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EXPERIMENTAL SHAKEDOWN ANALYSIS OF SPACE TRUSS NODES

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The purpose of the paper is to discuss the problem of the behaviour of the space truss node subjected to alternating loading greater than the maximum load carrying capacity in the elastic range. A certain experimental method is proposed which allows to investigate the plastic strain stabilization process. The results of shakedown investigations of full-size nodes composed of flat plates seem to confirm the practical applicability of the above method. During the experiment the strain variations were recorded with the help of strain gauges and photoelastic coating made of synthetic resin epidian 2.

1. Introduction

Space truss structures are usually analysed and designed by assuming the nodal joints to be more resistant than the strut elements, i.e. by assuming that only the latter ones may fail at the ultimate limit state. To keep this assumption valid, the nodes must be designed with a rather broad margin of safety. However, evaluation of the node carrying capacity is rather difficult and has been carried out, nearly exclusively, only experimentally, Ref. [1].

On the other hand, the determination of that load carrying capacity of nodes made of a ductile steel should account for plasticity effects. Since the loads acting upon a truss, and thus the forces acting upon a node, vary with time, the phenomena of alternating plasticity and/or of plastic strain accumulation should be prevented. Plastic strains could be allowed to appear but their final stabilization must be assured. Therefore shakedown methods should be employed here rather than the plastic limit analysis approach which is able to evaluate only the ultimate load.

However, analytical or even numerical methods of shakedown analysis seem to be hardly applicable to special nodes of complex shapes.

Therefore experimental determination of shakedown loads seems to be the only practical and reliable approach. The present paper proposes a certain systematic method which allows to investigate the plastic strain stabilization process in the course of a quasi-state cyclic loading. The method of photoelastic coating is used as in paper [2] but in a simpler manner in which, at least in principle, the precise determination of strain components can be avoided.

2. ESTIMATION OF SHAKEDOWN LOADS

The magnitudes of forces acting upon a given node of a space truss in the course of a given loading process can be determined by means of existing structural analysis computer programs. Those programs are now able to account for plastic deformations as well as for buckling of the struts, see Ref. [3]. Therefore the limits of loads acting upon a given node can be assumed to be known.

Every experimental shakedown investigation consists of the following:

a model (or a full-size structure) is subjected to a cyclic loading of a certain load amplitude; the structural deformations are recorded cycle by cycle;

convergence (stabilization) of the plastic deformations is exhibited when the total strains begin to assume the same magnitudes in subsequent cycles; after attaining the state of shakedown for a given load amplitude the latter would be increased to detect if the plastic strain stabilization appears, also, at the new load amplitude.

The whole procedure is to be continued until there is no plastic strain convergence any more. The highest load at which the shakedown still appears provides a safe (lower) bound to the shakedown load.

Now it is a practical question how the structural deformations should be measured and recorded. This depends on the type of structure investigated. For example, in the case of beams and plane frames it is sufficient to record some characteristic deflections measured by means of inductive or dial gauges. In the case of surface elements this may not suffice. In the case of plane stress, the simplest way might consist in making measurements at some selected points of all the strain components by means of a strain gauge rosette and analysing if their magnitudes repeat in subsequent load cycles. However, this may lead to neglecting some localized changes in the strain pattern. Therefore a more global inspection of the latter is necessary. For this purpose, the method of photoelastic coating, for example, could be employed.

It is important to stress that the knowledge of numerical values of the strain components is not necessary. Namely, the identity of the isochrom patterns in two subsequent load cycles implies, already, the identity of the strain fields and the plastic strain stabilization. Thus the involving procedure of determining the strain magnitudes from the numbers of isochroms does not need to be applied.

Such an approach can be used also in the case of space elements with sufficiently smooth surfaces as the changes of the strain fields within an element volume should result in changes of the surface deformations.

3. Arrangement of experiments

The general idea outlined above has been checked by using the experimental arrangement we have at our disposal at the Warsaw Technical University, Fig. 1. It enables to investigate full-size nodes loaded with up to 12 loads simulating forces from the struts intersecting at a given node. The loads are executed by means of hydraulic jacks which can act independently of each other or can be coupled into pairs or larger groups.

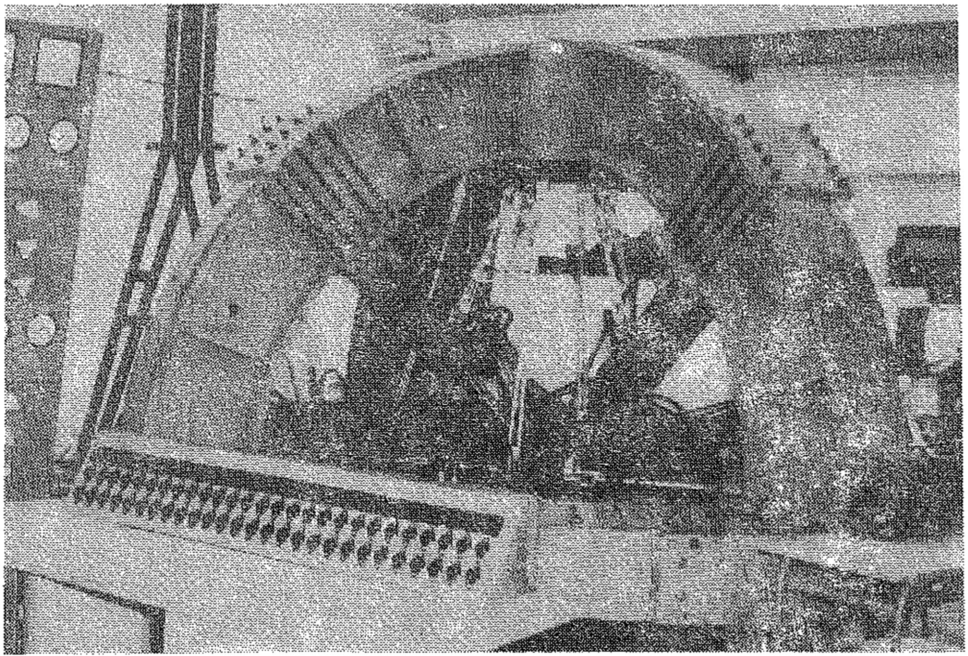

Fig. 1. Arrangement of the experimental stand.

The intensity of the force of every jack is controlled by manometers as well as by means of strain gauges placed on the jack tips.

We investigated steel nodes made of flat plates (see Fig. 2). The photoelastic coating made of the synthetic resin epidian 2 prepared in advance has been sticked to the plates. Strains within the plates were measured also by means of strain gauges. Magnitudes of strains were recorded after

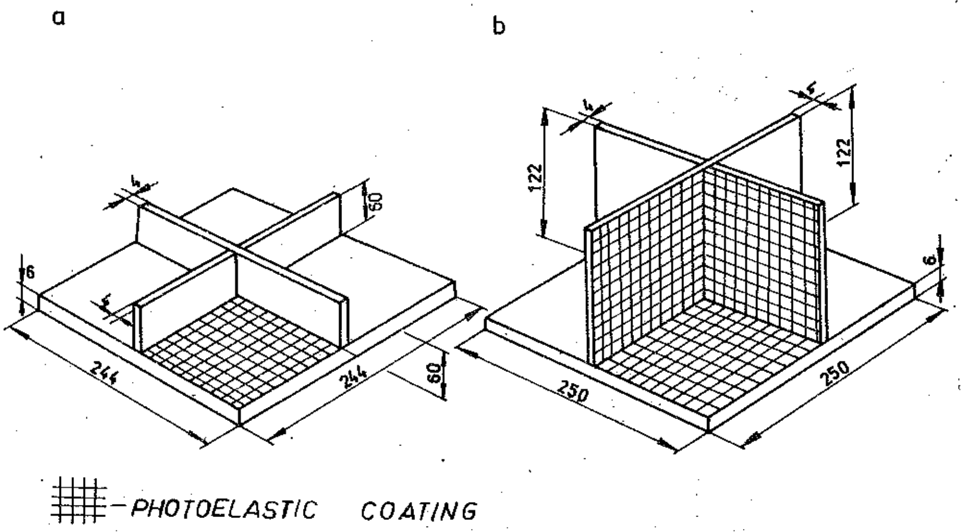

FIG. 2. Specimens investigated: a) the first series, b) the second series.

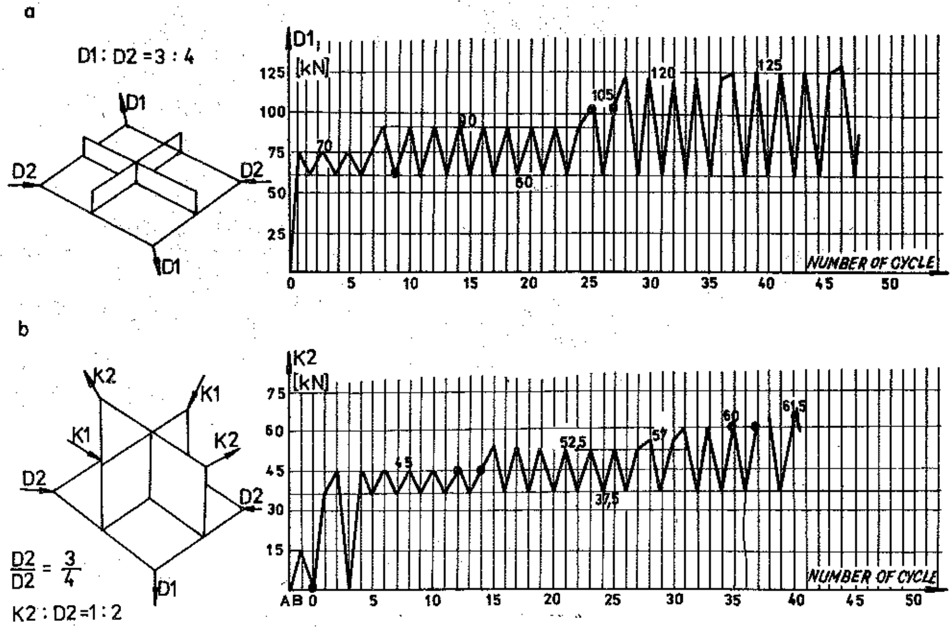

FIG. 3. Load patterns and load intensity variations a) the first series, b) the second series.

every load change with the five minutes of waiting time to avoid any possible influence of creep. Then also photos of the isochroms were made.

4. Experimental investigations

Two series of five specimens in each one of them have been investigated. They are shown in Fig. 2. In the previous investigations, aimed at determining the ultimate loads of nodes composed of flat plates, it has been found, Ref. [4], that such a node can be analysed as an assembly of flat plates (without bending), the interaction between them being simulated via appropriately defined boundary conditions of each one of the plates. Therefore, the first series contained cut-out nodes with the lower horizontal plate and the ribs simulating the influence of vertical plates. Specimens of the second series were complete nodes.

All the specimens were made of mild steel grade ST 3SX, thickness of the horizontal plate being 6 mm, thickness of the vertical ones — 4 mm. The yield point stress of the former has been found to be 250 MPa and 220 MPa, respectively.

The cyclic loadings of the specimens, see Fig. 3, has been assumed in a possibly stringent way following the analyses of a few space truss roofings within the elastic-plastic range. In the initial load cycles, the ratios between the dead and live loads have been assumed like in some typical civil engineering structures. After confirming that shakedown had been attained (cycles of loading until strains stabilization) the live load got a certain increment. Shaking down had been detected again after a few cycles and the live load had been given another increment etc. As seen in Fig. 3, these increments have been assumed smaller when approaching the expected shakedown limit.

In the course of experiments it was assumed that shakedown is attained when the difference in two subsequent cycles does not exceed 0.1 per cent. Then also a photo was made. The comparison of the photoelastic pictures allows to confirm the occurrence of shakedown, i.e. the perfectly elastic response of the node investigated. Figure 4—6 give examples of the isochrom patterns photographed on the specimen 01 of the first series. Figures 7—12 give the respective pictures of the vertical plate of the specimen 11 of the second series. The numbes given in the figures correspond to the load cycle numbers of Fig. 3. One can see, for example, that the photos of Figs. 5, 6 and 10, 11 taken after subsequent cycles, clearly imply shakedown.

The last load intensity at which shakedown has been attained provides a lower bound to the shakedown load.

Small circles which can be seen in the photos are holes in the photoelastic sheet and were prepared by means of a special technique introducing

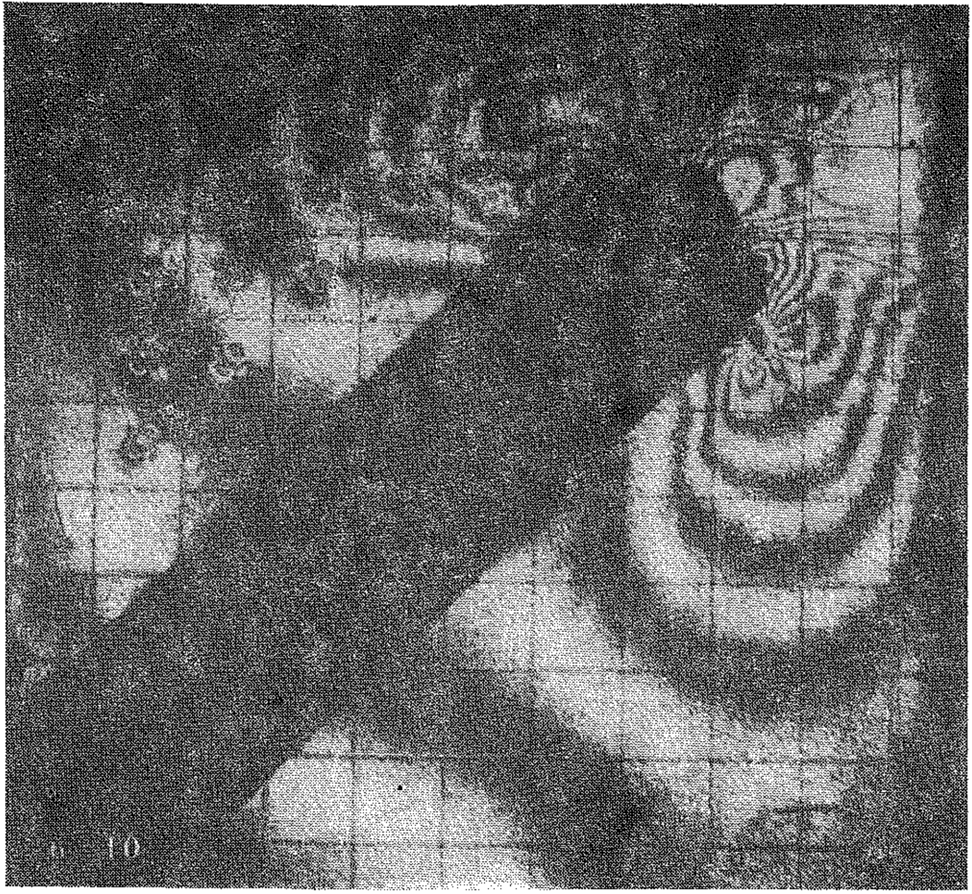

FIG. 4. Photo of isochrom picture — node 01, cycle 8–9–10, point 9.

FIG. 5. Photo of isochrom picture — node 01, cycle 22–23–25, point 25.

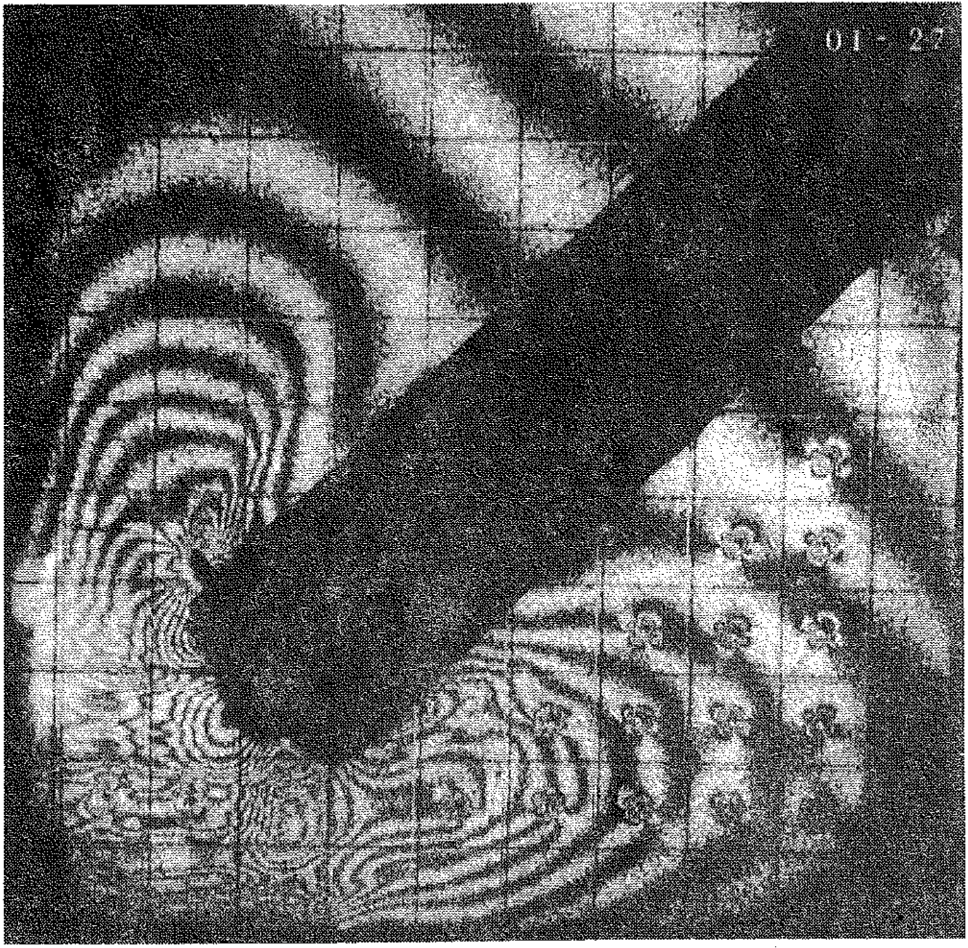

FIG. 6. Photo of isochrom picture — node 01, cycle 25–26–27, point 27.

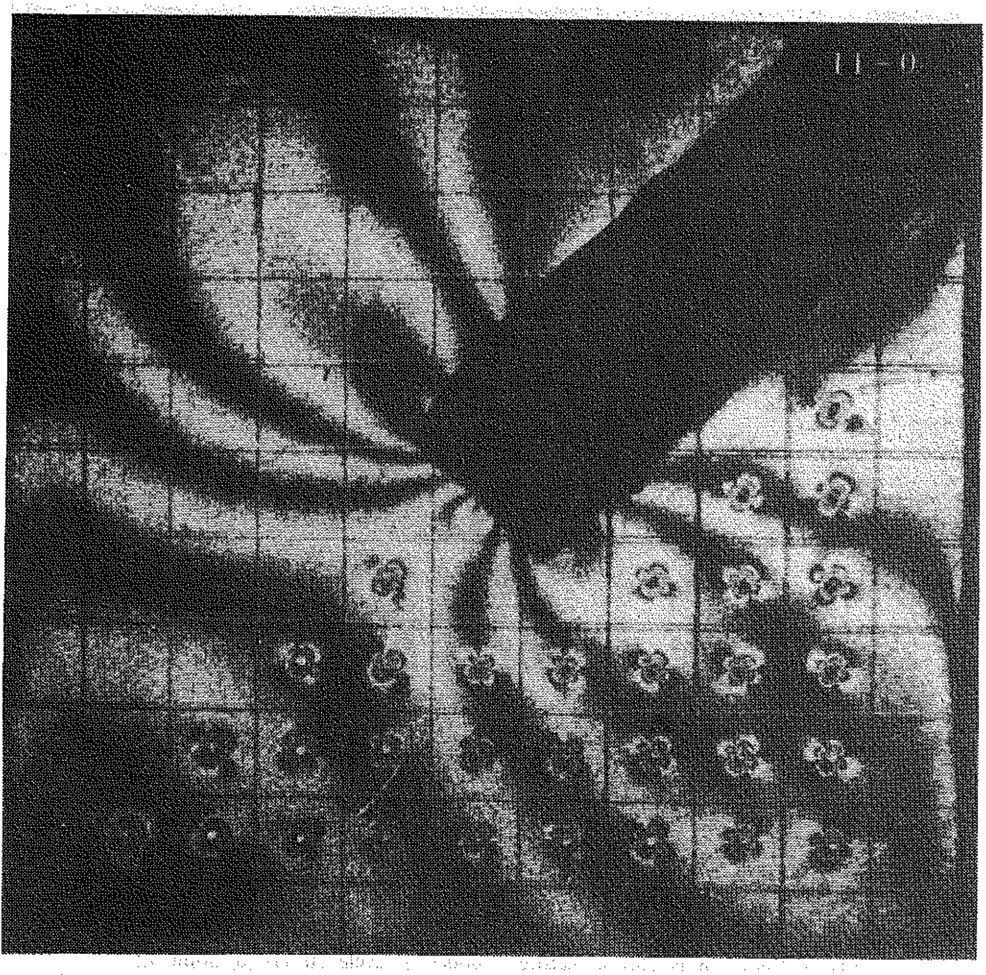

FIG. 7. Photo of isochrom picture — node 11, cycle A–B–0, point 0.

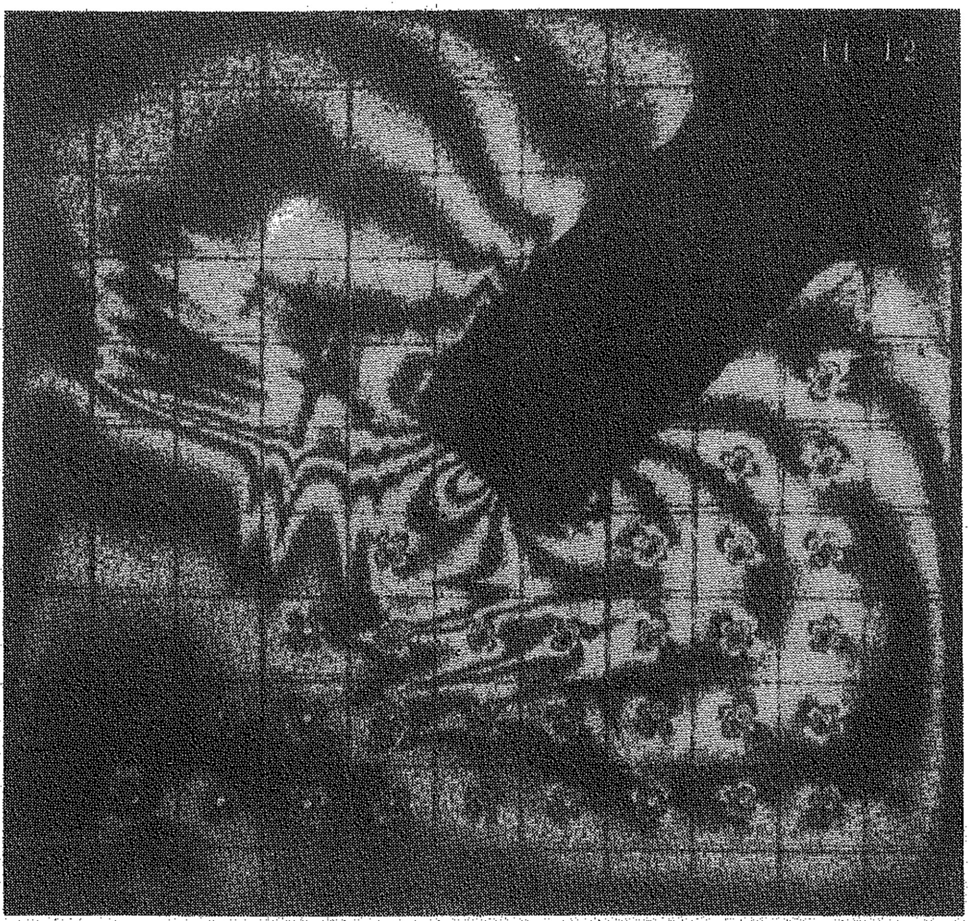

FIG. 8. Photo of isochrom picture — node 11, cycle 10–11–12, point 12.

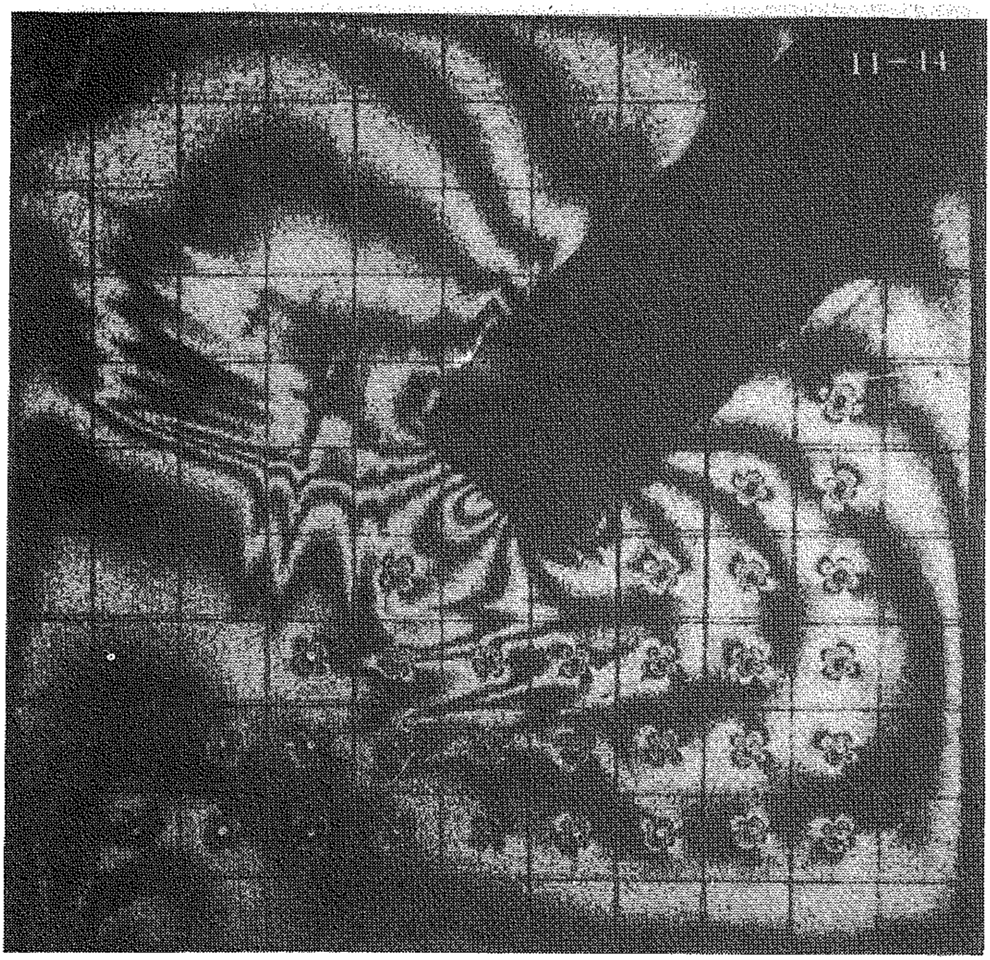

FIG. 9. Photo of isochrom picture — node 11, point 12–13–14, point 14.

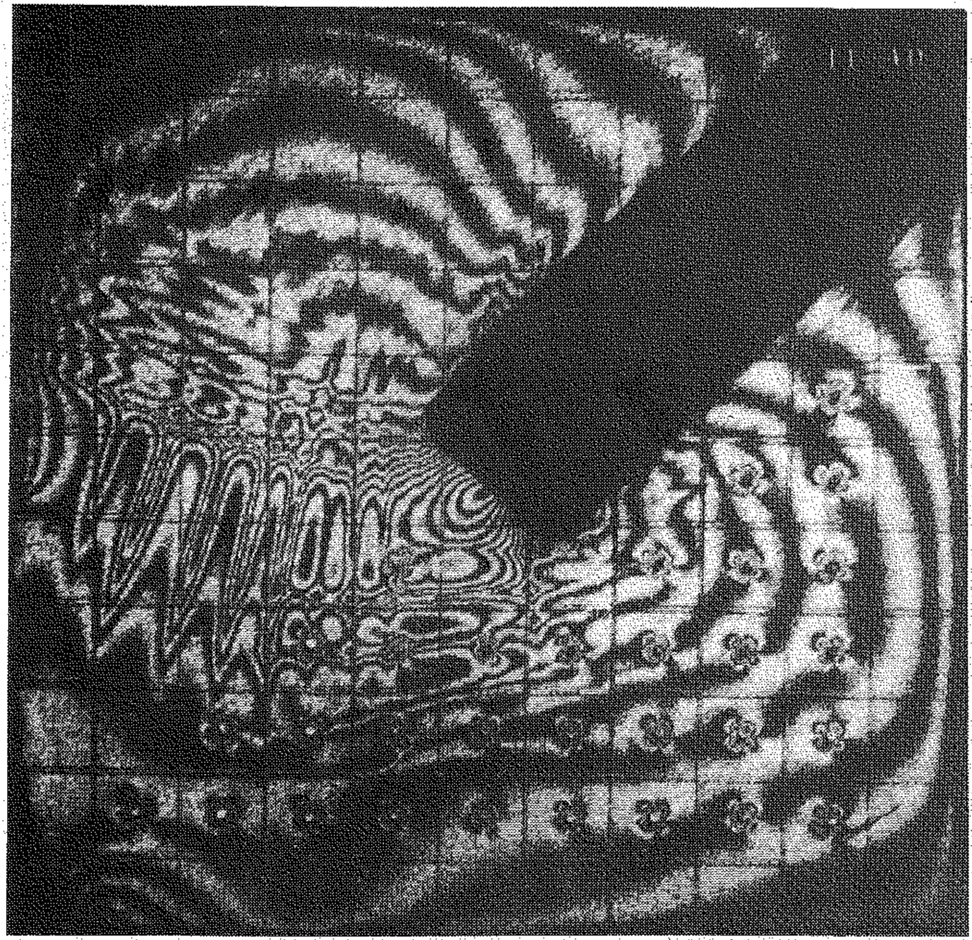

FIG. 10. Photo of isochrom picture — node 11, cycle 33–34–35, point 35.

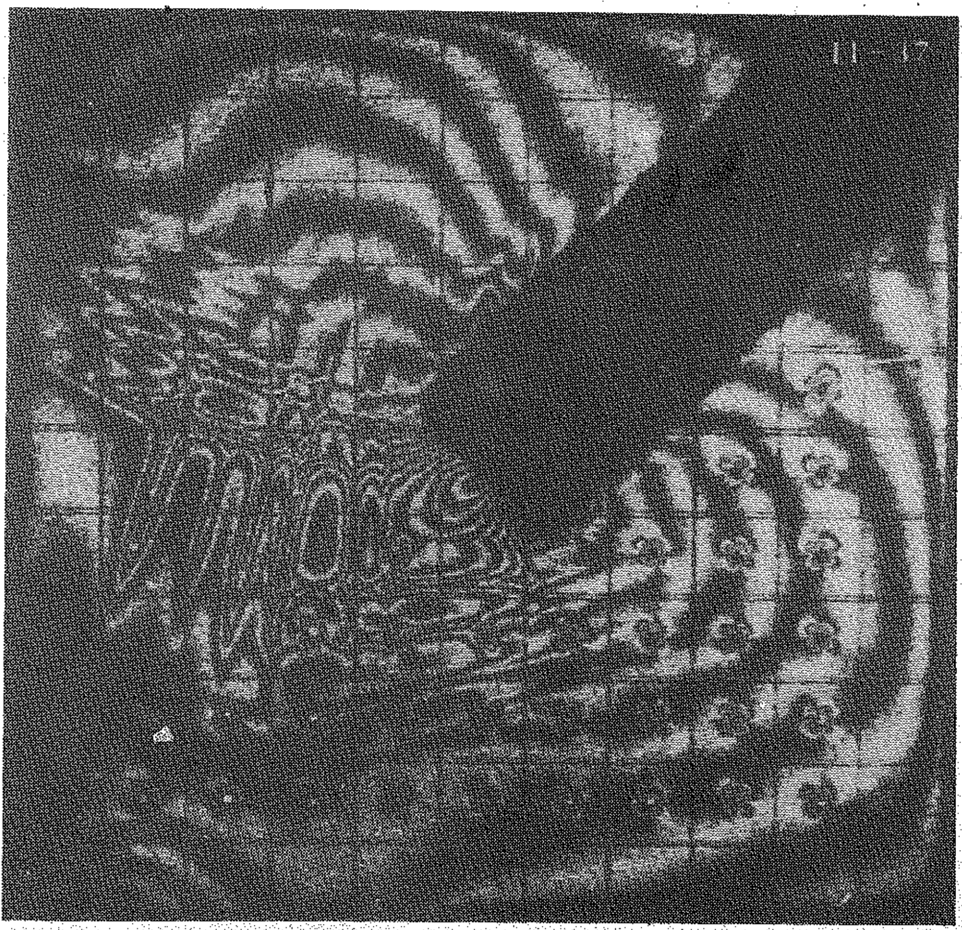

FIG. 11. Photo of isochrom picture — node 11, cycle 35–36–37, point 37.

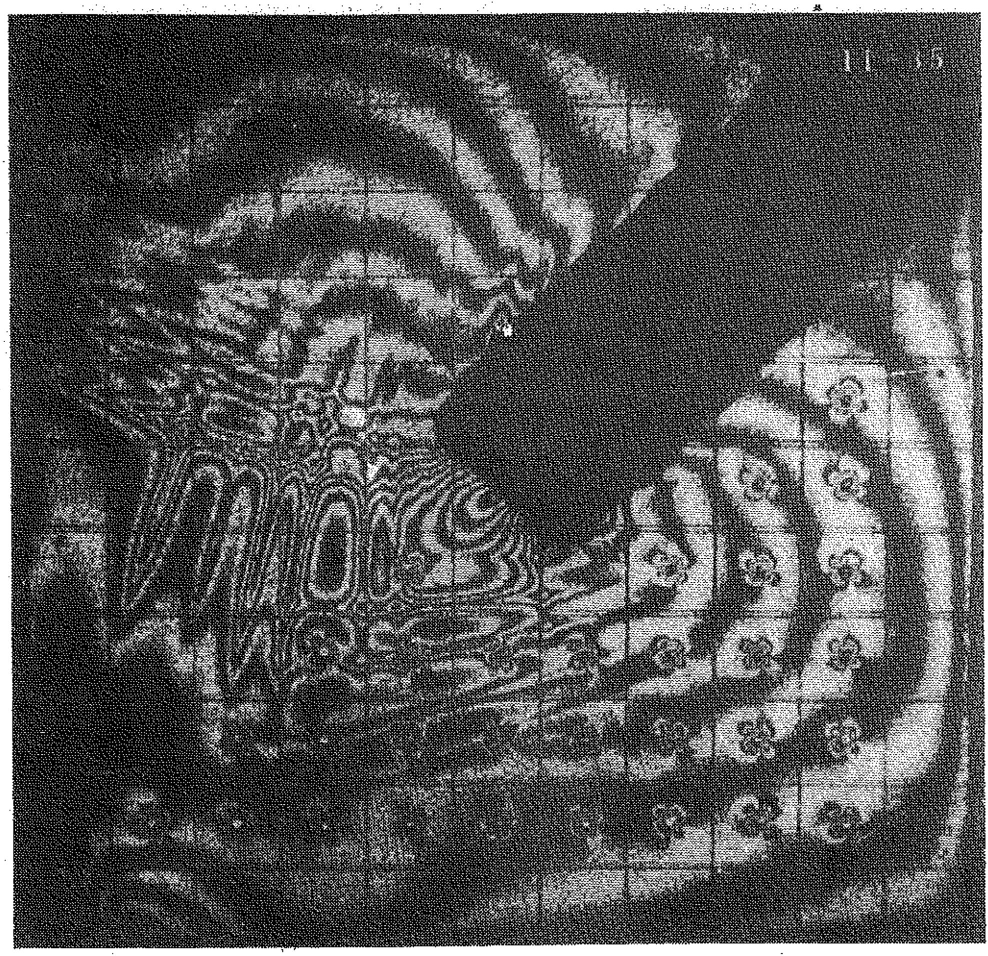

FIG. 12. Photo of isochrom picture — node 11, cycle 38–39–40, point 40.

Table 1. Result of the experimental investigations.

Series	Node No	Shakedown load (lower bound)		Ultimate load (calculated)	
		Lower plate kN	Vertical plate kN	Lower plate kN	Vertical plate kN
1	01	125.0	—	158.7	—
	02	135.0	—	158.7	—
	03	120.0	—	158.7	—
	04	105.0	—	158.7	—
	05	120.0	—	158.7	—
2	11	—	60.0	—	71.5
	12	—	57.0	—	71.5
	13	—	52.5	—	71.5
	14	—	57.0	—	71.5
	15	—	57.0	—	71.5

small local self-stresses in the vicinity of the holes. The photoelastic picture of that state, when superimposed on the applied stress, allows to determine the direction of principal stresses in the coating sheet. This, additionally can help in the comparisons of the pictures.

Table 1 gives a comparison of the experimental shakedown load with the theoretical magnitudes of the ultimate load obtained in previous investigations reported in [4].

5. CONCLUSION

1. It has been confirmed that the method enables to investigate shakedown of full-size nodes under cyclic loading.

2. The method, without major changes, could be employed to investigate nodes of more complex forms, e.g. with curvilinear surface. However, in such a case preparation of photoelastic coating would require more effort and attention.

3. Similarly to other cases, no direct correlation between the shakedown and ultimate load can be seen. In the first series of our investigations, the discrepancy between these two loads is considerable whereas in the second series it was much smaller.

4. It seems that also in the case of shakedown analysis, the assumption of limited interaction between different plates of the node and the lack of bending remain valid.

5. One could think about improving the technique of comparing the isochrom patterns, e.g. by means of telerecording and replay.

REFERENCES

1. H. B. WALKER, *The nodus space frame system*, 2nd International Conference on Space Structures, Guildford 1975.
2. J. KAPKOWSKI, J. STUPNICKI, *Badanie sprężysto-plastycznych płaskich stanów naprężeń metodą pokryć optycznie czynnych*, Arch. Bud. Masz., 1, 1971.
3. J. A. KARCZEWSKI, *Analiza sprężysto-plastycznej pracy obciążonych zmiennie konstrukcji prętowych*, Zesz. Nauk. Polit. Warszawskiej, Budownictwo, 46, Warszawa 1976.
4. J. A. KARCZEWSKI, J. CZERNECKI, J. A. KÖNIG, *The load-carrying capacity of space truss nodes composed of flat steel plates*, 3rd International Conference on Space Structures, Guilford 1984.

Резюме

ЭКСПЕРИМЕНТАЛЬНЫЙ АНАЛИЗ ПРИСПОСОБЛЕНИЯ УЗЛОВ ПРОСТРАНСТВЕННОЙ ФЕРМЫ

В работе рассмотрена проблема экспериментальной оценки несущей способности узлов пространственных ферм, подвергнутых действию нагрузки переменной во времени. Представлен метод оценки способности конструкций к приспособленщю, могущий найти примение так при проверке ресчетных теоретических моделей, как и непосредственно в процессе формирования конструкции. Рассуждения иллюстрированы результатами экспериментальных исследований, превеленными авторами в Варшавском Политинституте. Исследована способность к приспособлению пространственных узловж изготовленных из плоских стальных листов. Экспериментальные элементы изготовлены в натуральном масштабе. В первой серии исследованы нижние плиты узлов с ребрами, имитирующими воздействие вертикальных плит. Во второй серии исследованы полные узлы.

Измерение деформаций проведено при помощи поверхностного оптически чувствительного слоя и тензометров сопротивления.

Результаты экспериментальных исследований второй серии узлов показывают хорошее совпадение с аналитическими оценками. Немного большая расходимость результатов, полученных при исследовании первой серии, является результатом неучета в расчетах влияния ребер, помещенных на плите.

Streszczenie

DOŚWIADCZALNA ANALIZA PRZYSTOSOWANIA SIĘ WĘZŁÓW KRATOWNICY PRZESTRZENNEJ

Rozważono problem doświadczalnego szacowania nośności węzłów kratownic przestrzennych poddanych działaniu obciążenia zmiennego w czasie. Przedstawiono metodę oceny zdolności konstrukcji do przystosowania się, mogącą znaleźć zastosowanie zarówno przy weryfikacji obliczeniowych modeli teoretycznych jak i bezpośrednio w procesie kształtowania konstrukcji. Rozważania zilustrowano wynikami badań doświadczalnych przeprowadzonych przez autorów w Politechnice Warszawskiej. Badano zdolność do przystosowania się węzłów przestrzennych wykonanych z płaskich blach stalowych. Elementy doświadczalne wykonano w skali naturalnej. W pierwszej serii badano płyty dolne węzłów z żebrami symulującymi oddziaływanie płyt pionowych. W drugiej serii badane były kompletne węzły. Pomiar odkształceń prowadzono za pomocą powierzchniowej warstwy optycznie czułej i tensometrów elektrooporowych. Wyniki badań eksperymentalnych drugiej serii węzłów wykazują dobrą zbieżność z oszacowaniami analitycznymi. Nieco większa rozbieżność rezultatów uzyskanych przy badaniu pierwszej serii jest wynikiem nieuwzględnienia w obliczeniach wpływu żeber umieszczonych na płycie.

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