Analysis of Framed Buffer Structure around Bridge Pier

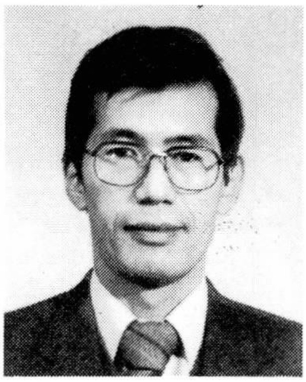
Analyse de la charpente de pare-choc autour de la pile du pont

Analyse von Pufferbau um den Brückenpfeiler

Yosho NAMITA
Dr. Eng. Chief Res. Eng.
Kobe Steel,
Kobe, Japan

Hiroshi NAKANISHI
Dr. Eng. Res. Eng.
Kobe Steel,
Kobe, Japan

Yoshio Namita, born 1934, got his doctorate at Osaka University, Japan. After making researches of bridge engineering in the Osaka University for thirteen years, he started working in the Structural Engineering Laboratory of Kobe Steel, Ltd, where he is now responsible for the research works on structural analyses.



Hiroshi Nakanishi, born 1946, got his doctorate at Osaka University, Japan. For thirteen years he has been making researches on structural analysis in the Structural Engineering Laboratory of Kobe Steel, Ltd. He is now responsible for developing the computer softwares of dynamic behaviour of offshore structures.

SUMMARY
A framed structural system is proposed for a buffer which prevents the damage to a bridge pier by ship's collision. Investigation is made into the load-deformation relation and the energy-absorbing capacity of the structure by means of inelastic large deformation analysis. Numerical results show that, from the viewpoint of energy absorption, the structural system of which truss layers collapse one after another with the headway of ship is more effective than that which suffers the local collapse of structural panels.

RÉSUMÉ
Un système de charpentes est proposé comme structure de pare-choc d'une pile de pont lors de la collision de navires. Des calculs sont effectués à l'aide de la méthode d'analyse de déformation inélastique et de la capacité de l'absorption d'énergie. Le résultat numérique montre que, du point de vue de l'absorption d'énergie, la structure, dont les couches de charpentes cèdent au fur et à mesure que le navire s'enfonce dans la charpente, est plus efficace que celle qui éprouve cumulativement la destruction locale de panneaux structuraux.

ZUSAMMENFASSUNG
Ein Fachwerk als Pufferbau, der gegen den Schaden des Brückenpfeilers durch Zusammenstoß eines Schiffs eingesetzt wird, wird vorgeschlagen. Die Belastungs-Verformungslinie des Pufferbaus und dessen Aufsaugvermögen der Verformungsenergie sind mittels der Analyse von unelastischer, großer Verformung studiert. Numerische Ergebnisse zeigen, daß, vom Standpunkt aus Energieaufsaugen, das Fachwerksystem, dessen Schichten eine nach der andern mit dem Eingreifen eines Schiffs nachgeben, wirkungsvoller, ist als dasjenige, das die Anhäufung des Lokalzerbrechens vom einzelnen Fachwerkfeld erleidet.

1. INTRODUCTION

When a bridge pier is constructed in a sea area, it is possible that accidents such as collision of a ship with the pier occur in stormy or foggy weather, especially under the severe condition such as heavy traffic and rapid tidal current.

As one of the measures to cope with the situation an idea of surrounding the bridge pier with a kind of buffer structure which would minimize the collisional damage to ship's hull as well as to the bridge pier is considered.

In this paper a framed structural system is proposed to be used as a buffer structure which prevents a ship from colliding directly with the bridge pier, and its buffering effect is investigated from the viewpoint of its energy-absorbing capacity.

2. DESIGN CRITERIA OF FRAMED BUFFER STRUCTURE

In case a ship, by accident, collides with a buffer structure surrounding a bridge pier, the following two points with regard to the buffering process should be noted in order to minimize the damage of both ship and pier:
1) The force caused by collision does not exceed the critical value for the collapse of either the ship's hull or the bridge pier,
2) The distance of ship's headway is limited within the value of the depth (from the front to the back) of the buffer structure (See Fig. 1 right).

In other words, the item 1) requires the buffer structure to have a cushioning effect that makes collisional impact small enough not to cause damage to either ship or pier, and the item 2) is for preventing the ship from coming into direct collision with the bridge pier.

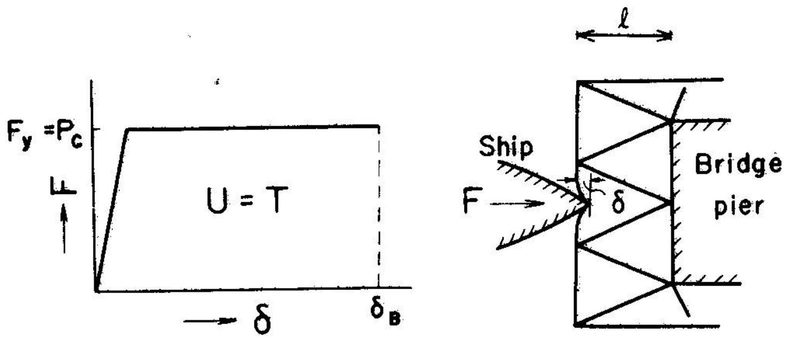


Fig. 1 Load-deflection relation of buffer structure

In general, it is considerably difficult to set up the design criteria for this kind of buffer structure because of the versatility of surrounding conditions such as size, weight and speed of ship, direction of collision, etc. In this paper, however, for the purpose of simplification and thus of making it possible to formulate the design process of the buffer structure, it is assumed that the bridge pier is surrounded by a three dimensional truss-typed framed structure, which is supposed to absorb the kinetic energy of a ship coming into collision as statical strain energy stored in the structural system during deformation.

Fig. 1 right shows a ship coming into collision with a buffer structure, which is gradually deformed and collapsed as the ship makes headway toward the pier. In this process the kinetic energy of the ship is transformed into the strain energy of the buffer structure suffering large deformation. Fig. 1 left shows a schematic load-deflection relation of buffer structure, where F is a force caused by collision and δ is the displacement of the point at which the force F acts. The structure behaves elastically so far as F is smaller than F_y and inelastic deformation occurs when F becomes F_y.
The displacement δ increases until it reaches δ_B, the ultimate displacement.

During this process the work done by the external force F is stored in the buffer structure as strain energy U.

In the present analysis the buffering effect of the structure is calculated under the following assumptions:
1) Ship's speed just before its collision with buffer is small and its dynamic effect can be neglected,
2) Mass of the buffer structure is small in comparison with that of the ship and is neglected, and
3) Ship has rigid hull.

Referring to Fig. 1 the necessary condition that the buffer structure functions in full effect is that $F_y \leqq P_c$ and $U \geqq T$. P_c is the allowable maximum impact force which is to be prescribed from the safety of the bridge pier proper and T is the kinetic energy of the ship just before its collision with the buffer. And, at the same time, the length by which the ship's bow gets stuck in the buffer structure at the end of ship's movement should be less than the horizontal depth of the buffer, i.e. $\delta_B \leqq \ell$ (See Fig. 1).

In this paper, a three dimensional framed system, as shown in Fig. 2, is proposed as the buffer structure which is made to satisfy these conditions by the numerical method of analysis calculating the strain energy of the structure.

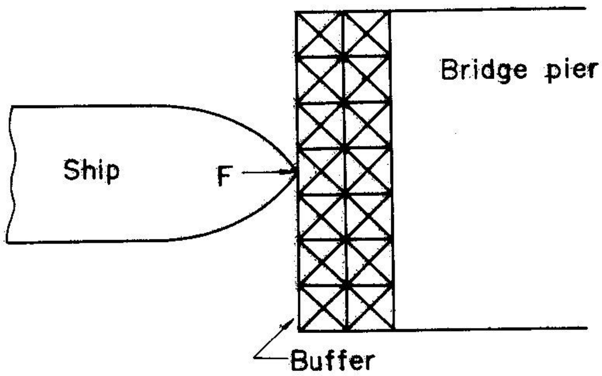


Fig.2 Framed structure for a buffer

3. METHOD OF ANALYSIS

Supposing the process of the deformation of buffer structure is perfectly traced from the beginning of ship's collision to the end of the ship's movement and the load-displacement (F-δ) relation is obtained as shown in Fig. 1, the strain energy U stored in the buffer structure can be calculated by the formula.

$$U = \int_0^{\delta_B} F \, d\delta$$

Therefore, the main purpose of analysis is to obtain the F-δ relationship of the structure at every loaded point.

As is clearly seen in Fig. 1 left, the work done by external force during elastic deformation is very small compared with that of inelastic range, therefore the strain energy stored in the buffer structure is composed, for the large part, of that due to large deformation in inelastic range. Hence, in order to analyze the present problem rigorously, the method of inelastic large deformation analysis is required, which takes fully into consideration the non-linearity of geometrical deformation and of inelastic mechanical properties of material used as well.

The method of analysis adopted in this paper for the purpose of obtaining the load-deformation relationship is the above-mentioned one based on the concept of energy principle.

As mentioned before, the object of the present analysis is a three dimensional truss-typed framed structure and the joints of its members are considered frictionless hinges. But, concerning the numerical examples shown in the following chapter, in addition to such truss-analysis, investigation was made into the behavior of the structures as rigid-jointed frameworks.

The result revealed that the bending stress in structural members made only a little contribution to the total amount of strain energy stored in the structure during its deformation up to collapse, and that a large portion of the total strain energy stored was brought about by the deformation of the structure after the formation of plastic hinges. Taking this result into account, the present analysis is limited to the one for truss-typed structure.

The method of analysis is as follows.

The total potential energy of the structure is generally shown in the form

$$W = \sum_{m=1}^{M} U_m - F^T x \tag{1}$$

where U_m is the strain energy of m-th member, F is the vector of external forces, x is the vector of joint displacements and M is the total number of members. The structure is in a equilibrium state when the total potential energy is minimized.

Fig. 3 shows a schematic illustration of the solution of member force-elongation relation which is expected to be obtained on the basis of the stress-strain relation. In Fig. 3 P_0 and e_0 are a member force and a elongation at the initial state.

Supposing the numerical computation is now under way in its i-th step (See Fig. 3), the strain energy stored in the m-th member up to the present state is expressed as

$$U = U_V + U_C \tag{2}$$

$$U_V = (P_i - \frac{E_i A}{L} e_i)e + \frac{E_i A}{2L} e^2 \tag{3}$$

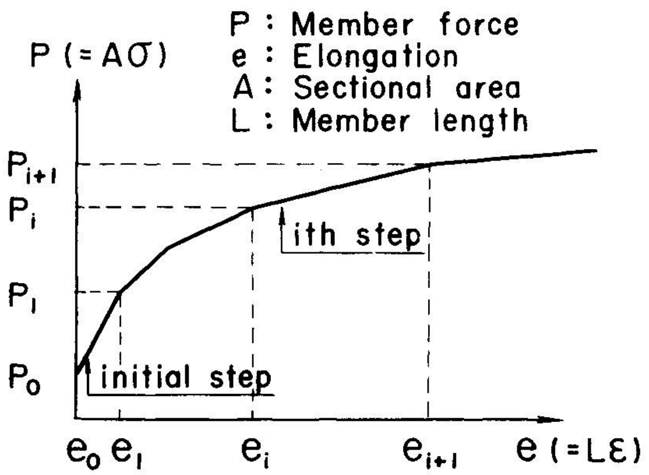


Fig. 3 Load-elongation relation of pin-jointed member

$$U_C = \frac{1}{2}(P_o+P_1)e_1 + \frac{1}{2}(P_1+P_2)(e_2-e_1) + \ldots\ldots + \frac{1}{2}(P_{i-1}+P_i)(e_i-e_{i-1}) + \frac{E_i A}{2L} e_i^2 - P_i e_i \tag{4}$$

where e is the total elongation of the member at an arbitrary state in the i-th step, and A and L are the sectional area and the length of the member respectively. In the initial step Eq. (2) becomes

$$U = P_o e + \frac{E_0 A}{2L} e^2 \tag{5}$$

(In the above equations suffix m in each term is omitted for simplicity).

The total potential energy W in Eq. (1) is minimized by the conjugate gradient method which is often used in the optimization problems [1], [2].

Now, W is calculated from Eqs. (1) and (2). U_C in Eq. (2), however, can be omitted in the minimizing process, for it does not include any terms of unknown joint displacements. Differentiation of Eq. (1) with respect to displacement x yields

$$R_{xj} = \sum_{m=1}^{N} \{ (P_{mj} - \frac{E_{mi} A_m}{L_m} e_{mi}) + \frac{E_{mi} A_m}{L_m} e_m \} \frac{\partial e_m}{\partial x_j} - F_{xj} \tag{6}$$

where N is the total number of members meeting at joint j. Eq. (6) gives the unbalanced force at the i-th iteration in X-direction of joint j. Similar forms are obtained with regard to ones in Y- and Z-directions.

4. SIMPLIFICATION OF THE PROBLEM

In the analysis of a buffer structure, the movement of the ship which gradually splits up the structural panel should be successively traced. For this purpose it is first necessary to make clear the loading condition, and the following assumptions are made:

1) Ship's bow is a wedge-shaped rigid body,
2) Buffer structure is a truss-typed framework and every load acts only at its joints,
3) The magnitude and the direction of load is dependent on the angle of bow Θ. Friction between the bow and structure is neglected and load F acts in direction normal to the bow (See Fig. 4),
4) Structural panel unit loses its load-carrying capacity when its diagonal members are broken by bow's headway. After the collapse of a panel unit the point of load application shifts its position,
5) Fig. 5 shows the shifting of load-application points as the bow advances. The structural panel unit directly suffering the bow's touching is broken up and immediately disappears. External forces caused by the bow act on the buffer structure in the form of Fig. 5 (b). The diagonal members of panel units are broken up with further headway of the bow (Fig. 5 (c)), and these broken panel units vanish and the structural system will be as shown in Fig. 5 (d).
6) A diagonal member does not resist a compression force at all.

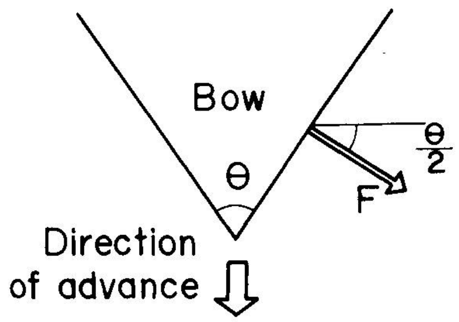


Fig. 4 Load acting on buffer

By the above-mentioned assumption computation becomes simple, and it can safely be said that the assumption causes no problem from the viewpoint of practical design calculation, for the majority of total energy absorbed by the structure is due to the deformation after the very break-up of diagonal compression members.

5. NUMERICAL INVESTIGATION

5.1 Collapse Pattern

Fig. 6 shows a collapse pattern of truss-typed buffer structure. This pattern means that panel units in one layer of the framework are simultaneously broken up and the structure is collapsed layer by layer as ship goes on (Fig. 6).

From the viewpoint of energy absorption, it can be said that this pattern is more effective than that which absorbs energy as the cumulation of the local collapse of each panel unit. Numerical investigations were made into finding out the condition under which the layer-collapse pattern occurs.

The governing factors which determine the collapse pattern of the trusses are the following:
1) Stress-strain relationship of material used,
2) Ultimate strain of material at its breaking point, and
3) Ratio of the sectional area of main (lateral or longitudinal) member to that of diagonal member.

A considerable number of numerical investigations were conducted under the assuption of Fig. 7 which provides the above-mentioned items 1) and 2). From these numerical results the item 3) was investigated.

Generally speaking, the bigger the ratio in item 3) becomes, the more likely the layer-collapse pattern is to occur; the more the number of panel units in one layer of truss-framework is, the more slender the diagonal members should be in order to cause this pattern.

An empirical conclusion was derived from the numerical results: Pattern of layer-collapse occurs when the ratio in item 3) above is larger than n+1, where n means the number of panel units in one layer of the truss.

Fig. 8 shows an example of the numerical result of a single-layer model having five panels.

Furthermore, the results with regard to multi-layer models which satisfy the above-mentioned empirical rule showed that, even when the first layer which suffers direct loading

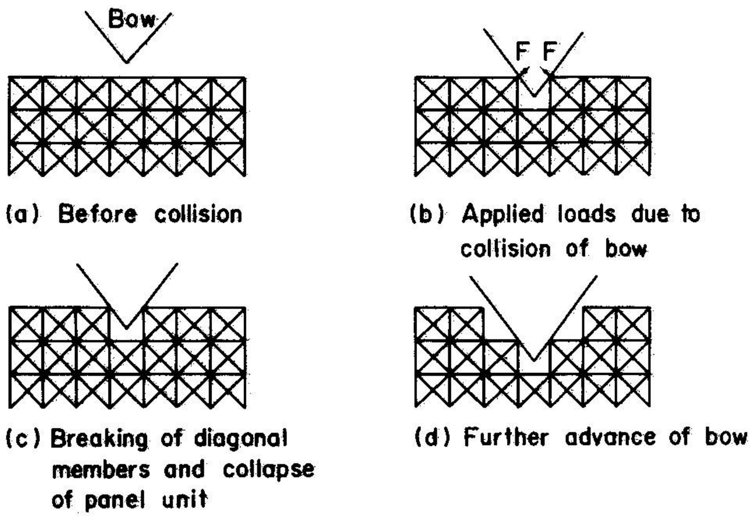


Fig. 5 Headway of ship and collapse of structural panel

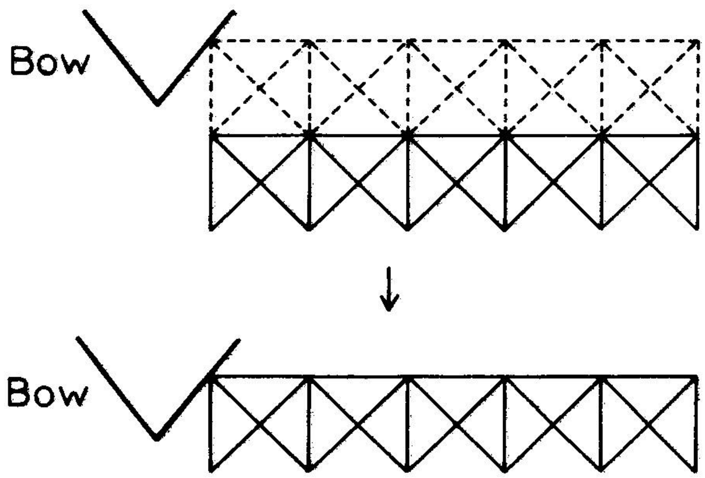


Fig. 6 Collapse pattern

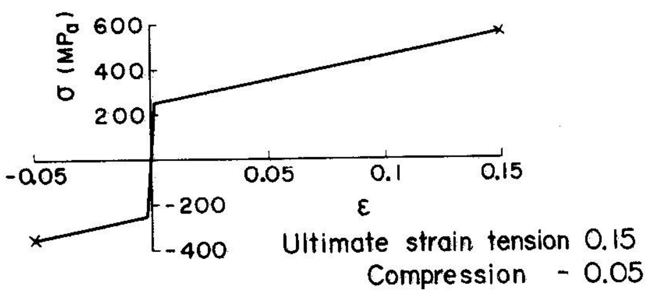
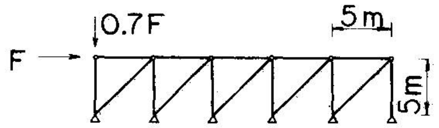


Fig. 7 Stress-strain relation

was mown down, member forces in remainder structural layers still remained in elastic range.

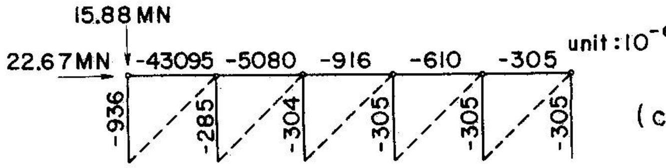


(a)

Structural model

	Sectional area
Chord member Vertical member	$900cm^2$
Diagonal member	$150cm^2$
Ratio of sectional area	6

(b)



(c)

Loads and strains when diagonal members are broken

Fig. 8 Example of collapse mode of a truss layer

5.2 Numerical example on multi-layer truss system

Here, a multi-layer structural model in Fig. 9 (a) is taken for numerical example and the behavior of its layer-by-layer collapse by ship's headway is examined. When the first layer has been overall collapsed, the structural system becomes a different one as shown in Fig. 9 (b) and at the same time a load application point shifts its position. This process goes on successively layer by layer and a load-deflection curve is drawn corresponding to each layer's process up to collapse. Fig. 10 shows the load-deflection curves of the structure in Fig. 9 (a). In this figure are drawn four curves one over another each of which shows the collapsing process of corresponding layer of the truss. The strain energy absorbed by each layer is obtained through integration of the load-deflection curve and is shown in the figure. As is seen in Fig. 10 four load-deflection curves resemble one another in their shape and the amount of energy absorbed by each layer is nearly equal to that of the other. In this example it can also be shown that, when a certain layer is in process of collapsing, the members of the remaining layers are still in the elastic range.

From the result of this numerical example, it can be said that the total amount of absorbed energy in multi-layer truss-typed structure is estimated by superposing the ones in each layer, so far as the structural system shows a layer-by-layer collapsing pattern.

The buffering effect of the above-mentioned structure, or the safety of bridge pier from ship's collision, is to be checked through confirming that the maximum reaction caused in pier is smaller than the allowable force and that the kinetic energy of the ship just before its collision is not larger than the energy absorbed in buffer structure during its collapsing process.

6. CONCLUSION

The results obtained in this paper are summarized as follows:

1) The computer program of inelastic large deformation analysis for trussed framework based on energy method was developed and applied to the analysis of buffer structure. The buffering effect of the structure is evaluated with the amount of strain energy which is absorbed in the structure during the process of collapse,

2) The possibility of finding out a multi-layered framework which showed the pattern of collapsing layer by layer with the penetration of ship was discussed. By employing such a system as a buffer structure, the buffering effect is considerably enhanced, and at the same time, design calculation is simplified on account of the availability for the superposition of energy absorbed in each structural layer.

In this paper the scope of the research is limited within the above-mentioned item. In practical construction, however, there remain many problems unsolved: for example, the method of installation at bridge pier, dynamic effect of wave forces, fatigue of structural members, corrosion prevention etc. Further investigations are expected to cope with these problems.

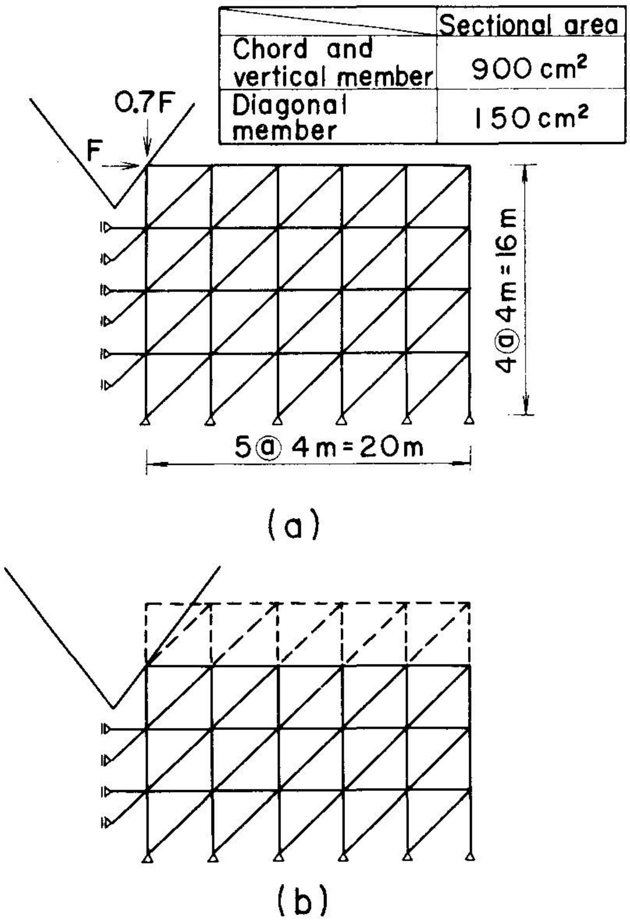


Fig. 9 Example of multi-layer truss

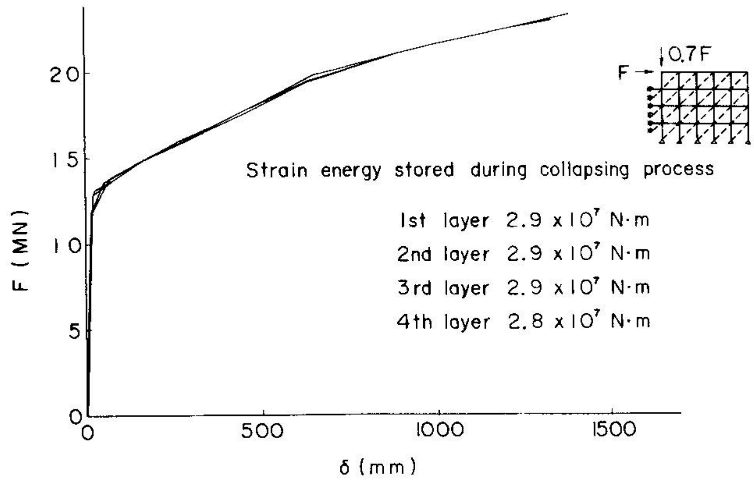


Fig. 10 Load-deflection diagram of multi-layer truss

REFERENCES

1. NAMITA, Y., T. SHINKE and K. HIRONAKA, Computer analysis and model experiment of cable structures, Preliminary Report of Ninth Congress of IABSE, May 1972
2. KOWALIK, J. and M.R. OSBORNE, Methods for Unconstrained Optimization Problems, Elsevier, New York, 1968