design Rule requires that the defined passenger survival space within a passenger compartment not be intruded both during and after a standard roll-over test or equivalent simulation. This involves a bus rolling off a 0.8 m high platform onto a rigid lower base. The modelling method described in this paper is aimed at providing a method that can be used at the early stages of design to quickly evaluate whether potential vehicle designs have adequate roll-over protection (5). While a frame made from square thin-walled tubes is modelled because many passenger buses are made from this material, this technique also has application for the design of any thin-walled structure that displays drooping load-deflection behaviour and requires a large-deflection design technique.

2. MODELLING THE ROLL-OVER OF A PASSENGER BUS

To define and standardise the effects of a roll-over accident for modelling purposes, it is reasonable to adopt the definition of the standard roll-over test described in ADR 59/00 (4). The rolling over of a bus from a 0.8 m high platform to the rigid lower base involves a loss of potential energy that becomes the kinetic energy of the vehicle. The bus superstructure must absorb this energy by plastic deformation to bring the bus to rest.

A reasonable first approximation is to analyse the deformation of a bus in a static manner, ignoring dynamic effects (6). Bus roll-over accidents are particularly suited to static analyses because most bus roll-overs tend to occur laterally at low speeds (7),(8). Inertial effects can be neglected because the deformation is largely confined to the superstructure ot the bus, while most of the bus's mass is concentrated close to the floor. In addition, at least for square thin-walled tubes, the dynamic collapse modes in bending are the same as the static ones (9). Moreover, the dynamic enhancement of the material yield stress and the flow stress at large plastic strains can be accounted for to some extent by known multiplicative factors, e.g. (10).

When a bus rolls over. a roof corner first contacts the ground. For typical Australian buses, the line of action of the resulting load passes through the roof corner and is inclined at about 15° from the horizontal. This is equivalent to a load applied at an angle 15° downward to an upright bus frame. The horizontal load component is the most important component of the applied load in a lateral roll-over (6),(7),(11), being far, more critical than the vertical crush load on the roof due to the vehicle self-weight (12). Bus designs that can withstand the vehicle's static self-weight are usually strong enough to prevent roof crush in the relatively few accidents where the vehicle 'flips over' directly onto its roof without impacting the side wall (6). The horizontal load component will cause the bus frame to sway laterally.

As a first approximation, a three-dimensional passenger bus can be modelled as a combination of statically loaded two-dimensional frames (5). This approach is possible because of the prismatic rectangular shape of a full three-dimensional bus. The energy absorption of each component frame can be simply added to obtain the total energy absorption of a deforming bus. This assumes that the whole length of a bus contacts the ground at the same time and deforms evenly. Although this assumption is idealised, it is part of approved modelling procedures (13),(14),(15).

An advantage of the two-dimensional approach is that it is relatively easy to combine results from various types of two-dimensional bus frames to satisfy the particular energy absorption requirements of different variants of a specific type of bus (16). This approach negates the need for an excessive numberof expensive full-scale roll-overtests orthree-dimensional analyses. Two-dimensional analysis, therefore, is a satisfactory first-order means of designing buses to meet the requirements of ADR 59/00 (4). In practice, however, real bus frames must also be tested to confirm model predict ions because the actual strengt h of such frames strongly depends on intangibles such as the strength of the joints and connections whose behaviour to large deflections is difficult to predict (5).

In general, two-dimensional frame analysis will be conservative as longitudinal contributions to the strength of the overall bus frame are neglected. For instance, a strong longitudinal waist rail would be beneficial in buses that have individual frames of unequal strength along their length. This is because part of the bending resistance of the stronger frames is shared with the weaker frames. In fact, other workers have modified two-dimensional analyses to accommodate the strengthening effect of strong longitudinal waist rails which in certain cases can cause plastic hinges to form above the waist rails (14). It is particularly important that the assumed collapse mode of a two-dimensional bus frame should be the same as that which occurs in practice. The importance of thisfactorwill be in discussed in a later section.

3. THE STRUCTURAL COLLAPSE OF A BUS FRAME

The response of a bus frame to a roll-over accident is best quantified by its load-displacement behaviour, measured from the point near the roof which first contacts the ground. A schematic load-displacement response is shown in Fig. 1. The bus frame initially responds in elastic bending which is then followed by a loss of stiffness caused by plastic deformation in the various component members and joints of the structure. Eventually, as plasticity is developed across the cross-section of a component member, plastic hinges are formed, and these effectively act as hinges in the frame. The plastic hinges that form in thin-walled members are best described as local plastic collapse mechanisms (1), because they involve large localised plastic deformations, with geometrical folding and significant changes in their cross-sectional profile. When a sufficient numberof plastic hinges haveformed in a frame to enable it to be a kinematically movable system, structural collapse occurs. Structural collapse occurs by the frame pivoting or hinging about its plastic hinges, all further deformation being concentrated in these locations. Since the strength of local plastic collapse mechanisms diminishes with deformation, a drooping load-displacement curve is exhibited by the frame beyond the peak load. The fall in the strength of the frame causes the component members of the structure to unload with further deformation. This is reflected in the recovery of the elastically stressed portions of the frame.

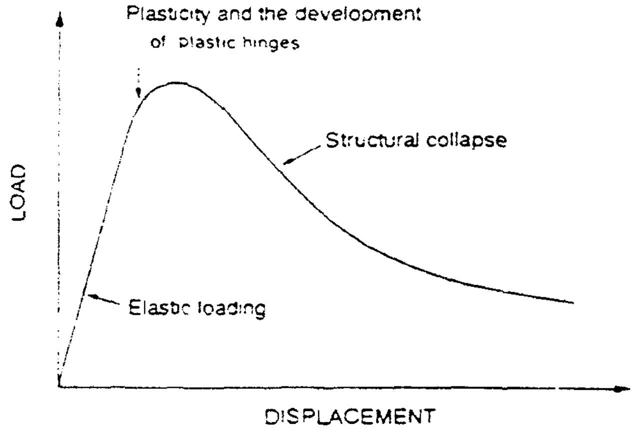

Figure 1: Schematic load-displacement curve for a collapsing bus frame.

The total area under a load-displacement curve, such as Fig. 1, is equivalent to the energy absorbed by the deforming bus structure. In a simulation of an actual roll-over the total energy absorbed by the bus at the point at which the residual passenger survival space is intruded should be equal to or greater than the kinetic energy of the rolling bus. This is implicit in ADR 59/00 (4). The other criteria important in bus frame design, viz, ultimate strength and suddenness of collapse, can be obtained from such a load-displacement curve.

4. EXPERIMENTAL DETERMINATION OF SECTION BENDING PROPERTIES AND BUS FRAME LOAD-DEFLECTION BEHAVIOUR

4.1. Frame Testing

An idealised bus frame was tested to confirm the validity of the model predictions (5). The experimental load-displacement response of the frame was obtained by simply displacing the frame by means of a hydraulic tension jack that pulled from an initial angle of 15°. The applied load and the movement of its point of application were measured as deformation proceeded.

4.2. Large-Deflection Bending Properties of Square Thin-Walled Tubes

The bending properties of the square thin-walled tubes from which the frame was constructed had to be characterised into the large-deflection range. This is not straightforward because of the large member rotations that the tubes must undergo as they form local plastic collapse mechanisms.

Cantilever bending is commonly used to obtain collapse curves of thin-walled sections but the method usually has a number of limitations (5). The main problem is that the eventual plastic collapse mechanism will be initiated at the root of the cantilever where the maximum moment is found. The plastic collapse mechanism forms in a region of non-constant bending moment which makes its characterisation difficult. Furthermore the magnitude of the moment in the vicinity of collapse is usually uncertain because the length of the moment-arm is ill-defined in the transition from elastic bending to the initial development of a localised plastic collapse mechanism. To overcome these problems, a unique pure bending rig was constructed which stressed a tubular specimen in a state of pure bending, and maintained a constant bendingmomentoverthecentralportionofthespecimen to large rotations beyond bending collapse. This rig and the details of the experiments are described elsewhere (5) ,(17). One important feature of this bending rig was the minimisation of the development of tensile forces in the test specimens.

Fig. 2 is a typical moment-rotation curve that was obtained for a square tube in pure bending. The ends of the tube were made rigid by the insertion of solid square bars. A 100 mm deformable length was left in the centre of the tube into which the local plastic collapse mechanism could initiate and develop (5),(17). For a specimen of such a deformable length, the elastic properties are negligible, Fig. 2 being a measure of the moment-rotation properties of the local plastic collapse mechanism that forms in a tube of this length. The main advantage of the pure bending rig is that it allows the extent of the constant moment bending prior to collapse to be meaningfully and easily measured. It is also seen that an enormous amount of energy can be absorbed by a member after the point of collapse. The key information from such a moment-rotation curve that is required for modelling purposes is: the collapse curve (obtained by curve fitting), the maximum load and importantly, the angle at which collapse occurs.

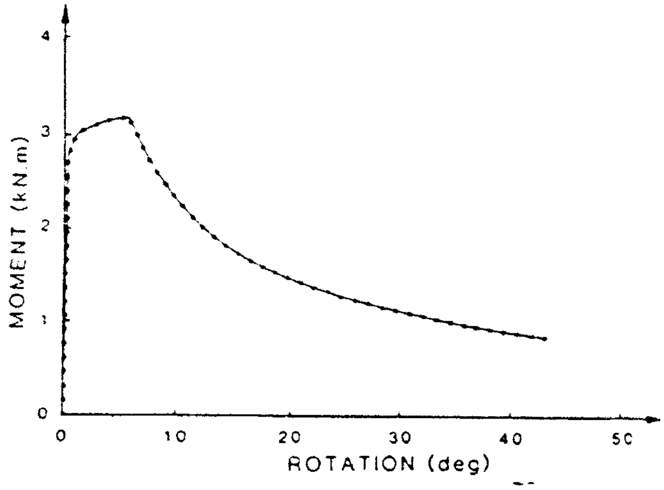

Figure 2: Typical pure bending moment-rotation curve for a 50x50x2 mm square tube.

5. MODELLING BY SUPERIMPOSING SEPARATE ELASTIC AND RIGID-PLASTIC TECHNIQUES

5.1. Elastic Model of Frame

The direct stiffness method was used to derive a simple elastic model (5) for rectangular frames that are subjected to a load horizontally applied at a roof-member side-pillar joint, Fig. 3. Only the horizontal component of the applied load was considered to have a significant effect on the elastic sway of the frame. While the effect of the vertical component of load will increase as deformation proceeds due to the P-δ Effect (1), this constituent was considered negligible for elastic deformation and therefore ignored. Assuming the rotation at each corner of the frame was equal, the following equations were obtained:

$$4khl\theta + 6h^2\theta - 6kl\delta = 0 \qquad (1)$$

$$\frac{Ph^3}{EI} = -12kh\theta + 24k\delta \qquad (2),$$

where P is the horizontal load, θ is the rotation at each top corner of the frame and δ is the lateral sway of the roof. The frame to be modelled has the following material and geometric properties: Young's Modulus, E, 206x10^6 kNm^{-2}, Moment of Inertia I,147712x10^{-12}m^4,h=1.025 m, 1=1.180 m, and k=1. The above equations were solved to obtain the elastic response of the frame:

$$P = 457.3\delta \qquad (3)$$

where P is in kN and δ is in mm

For a frame of the above specifications, the maximum moment at the fixed ends of the side-members can be obtained:

$$M = 0.30305P$$

where M is in kNm and P is in kN

The point of first-yield in this frame can be determined from equation 4. The yield-moment of 2.60 kNm is reached at the base of the frame when the applied load is 8.6 kN.

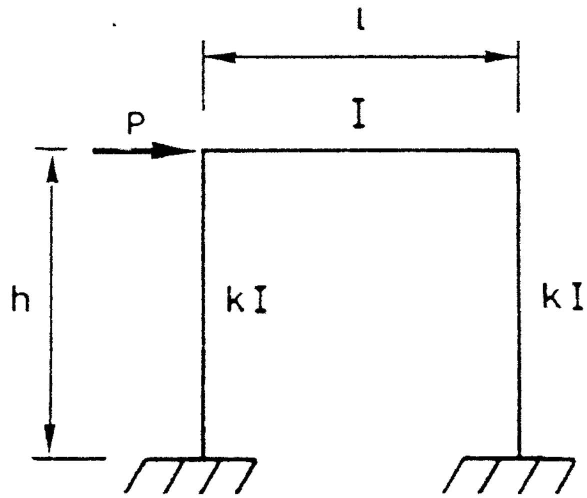

Figure 3: Geometry for the elastic model of a two-dimensional frame of height, h, and width, l. that is subjected to a horizontal load, P. The ratio of the moment of inertia of the side-pillars to the roof-member is k.

5.2. Rigid-plastic Model of Frame

A method of frame analysis used in structural engineering, termed simple plastic analysis, is commonly used to estimate the ultimate load-carrying capacity of steel structures (18). This technique was extended into the large-deflection range to form the basis of a rigid-plastic modelling procedure for modelling the complete load-deflection behaviour of collapsing frames (5). Such rigid-plastic modelling requires that the following assumptions be made: all deformation after collapse occurs at the locations of the plastic hinges; and, upon collapse, the frame behaves as a mechanism with all four plastic hinges connected by rigid-links.

It is easy to predict by inspection that four plastic hinges, approximately located at the four corners of the frame, will be required to form for structural collapse. For modelling purposes, the plastic hinges were considered to form at the locations found experimentally. Once the plastic hinge locations were defined so too was the frame's deformed geometry. This is because once sufficient plastic hinges form to enable structural collapse to occur, no further plastic hinges initiate. Upon collapse all further deformation is concentrated at the sites of the plastic hinges, the frame behaving as a mechanism, pivoting about four plastic hinges that are assumed to be connected by rigid-members.

Using the deformed geometry of the frame, the static equations of equilibrium for the frame were extended into the collapse regime. The values of the resisting moments of the plastic hinges (obtained experimentally) were then simply inserted into these equations as collapse proceeded. This is an example of a heuristic solution technique, as the problem depends on inductive reasoning from past experience for a solution (19). The precise details of the deformation at the plastic hinges are unimportant. All that is required for a solution are the externally recognised resisting moments of each plastic hinge.

5.2.1. Deformed Geometry

The deformed geometry of the frame can be defined by the positions of the plastic hinges. Fig. 4 shows the initial and assumed deformed geometry. The positions of the plastic hinges are determined as a function of a given hinge rotation, θ:

Hinge A $$x(A) = 0,\ y(A) = 0 \qquad (5)$$

Hinge D $$x(D) = 1.180,\ y(D) = 0 \qquad (6)$$

Hinge B $$x(B) = 0.950\sin\theta \qquad (7)$$

$$y(B) = 0.950\cos\theta \qquad (8)$$

Hinge C $$x(C) = 0.950\sin\theta + 1.105 \qquad (9)$$

$$y(C) = 0.950\cos\theta + 0.075 \qquad (10)$$

where the units for these equations are given in metres. Equations describing the rotation of each plastic hinge were determined from an analysis of the deformed geometry of the frame, Fig. 4(b), on the basis of a given horizontal displacement of the loading point, δ. This causes a rotation, θ, of Hinge A and Hinge B,

$$\theta = \operatorname{asin}(\delta/0.950) \qquad (11)$$

The rotation of Hinge C can be shown by simple geometry to be the angle θc, depicted in Fig. 4(b), i.e.

$$\theta_C = 90 - \operatorname{acos}\left\{\frac{x(C)-x(D)}{\sqrt{(x(C)-x(D))^2 + (y(C)-y(D))^2}}\right\} \qquad (12),$$

where θ is in degrees. The rigid-link between Hinges C and D is effectively the shortest distance between them. However, Hinge D will effectively experience the same rotation, θ, as Hinge A and Hinge B.

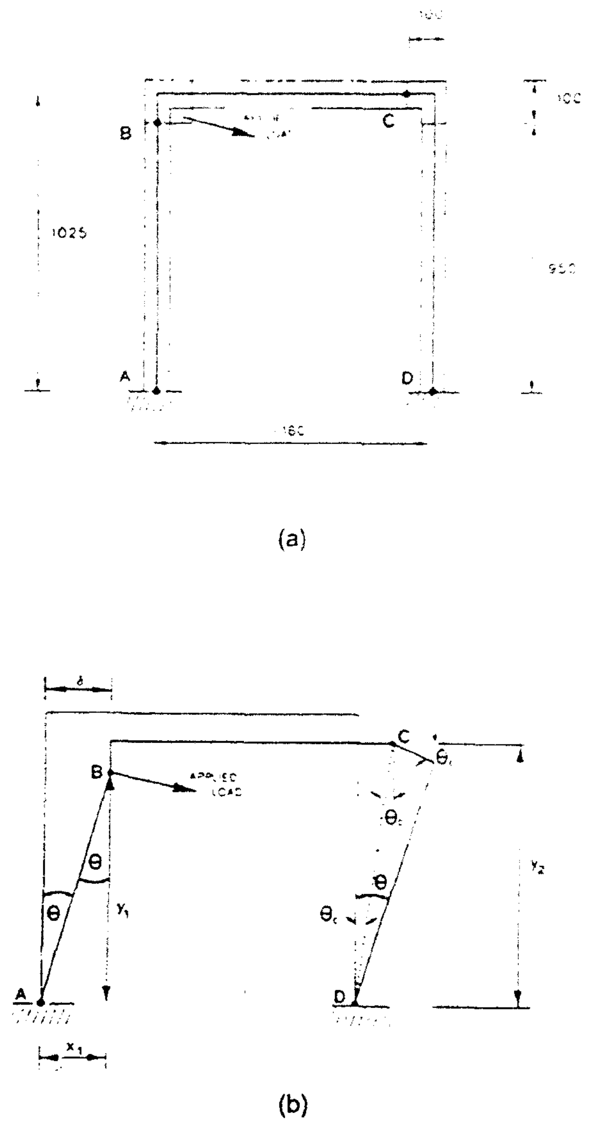

Figure 4: Initial frame geometry, (a), and deformed geometry, (b). δ is the horizontal displacement of the loading point. All dimensions in mm.

5.2.2. Resisting moment

The resisting moment was obtained from an empirical model of the moment-rotation curves of a number of different specimens (5), viz,

$$M = 3.12 \qquad \text{for } \theta \le 5.95°$$

$$0.8344 + 4.079e^{-0.09230\theta} \qquad \text{for } 5.95° < \theta \le 42°$$

$$-0.4130 + 0.03080\theta \qquad \text{for } \theta > 42° \qquad (13),$$

where M is in kNm and θ is in degrees. Each local plastic collapse mechanism was assumed to maintain a maximum moment of 3.12 kNm up to 5.95° rotation. When the collapse angle of 5.95° is reached, structural collapse occurs and the collapse portion of the moment-rotation curve is assumed to apply.

5.2.3. Free-body diagram

Static equilibrium equations were derived by treating the members between the plastic hinges as rigid-bodies, ignoring shear effects. Fig. 5 shows the free-body diagrams for the side-members of the frame. To simplify modelling, the loading point was assumed to be located at Hinge B, because the material between the roof and side-members is rigid. The geometry of the free-body diagrams varies according to, x_1, y_1 and y_2, which are:

$$x_1 = x(B)-x(A) \tag{14}$$

$$y_1 = y(B)-y(A) \tag{15}$$

$$y_2 = y(C)-y(D) \tag{16}$$

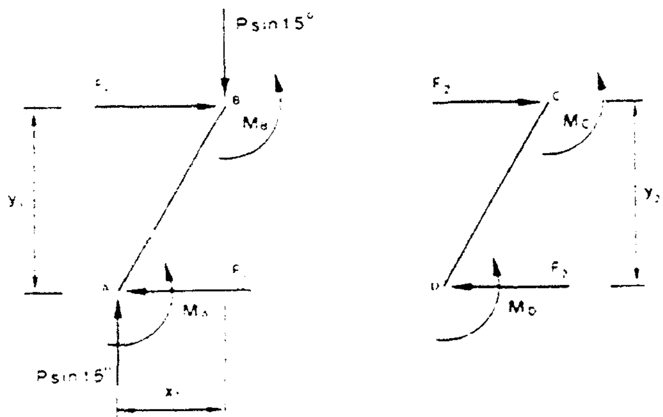

Figure 5: Free-body diagrams for the side members of the frame.

Now assuming that $M_A = M_B = M_D = M$ and that M_C has a different value (because of the different rotation of the plastic hinge), a moment equilibrium about Hinge C in the right side-member is:

$$Mc + M = F_2 y_2$$

$$F_2 = \frac{M + Mc}{y_2} \tag{17}$$

A horizontal force equilibrium for the entire frame is:

$$F_1 = P\cos(15) - F_2 \tag{18}$$

A moment equilibrium about Hinge B in the left side-member is:

$$M + M = F_1 y_1 - P\sin(15)x_1 \tag{19}$$

Substituting equations 17 and 18 into equation 19 the following equation is obtained for the applied load:

$$P = \frac{2M + (Mc + M)(y_1/y_2)}{(\cos(15)y_1 + \sin(15)x_1)} \tag{20}$$

5.2.4. Modelling the rigid-plastic load-displacement curve

The calculation of the frame's rigid-plastic load-displacement curve is straightforward. The loading point is displaced, δ, the hinge rotations being obtained from equations 11 and 12, the resisting moments from equation 13 and finally the load of the frame from equation 20. The modelling procedure can be summarised for each horizontal increment of displacement of the point of load application:

1/ calculate the rotation of each plastic hinge;

2/ using the result of step 1, calculate the resisting moment of each plastic hinge; and

3/ using the result of step 2, calculate the load of the frame from the equilibrium equations of the free-body diagram.

Theoretically, plastic hinges will first form near the base of the side-pillars well before plastic hinges form at the roof joints. In practice, once the first plastic hinge initiates, the resulting loss of stiffness ensures that the other plastic hinges necessary for the frame's structural collapse form shortly afterward. For the purposes of the model, all four plastic hinges were assumed to begin rotating from zero displacement. Overall, however, the frame was considered to collapse when the load predicted by equation 20 began to fall.

The rigid-plastic model and the elastic model of equation 3 were superimposed to model the complete load-displacement curve of the frame. Fig. 6 compares the predictions of the models with the experimental load-displacement curve. The elastic model over-predicts the stiffness of the frame because the joints within the frame were not perfectly rigid and because this model fails to take into account the changing geometry of the structure. The modelling of the load-displacement curve's elasto-plastic transition was improved by sketching a curve which asymptotes to both the elastic line at the point of first-yield and the rigid-plastic line at the point of collapse. This is an accepted method of modelling the collapse of thin-walled structures (1) and is surprisingly accurate because the maximum load capacity of thin-walled structures is generally close to the point of first-yield. The load-displacement curve beyond collapse is faithfully modelled up to the point where the folds of the plastic hinges interact with the fixed supports of the frame.

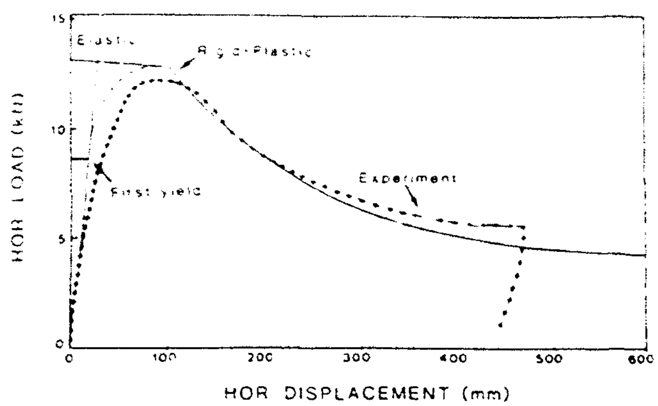

Figure 6: The theoretical load-displacement curve of the frame compared with experimental results.

While the rigid-plastic model was formulated for a horizontal displacement of the loading point, the experimental load-displacement curve was originally based on the displacement of a load inclined at an angle of 15° to the horizontal that described an arc as it moved through space. The displacement parameter in the experimental results was therefore converted into a horizontal component so that an appropriate comparison was able to be made with the rigid-plastic model (5). The vertical displacement of the loading point will also, of course, contribute to the energy absorption of the frame. This component, however, is of negligible magnitude because the frame only has a small residual strength when the vertical displacement of the loading point is large. The above rigid-plastic model will then be of sufficient accuracy.

5.2.5. Critical assumptions associated with the rigid-plastic model

The combined elastic and separate rigid-plastic approach was able to faithfully model the load-displacement behaviour of the collapsing frame to large deflections. Additionally, the combination of these two separate models was able to adequately define the elasto-plastic transition prior to collapse. The accuracy of the rigid-plastic model depended on two critical assumptions,viz; all deformation after collapse occurs at the plastic hinges and; upon collapse, the frame behaves as a mechanism with all four plastic hinges connected by rigid-links. These assumptions were surprisingly accurate and allowed the deformed geometry of the frame to be determined to large deflections. An accurate estimation of the deformed geometry was a necessary part of the rigid-plastic modelling technique for the load-displacement curve.

The assumptions above relied on the fact that once a plastic hinge forms, its drooping moment-rotation properties ensure that all further deformation is concentrated at that location. Once collapse occurs, the frame behaves as a kinematically movable system whose strength solely depends on the residual bending resistance of the plastic hinges. The elastically stressed portions of tube recover to the moment supported by the plastic hinges. This will not affect a structure's load-displacement curve because the associated deflections produce no net displacement in the direction of the applied load. The point of load application will not move, for instance, because its deformation is determined by the displacement of the external hydraulic jack. The stresses in the connecting members between the plastic hinges can then be ignored, and therefore treated as rigid-links.

The rigid-plastic modelling procedure analyses the collapse of the frame by an upper-bound approach (1). In this method of analysis a sufficient number of plastic hinges are considered to form so that the frame behaves as a mechanism (the so-called mechanism condition). The locations of these plastic hinges are therefore assumed and equilibrium satisfied. However, if the hinge locations are poorly chosen, the calculated failure load of a frame will be greater than the actual failure load because the maximum bending moment will be exceeded at locations in the frame other than those assumed for the plastic hinges, a violation of the so-called yield condition. Hence the upper-bound classification of this approach. The plastic hinge locations must therefore be carefully chosen. For the tested frame these positions can be derived by inspection. For more complex frames more systematic methods such as the Neal-Symonds method (20) can be used to determine the optimum hinge locations. Moreover, there are now computer methods using Step-By-Step Analysis, for instance, that can be used as well (5). It is also important that the moment capacity of the plastic hinges is accurately determined for a given member rotation. If the moment capacity of a plastic hinge is over-estimated, the strength of the frame at a given displacement will be over-predicted. The converse is also true. The moment-rotation properties of the thin-walled square tubes must be accurately characterised so that the behaviour of the frame can be correctly predicted .

6. CONCLUSION

The load-deflection behaviour of thin-walled tubular bus frames can be easily and accurately modelled to well beyond collapse by the application of separate elastic and rigid-plastic models. The formulation of the rigid-plastic model requires an accurate prediction of the frame's deformed geometry. This is readily achieved because the moment-rotation curves of collapsing thin-walled tubes characteristically exhibit a decrease in strength. A heuristic solution technique involving the direct insertion of the moment-rotation properties of the collapsing thin-walled tubes into such a rigid-plastic analysis is also required.

7. ACKNOWLEDGMENTS

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