200. Ductile truss structures and scaled model experiments

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SYNOPSIS. It is quite difficult to perform seismic design for steel truss structures by allowing plastic deformation of members, because of the brittle buckling behaviour of compressive members. In order to protect the member from buckling and enhance ductility, the authors insert a central tube into the truss tube member and implement a ductile truss structure using these non-buckling members. Experiments have been performed on three types of small scale truss structures, using an automated loading system with stepping motors which proved the effectiveness of the compound member in plastic design.

INTRODUCTION

1. The social needs of large span structures are increasing, for such purposes as atria attached to tall buildings or baseball stadium roofs. Such structures include shell structures using reinforced concrete and air-inflated membrane structures, but steel trusses are the most common. In Japan, a seismically active land, it is very important to ensure safety against earthquakes for steel truss structures as well as for general buildings.

2. In the seismic design of general buildings, plastic deformations are permitted for some structural members in order to absorb the large earthquake input energy. However, in steel truss structures, it is quite difficult to perform seismic design by allowing plastic deformation of members because of the brittle buckling behaviour of compressive members. If such plastic deformation could be allowed for in steel truss structures, a more rational seismic design method could be used.

3. To enable plastic deformation, members subjected to a large force or deformation are required to have high ductility. Actually, the slenderness ratio of many members is over 100 and not much ductility remains in the member after buckling due to compressive forces. Thus it is difficult to apply plastic design to truss structures.

4. In this study, the authors have insert a central tube into the tube of a truss member, which acts as a ductile compressive member. The elastic buckling force of this central tube is designed to be larger than the axial yield force of the outer tube. This combination protects the tube from buckling and enhances ductility and

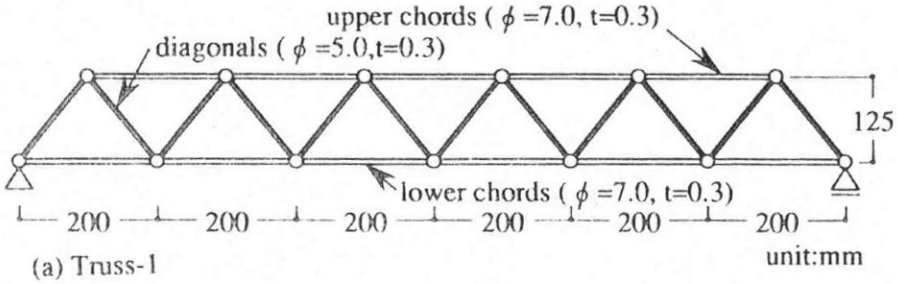
consequently the whole structure should have a higher loading capacity and larger deformability. This tube will be referred to hereafter as a "non-buckling member". The non-buckling member is functionally equivalent to a plate steel brace inserted in a pre-cast concrete wall panel, or a steel brace covered by reinforced concrete to prevent buckling. Double tube truss members have also been investigated by Tada, et al.

5. In this study, an experiment using reduced scale models of steel truss structures, which included the non-buckling members as mentioned above, was performed to investigate the structural mechanical properties. As the model becomes smaller, the strength reduced and in the case of a distributed load, the load at each loading point becomes extremely small. Therefore it is difficult to control all the load increments simultaneously, and the applied load has been substituted by the load specified by the tournament method. Here, the authors developed an automatic loading system which controls the loads at multiple points concurrently.

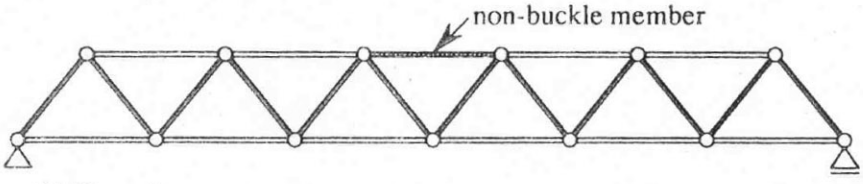
SPECIMENS AND LOADING SYSTEM

Specimens

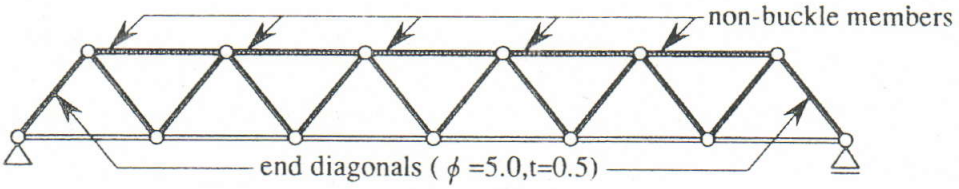
6. Experiments for the three types of specimen were carried out as follows:
(a) Normal Truss Structure (Fig. 1; Truss-l);
statically determinate plane truss structure, total span 120 cm, height 12.5 cm, grid length 20 cm.
(b) Truss structure with one non-buckling member (Fig. 1; Truss-2);
one non-buckling member installed in the central upper chord.
(c) Truss structure with five non-buckling members (Fig. 2; Truss-3);
non-buckling members installed in all upper chords.



(a) Truss-1



(b) Truss-2



(c) Truss-3

Fig. 1. Three specimens.

7. For the truss members, stainless steel tubes were used, 7.0mm diameter with a wall thickness of 0.3mm, for chord members, and 5.0mm diameter and 0.3mm wall thickness for the diagonal members. Joints are connected to truss members by silver brazing (Photo 1). The details of the non-buckling member are shown in Fig. 2. The central tube has a 6.0mm diameter and 1.0mm wall thickness. By setting the central tube very slightly apart from the outer tube and both joints, the axial force will not be transmitted into the central tube. The sectional area is calculated so that the yield strength of the outer tube (P_Y = 1523N) will be lower than the Euler buckling load of the central tube ($P_E = \pi^2 EI/\ell^2 =$ 2428N) and the safety factor (P_E/P_Y) is 1.59. The stainless tube is manufactured by cold rolling and the material test results indicate that the 0.2%-strength is 3.1 times higher than the strength of normal stainless steel. Accordingly the silver brazed joint is the weak point, and in order to compensate for this, the stainless steel tube was annealed by heating to 1050°C for 5 minutes and cooling in air at room temperature.

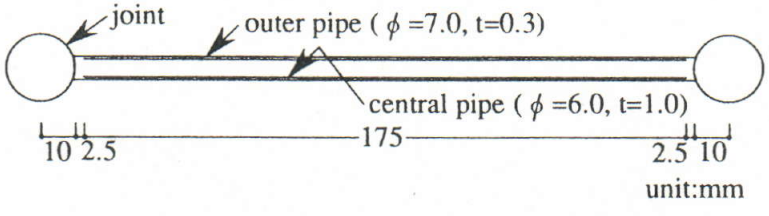


Fig. 2. Detail of non buckling member.

Loading System

8. Fig. 3 and Photo 2 show the loading apparatus. A female screw is placed in the centre of a worm-wheel and a worm-gear is rotated by a stepping motor controlled by a personal computer. This mechanism provides a tension force to the rod through the shaft. There is a groove in the shaft and a ball bearing is put

into this groove and supported by the top and bottom bearing cylinders to prevent co-rotating caused by the worm-gear.

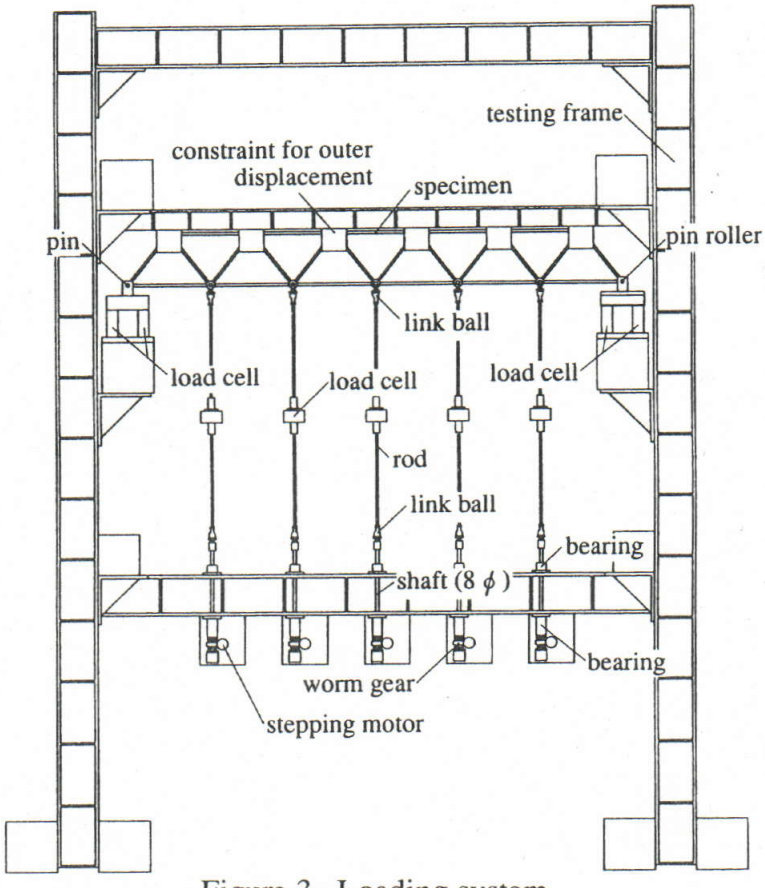


Figure 3. Loading system.

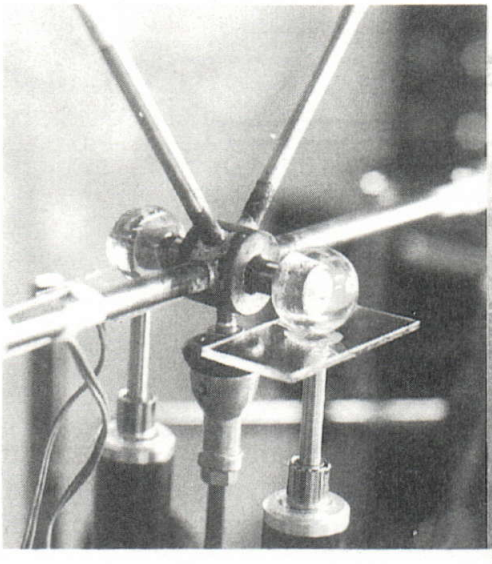


Photo 1. Detail around joint.

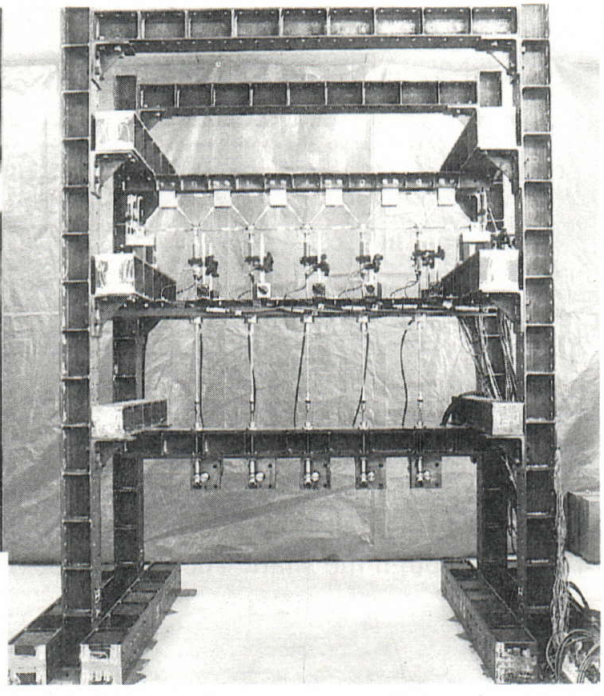


Photo 2. Loading apparatus.

9. Two link-balls are attached to each end of the rod so that the bending moment does not act on the central load-cell. Thus the loading point can move freely in accordance with the lateral and vertical deformation of each truss joint. Load is applied until the vertical displacement of the joint, of the lower chords, reaches 30mm; loading is controlled to be equal on all the load-cells attached to tensioned rods.

10. The deformations of the truss structure are measured by displacement transducers at each joint on the lower chords, the total applied load is checked by load-cells attached to the right and left supports and the strain is measured by strain gauges attached to the centre of each member.

LOADING CONTROL SYSTEM

Loading System

11. The personal computer is connected to the multi-axial controller through an RS232C and it is also connected to the measuring instrument through a GPIB. This system measures the load and displacement automatically and controls five stepping motors simultaneously. There is a displacement transducer and load cell for each stepping motor. The computer compares the measured load and displacement values with the base control value and controls the stepping motors accordingly. A stepping motor can control displacement more precisely than a hydraulic pump, and it has high stiffness as a loading mechanism. With these characteristics, the negative slope of load-displacement relationship after buckling can be controlled.

Motor Control System

12. The base control value is the load value of the load-cell corresponding to the base motor (P3), and other load values are set in proportion to this base value. In the elastic region, the motor is controlled by the load value of the base point. Around the maximum strength region or in the plastic region, it is controlled by the displacement value of the base point.

13. The on/off procedure of the motor is controlled as follows. The motor at the base point is set to be stopped when the value of corresponding load or displacement becomes greater than the base control value ± the allowance. Other motors are stopped when the measured load or displacement is greater than the load value of the base motor and they are activated when both values are less than it.

RESULTS

Motor Control

14. Unlike a hydraulic pump, a stepping motor can easily control the displacement and it has a stiffness as a loading system about 100 times higher than the truss specimens. Furthermore the negative slope of the specimens after buckling is of the same order as their elastic stiffness. Therefore the data in the negative slope region are easily measured even after the structure reaches an unstable condition.

Relationship between Load and Displacement

15. Fig. 4 shows the relationship between the total load of each truss structure and the vertical displacement of each joint of the lower chords. The nomenclature (a), (b) and (c) indicate Truss-1, Truss-2 and Truss-3. v_1, v_2, ~v_5 express the vertical displacement of each lower chord joint from left to right. Table 1 lists the maximum strength values of three truss structures. The value for Truss-3 is the strength at the end of the experiment, where v_3 = 21mm.

Table 1. Total maximum strength of each specimen.

Specimens	Truss.1	Truss.2	Truss.3
Total maximum strength(N)	812.80	912.44	1184.20
(Ratio)	(1.000)	(1.123)	(1.457)

16. In Truss-1, the strength is drastically decreased by the buckling of the central member of the upper chords. In Truss-2, the strength of the early stage is relatively higher than Truss-1 because the central member does not buckle. But later the strength is reduced due to the buckling of an upper chord member next to the central non-buckling member. As a result, the deformability of the truss structure itself was not improved. This reason is analysed as follows. The total load which makes the central member yield is quite close to the total load which makes the neighbouring member buckle. Thus the neighbouring member buckled before the non-buckling member reached a stable yield. Using one non-buckling member is not effective for the improvement of the deformability.

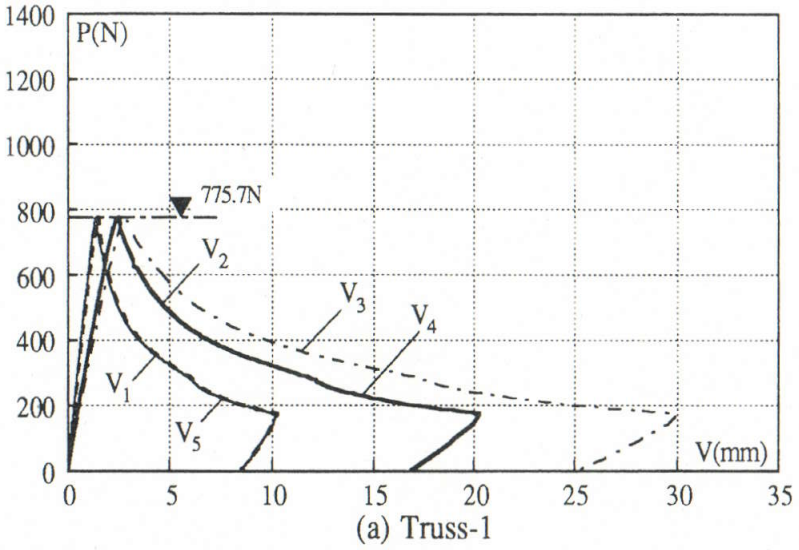
17. In Truss-3, the strength continued to increase even after the stiffness reduction around the point P = 941N and consequently large deformability was obtained.

Relationship between Total Applied Load and Axial Strain of Member

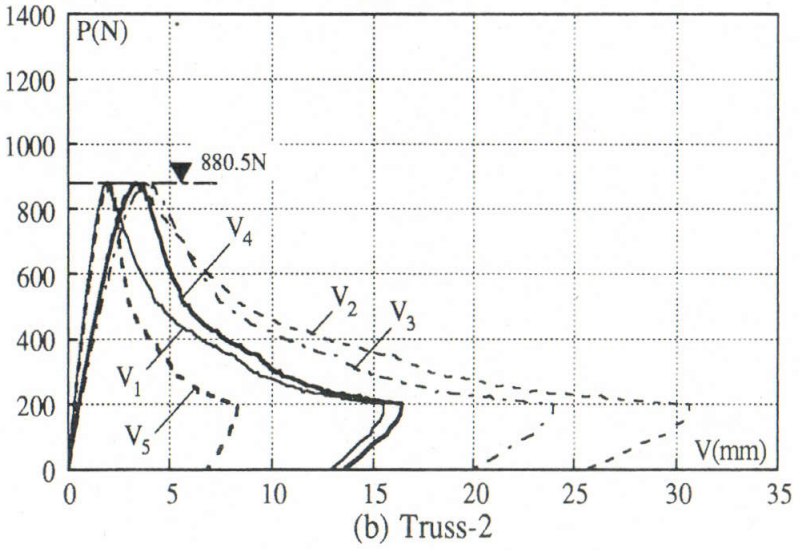
18. Figs 5 to 7 describe the relationship between the total applied load and the axial strain in upper chord members U2 and U3 (central member) for Trusses-1 to -3.

19. In Truss-1, shown in Fig. 5, the central upper chord (U3) buckled first. After buckling, its neighbouring members are subjected to a bending moment caused by the shortening of the central upper chord.

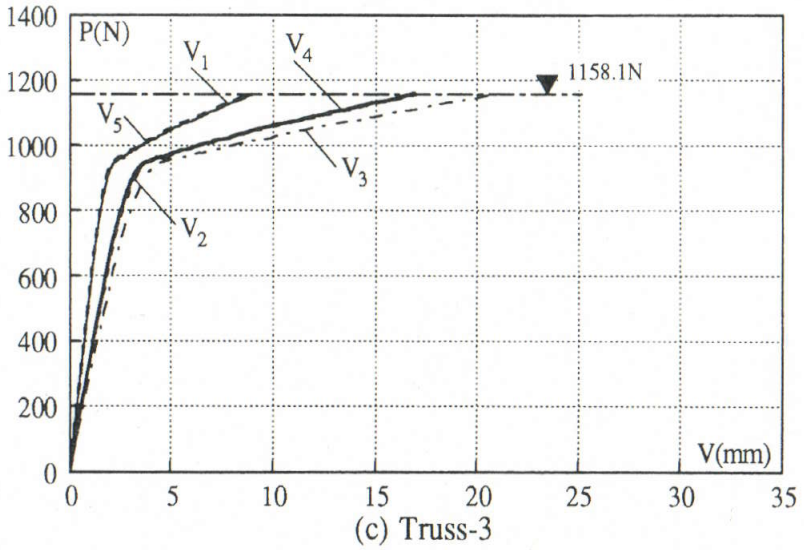
20. In Truss-2, shown in Fig. 6, plastic deformation without buckling of the central member starts at around the maximum structural strength point. The strength of the structure is reduced after the neighbouring upper chord member (U2) buckles. Truss-2 undergoes a similar change to Truss-1 after the buckling of member U2.



(a) Truss-1



(b) Truss-2



(c) Truss-3

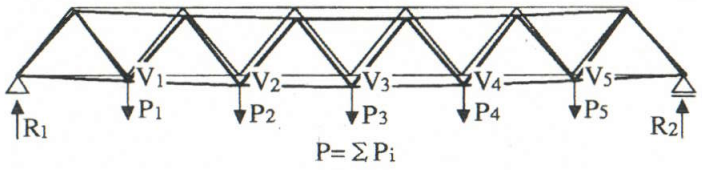
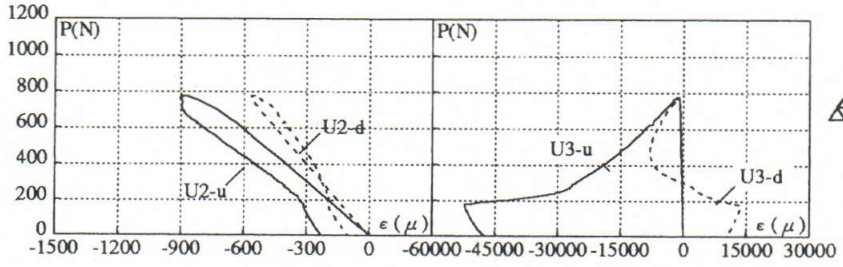


Figure 4. Total load vs. displacements of each specimen.

21. In Truss-3, shown in Fig. 7, the non-buckling members U2, U3 and U4 are subjected to a compressive force. The axial strains of U2, U3 and U4 are over 0.55%, 0.92% and 0.51%, respectively, when the plastic deformations take place. The non-buckling members are confirmed to work efficiently in this structure type. With this strength enhancement, the central two members of the lower chords yield in tension, forming a ductile truss structure.

22. From the experimental results of Truss-2 and Truss-3, the authors concluded that for the improvement of structural deformability, non-buckling members should be installed not only for the member with the largest compressive axial force but also for members with an axial force close to this value.



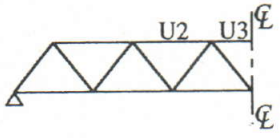
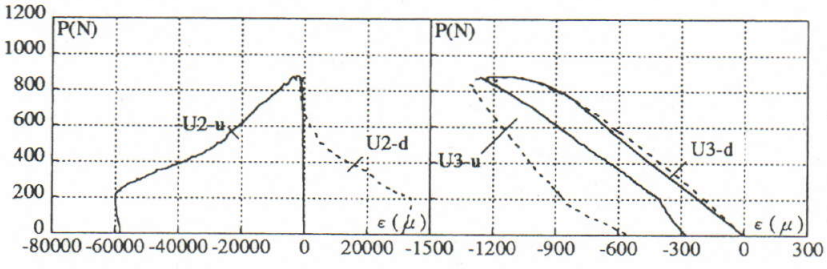


Figure 5.
Strain in Truss-1



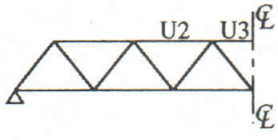
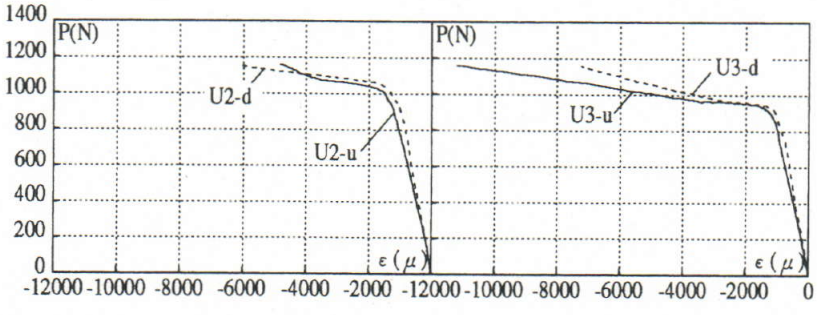


Figure 6.
Strain in Truss-2



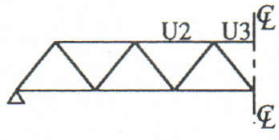


Figure 7.
Strain in Truss-3

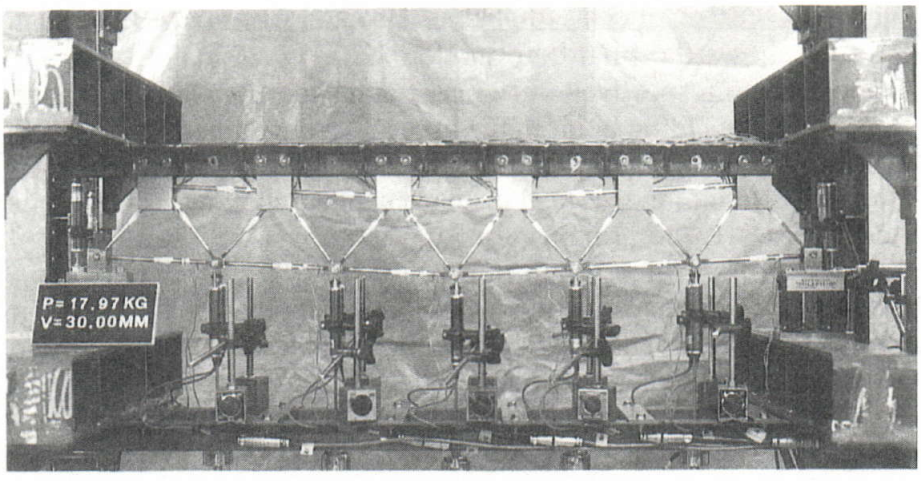


Photo 3 (a). Final Deformation of Truss-1

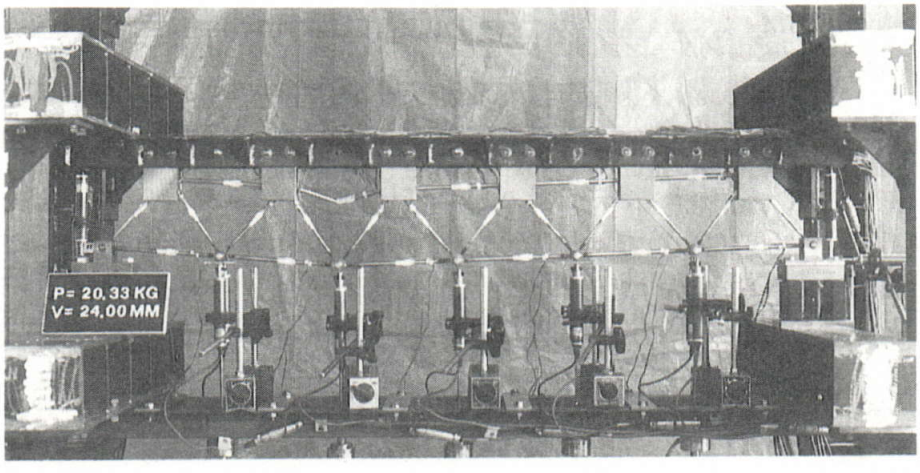


Photo 3 (b). Final Deformation of Truss-2

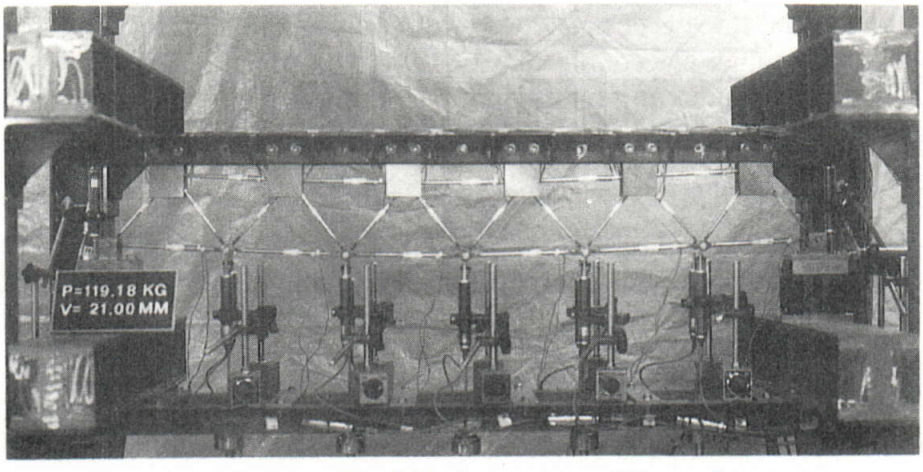


Photo 3 (c). Final Deformation of Truss-3

Deformation at the Experiment Completion

23. Photo 3 shows the final deformation state; (a) ,(b) and (c) are Truss-1, Truss-2 and Truss-3 respectively. In Truss-1 and Truss-2, a hinge in the structure was formed at the buckling point in the upper chord members, then the structure became a 3-hinged mechanism, and finally the whole structure collapsed. From Fig. 4, the proportion of the vertical displacements of the lower chord joints were obtained. In Truss-1, the proportion of v1: v2: v3: v4: v5 is 1.00: 1.99: 2.94: 1.99 :1.01. In Truss-2, this proportion is 1.00: 1.98 :1.55: 1.06 :0.54. The V line is determined by connecting the lower joint under the buckled upper member to both right and left supports. After buckling, it is found that this structure has transformed into this V shaped mode.

CONCLUSIONS

24. In this study the authors proposed a ductile truss structure and proved its effectiveness in plastic design by undertaking experiments. The authors performed experiments on three types of small scale truss structure using an automated loading system with stepping motors. The following conclusions were drawn.

a) Accurate load control is accomplished by controlling the stepping motors and worm-gears automatically using a personal computer. A high stiffness loading mechanism, which can catch negative slope data after the buckling of the chord member, was obtained.

b) In a statically determinate plane truss structure, our proposed non-buckling member has proved to work efficiently to protect buckling and enlarge the deformability. This non-buckling member is made by inserting a central tube into the truss tube, and is used for the members which are subjected to large compressive force.

c) For the improvement of the load capacity and deformability of the truss structure, it is necessary to install this non-buckling tube not only for the member with the largest compressive axial force but also for members with compressive axial force close to the largest one. But when the member with the largest compressive axial force is designed to be relatively small, it is considered that one non-buckling member placed in its position could be effective.

d) By using non-buckling members for compressive members, ductile truss structures could be created, where the plastic deformation were allowed during earthquakes.

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