EXPERIMENTAL RESEARCH ON ELASTO-PLASTIC BEHAVIOUR AND COLLAPSE LOAD OF STATICALLY INDETERMINED SPACE TUBULAR BEAMS

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SUMMARY

Some models of tubular space beams, fixed at their flanged ends and subjected to a concentrated load, have been tested at "Istituto di Impianti Nucleari" (Nuclear Plants Institute) of Pisa University. The research has been supported by Comitato Nazionale per l'Energia Nucleare.

Structural Nuclear Codes permit or prescribe in some cases (particularly for emergency and faulted operating conditions) the use of plastic analysis techniques to compute the collapse loads of structures, normally a "collapse load-lower bound" calculated by limit analysis methods.

The aim of the present work is to check, by experimental verification, the adequacy of plastic analysis techniques, particularly limit analysis techniques, for the determination of the load carrying capacity for the particular matter of thin, tubular, statically indetermined space beams. Experimental results in the literature are really inadequate in this field. The work performed is a contribution to cover partially that inadequacy.

Ten models have been tested. Eight models are manufactured in stainless steel (AISI 316) and two in carbon steel (Fe 42). They have different diameters and different diameter-to-thickness ratios. The axis line is the same for all the models.

The models have been tested under quasi-static concentrated load, increasing until collapse. The collapse is caused mainly by combined action of bending and twisting moments. The load-deflection relationship and the plastic hinge formation mechanism have been studied. Particular attention, in the analysis of results, has been dedicated to local plastic instability and to out-of-roundness deformation effects of sections and to their influence on the collapse load.

The tests have been performed on a testing facility designed to the specific aim of these model structures.

The calculated values of collapse loads have been determined by limit analysis, on the basis of the lower-bound theorem, using linear programming on an IBM 360/67 system.

1. Introduction

Herein it is accepted the criterion of plastic analysis in nuclear power plant component design, subjected to particular operating conditions. Examples are the "emergency" and "faulted" conditions of the ASME III Pressure Vessel Code |1|. The collapse loads are determined by a limit analysis procedure on the basis of the lower bound theorem, considering a rigid-plastic behaviour of the material |2|.

At present there are but few data to control whether there is agreement between experiments and limit analysis results; this is particularly true where the structures are piping systems. Some studies |3,4,5| performed at Lehigh University concern large beams and frames. The beams are of I section. An old paper,written by Hill and Siebel |6|, presents experimental interaction curves representing bending moment-curvature and torsional moment-angle of twist for steel beams with circular section, loaded in elastic-plastic range by combined action of bending and torsional moments with costant ratio.

The present paper gives results of collapse tests on ten models of statically indetermined space tubular beams. Two models are of plain carbon steel (Fe 42 UNI 5334/64) and eight of stainless steel (AISI 316). The models are clamped by their flanged ends and are subjected to a concentrated load. The axis line and the position of the load have been chosed for obtaining a pronounced spatial condition, with bending and tortional moments of the same order of magnitude.

The experimental load-deflection curves are discussed in comparison with limit analysis results. During the collapse attention was placed to elasto-plastic buckling and tube cross section out of roundness phenomena.

The tests have been performed at "Istituto di Impianti Nucleari" of Pisa University.The researche has been supported by "Comitato Nazionale per l'Energia Nucleare" (CNEN).

2. Models and experimental apparatus

The ten models have the same axis line with three straight segments according to the three orthogonal axes x,y,z(fig. 1). The lengths of the segments are, in order, 375,1250,205 mm..The ends of the model are fixed to very rigid flanges by welding and a fixing device ficted with cones, placed into the tube.

The elbows segments are connected to the straigth ones with V butt welds.Standard elbows have been used.

Load acts in a plane parallel to the plane xz and forms an angle of 15° with z axis. It is applied to the segment y of the model, near the elbow that connects segments x and y. The application of the load to the pipe is made by means of an attachment that does not permit the local deformation of the cross section.

The models have the following diameters: 60.3, 70, 76 mm..The wall thickness are from 1.65 to 4.5 mm.. The dimensions of each model are in tab.I.

The yield strengths assumed (tab. I) are the average values obtained in the tests with two specimens of each model. The specimens have been obtained by some pieces of the tubes used for manufacturing the models and have been tested in the standard traction test.

The flanged ends of the model are clamped with bolts to a test apparatus designed to the specific aim of this research (fig. 2). The apparatus consists of a welded beam of hollow rectangular cross section. The beam has a considerable bending and torsional stiffness.The model flanges are fixed to two rigid supports connected to the beam by a bolted joint.

A structure for the application of the load to the model is fixed to the main beam of the device. The structure consists of two I beams trasversal frames. Over the frames is fixed a beam with the hydraulic jack for the application of the load. The jack is able to act with a maximum traction force of 5000 kg. and a maximum displacement of 150 mm.. The actionement is done through a manual pump. The jack is connected to the beam with the interposition of a sphericaljoint that permits the application of a pure force. The loading system from the jack to the attachmenton the model is constituted by a traction arm with two hinges and with a dial gage dynamometer interposed.

The load measure is made by reading the dial gagewhich shows the dilatation of the trasversal diameter of the ring shaped dynamometer. The dynamometer has been designed and built for the specific use of this research. The complete experimental apparatus is illustrated in fig. 3. Fig. 4 shows the arrangement for the measure of the deflection of the tube axis at a section . Several of these devices have been used for the determination of the deflection pattern. An open ring with a spherical external surface is fixed by means of three pressure screws on the section of the pipe where it is to be mesured the deflection. Two dial gage comparators, fitted with a plane disk, are pressed against the spherical surface of the ring to obtain the mesure of horizontal and vertical deflections. As the ring spherical surface center is placed on the axis of the pipe, the measured deflections are correlated to a point of the axis. On the same sections where the deflections are measured by means of the spherical rings, are connected two pendula for the measure of twisting and vertical bending rotations.

3. Limit analysis results

The numerical determination of the collapse load for the ten models has been performed by limit analysis procedure on the basis of the load-lower bound theorem. It has been considered significant for the yielding of the sections of the pipe the torsional and the bending moments only. For the elbows of the models have been used the flexibility factors calculated by the equation $k=1.65/h$, where h is the ratio of product bend radius of the curve for the pipe wall thickness to mean radius of the pipe, as indicated in ASME III Code.

To perform the analysis, the model axis has been divided in eigth segments. The nodal points between consecutive segments should be selected where is possible the plastic hinge rise in agreement with limit analysis. Points of this type are surely those at the ends of the straigth parts of the model and the point under the load. On the contrary it is not "a priori" determined the position of the possible plastic hinges in the elbows, on account of the non linear behaviour of torsional and bending moments along the axis. The elbows are indeed short and by consequence it is an acceptable approximation to consider nodal points the middle of the curve axis.The other nodal points are, of course, the ends of the straigth segments and the point under the load. It has been then considered an isostatic system obtained from the hyperstatic one corresponding to the model beam outline, by the elimination of some connections. At last the three stress characteristics (two bending moments and torsional moment) have been written as function of the load and of the six hyperstatic quantities of the structure. This has been made for each nodal point. A total of 27 relations has been obtained. It has then been evaluated the yield condition in the cross sections corresponding to each nodal point. The yield condition here considered is given by a spherical surface in the space determined by three variables (the three moments).

With the replacement of the obtained relations in the yield conditions 9 disequations have been obtained with 7 unknown values: the collapse load and the six hyperstatic quantities. The maximum load that satisfies the disequations is a less than or equal to the collapse load. This is due to the lower-load bound theorem of limit analysis. An approximation which has been introduced for making easier the calculus consists in the linearization of the yield surface. The spherical surface has been replaced by an inscribed polyhedral one with 48 triangular faces. The linear programming problem given by the system of the obtained equations and disequations for each face of the polyhedron has then solved by means of MOSS program on an IBM 360/67 System.

The tab. II shows the calculated collapse loads. P_L is collapse load calculated on the basis of experimental yield stress obtained with the specimens of the material used for the models. P_L^* is instead calculated on the basis of yield stress specified in standard tables for the the two materials used for the models.

4. Tests and tests results

The load has been applied to the models on smoothly, gradually changing way, with the aim of not introduce time effects.

Fig. 1 and tab. I show the sections where have been measured deflections and rotations.

Figures 5, 6, 7 show some curves which represent load-vertical deflection for the C section (the nearest one to the load). Diagrams of figures 5, 6, 7 also show loads P_L, P_L^* and the conventional experimental collapse load P_E (see the next paragraph).

Fig. 8 gives, as an example, the shape of model 9 at the end of the collapse test. The deflections are in the same scale of the model drawing.

During the tests attention has been dedicated to local plastic instability and to the elbows cross sections out of roundness phenomena. The first effect was present only where the pipe was clamped in the vertical flange. Photograph of fig. 9 shows the wrinkle occurred in the model 4 for elasto-plastic buckling. Other models have presented the same phenomena, but with less effect. Otherwise, the instability effects manifested themselves after the models were highly deformed in plastic manner.

As an example, fig. 10 shows some diagrams with the deformation of two perpendicular diameters of the cross sections of the elbow, which has the axis in the yz plane, for the model 9.

5. Discussion of results and conclusion.

A comparison between the experimental results (in practice the load-deflections curves) and the calculated collapse loads obviously requires a previous definition of "experimental collapse load". Every such definition is always partially subjective. According to the proposed definition of "experimental limit pressure" for internal pressure vessels |7| , for tested models can be defined as follow the experimental collapse load P_E: the load which causes a deflection, measured on a suitable section of the beam axis, equal to three times the value which can be obtained for the same load, in the hypothesis of elastic and linear structural behaviour. In practice, this load can be determined intersecting the load-deflection curve with a straigth line drawn through the origin of the axes; this line must be inclined in respect to the load axis at an angle which has the tangent equal to three times the tangent of the angle of the line which describes the elastic behaviour of the structure (figures 5,6,7).

In table II, for each model, there are reported the following values:

- the experimental collapse load P_E, defined as before;
- the collapse load P_L, calculated on the basis of limit analysis and of the experimental yield stress (0,2% permanent strain yield stress) for each model;
- the collapse load P_L^* calculated on the basis of the minimum standard tables material yield stress;
- the ratios P_E/P_L and P_E/P_L^* .

The ratio P_E/P_L for the models 1 and 10 manufactured with plain carbon steel results respectively 1.11 and 1.31; for the eigth models in stainless steel the same ratio results variable between 1.16 and 1.39. The ratio P_E/P_L^* gives the values 1.96 and 1.72 for the models 1 and 10, and values between 1.28 and 1.83 for the other models.

Therefore for all models the experimental collapse load is quite large than the calculated one on the basis of the actual material yield stress. For this reason the calculus results bring always to a safe evaluation. This is more true if we consider that the before defined experimental collapse load still corresponds to small deflection of the model, while the load is still growing with the deflection. Really, during some tests (i.e. models 7,9, 10) that have been carried on until the C point deflection was three times the one obtained for the load P_E, the load was always growing with the deflection. In the model 5 test has been reached the condition of growing deflection at constant load for a load 1.2 times the load P_E and with a deflection more than three times the one that corresponds to P_E.

The positive difference betweeen the experimental and the calculated collapse load is partially due to the fact that the limit analysis theory neglets the material strain hardening when the elastic limit is exceeded. There are other approximations which determine a reduction of the calculated load: first the use of the load-lower bound theorem of limit analysis; second the replacement of the surface corresponding to the yielding condition by an inscribed polyhedron.

There is some remarkable difference between qualitative behaviour of the models in Fe 42 and those in AISI 316 illustrated in the figures 5, 6, 7. The curves regarding the models 1 and 10 in Fe 42, present pronounced knees corresponding to the plastic hinges forming. This is clearly due to the strain hardening smaller for plain carbon steel than for stainless steel.

Other factors that justify a difference between calculated and experimentals loads are due to the local buckling and to the curves cross sections out of roundness phenomena that have occurred during the tests.

For all the models the displacements of the pipe have been qualitatively similar to those shown in fig. 8 for the model 9. The first yield hinge has always occurred in correspondence to the vertical flange. Near to the same flange has also always occurred the buckling with wrinkle forming (photo in fig.9 for the model 4). In practice the collapse mechanism starts with the rise of a second hinge at the curve which lies on the yz plane (fig. 1).

In the load deflection curves never there is an irregularity of the shape due to sudden appearing of the buckling phenomena. In agreement with what said before it is possible that buckling phenomena may have but small influence on experimental collapse load. Likewise it is probable that cross section out of roundness phenomena have a small influence on collapse loads too.

The ratio P_E/P_L^* represents an interesting index og the safety coefficient that we really should have in case of design based on standard yield strength data. The spread values of the ratio P_E/P_L^* are quite to ascribe to the spread values of the real yield strength of the materials. An important conclusion which can be drawn is that the ten models, two manufactured in plain carbon steel and eight in stainless steel, made up with pipes each of different diameter and wall thickness, of spatial axis line and clamped at the flanged ends, have always shown an experimental load capacity greater than the calculated one on the basis of limit analysis.

On the basis of the conventional experimental collapse load, as before defined, the ratio P_E/P_L has always resulted greater than 1.1.

The difference between experimental and calculated collapse load values may be justified by several factors influence.

The ASME III Code |1| for nuclear power plant components prescribes that in the operative conditions "emergency" and "faulted", if a limit analysis procedure is used for the design, the admissible load should be not greater than 0.8 and 1 the calculated one. The results of the present experimental research justifies this assumption.

ACKNOWLEDGEMENT

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Table I - Models dimensions and material yield stress.

Model	Material	ø (mm.)	t (mm.)	a (mm.)	b (mm.)	c (mm.)	d (mm.)	e (mm.)	R (mm.)	σ_y (kg./mm.^{2})	σ_y (kg./mm.^{2})
1	Fe 42	60.3	3.50	273	579	-	250	-	80	40.7	23.0
2	AISI 316	60.3	3.90	220	700	1100	270	90	80	26.5	24.0
3	AISI 316	60.3	2.60	220	700	1100	270	90	80	31.5	24.0
4	AISI 316	60.3	1.65	220	700	1100	270	90	80	24.8	24.0
5	AISI 316	70.0	2.00	220	700	1100	270	90	95	35.0	24.0
6	AISI 316	70.0	2.90	220	700	1100	270	90	95	27.6	24.0
7	AISI 316	70.0	4.50	220	700	1100	270	90	95	28.2	24.0
8	AISI 316	76.0	2.00	220	700	1100	270	90	90	32.2	24.0
9	AISI 316	76.0	3.70	220	700	1100	270	90	90	27.4	24.0
10	Fe 42	76.0	2.90	220	700	1100	270	90	90	31.2	23.0

Table II - Calculated and experimental loads.

Model	Material	(mm.)	(mm.)	P_L (kg.)	P_L^* (kg.)	P_E (kg.)	P_E/P_L	P_E/P_L^*
1	Fe 42	60.3	3.50	1930	1090	2140	1.11	1.96
2	AISI 316	60.3	3.90	1380	1250	1725	1.25	1.38
3	AISI 316	60.3	2.60	1143	870	1595	1.39	1.83
4	AISI 316	60.3	1.65	573	554	707	1.23	1.28
5	AISI 316	70.0	2.00	1356	930	1570	1.16	1.69
6	AISI 316	70.0	2.90	1510	1310	1900	1.26	1.45
7	AISI 316	70.0	4.50	2284	1990	2640	1.15	1.33
8	AISI 316	76.0	2.00	1476	1100	1805	1.22	1.64
9	AISI 316	76.0	3.70	2220	1950	2740	1.23	1.40
10	Fe 42	76.0	2.90	2025	1550	2680	1.31	1.72

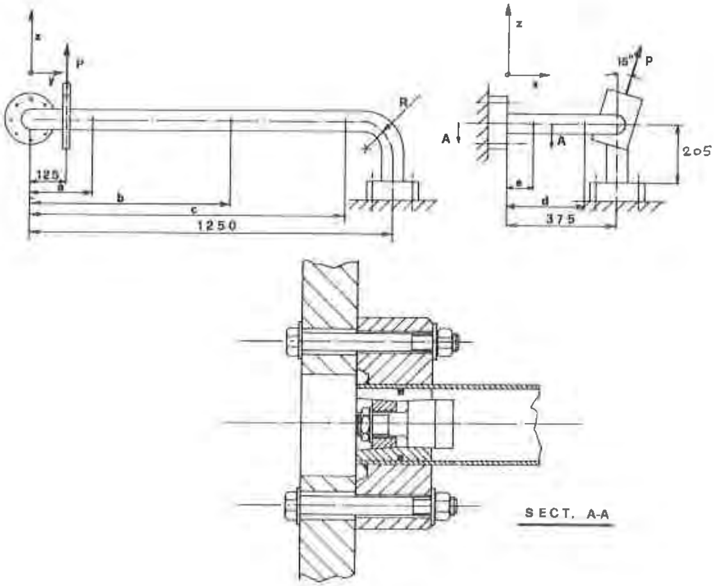

Fig. 1 - Models

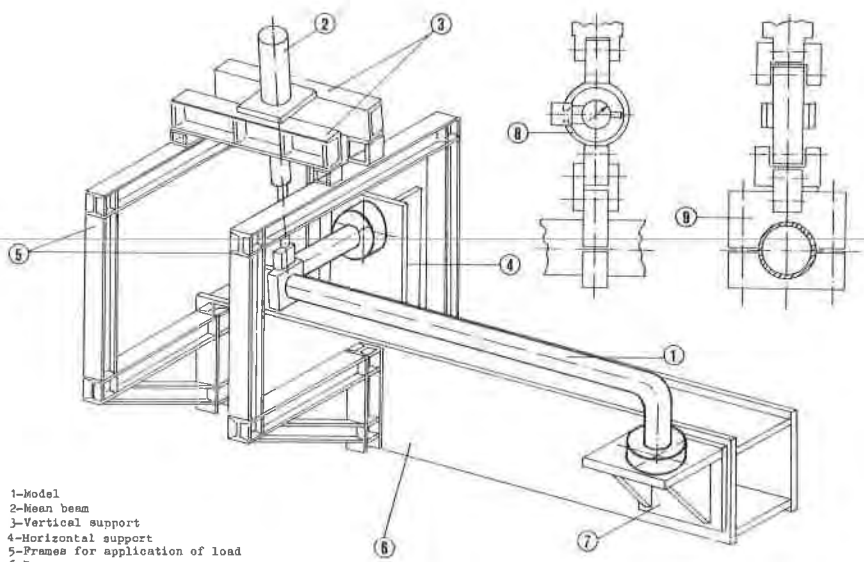

Fig. 2 - Sketch of the test apparatus

Fig. 3 - Test apparatus

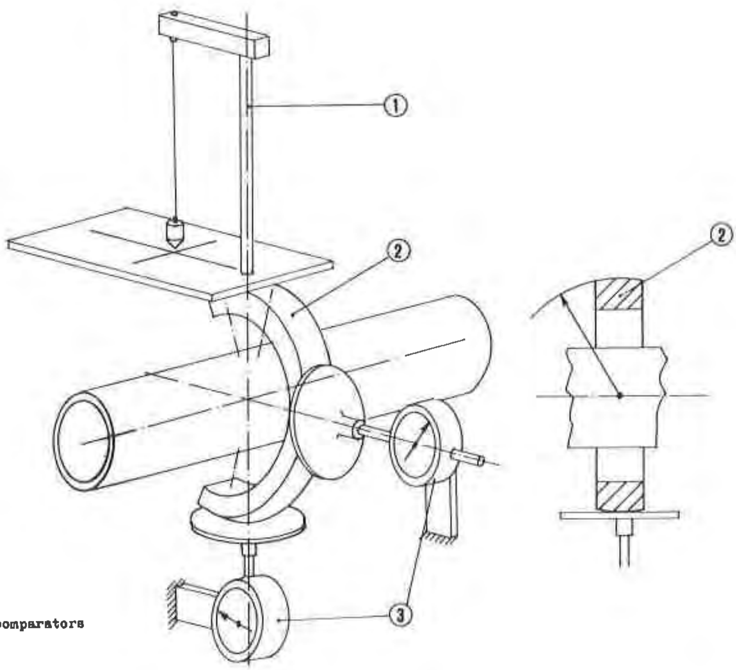

Fig. 4 - Device for measuring deflections and rotations

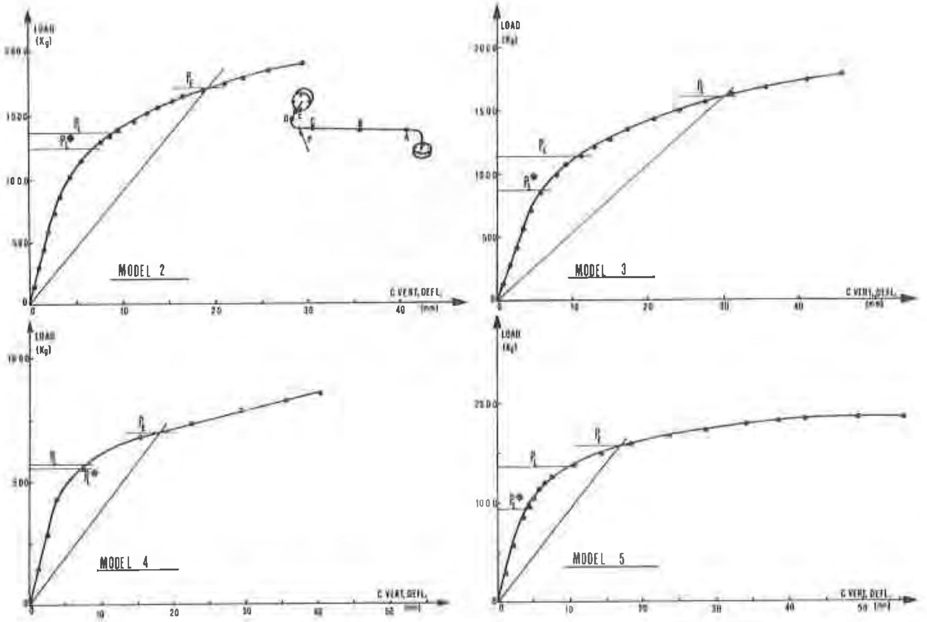

Fig. 5 - Load-deflêctions curves

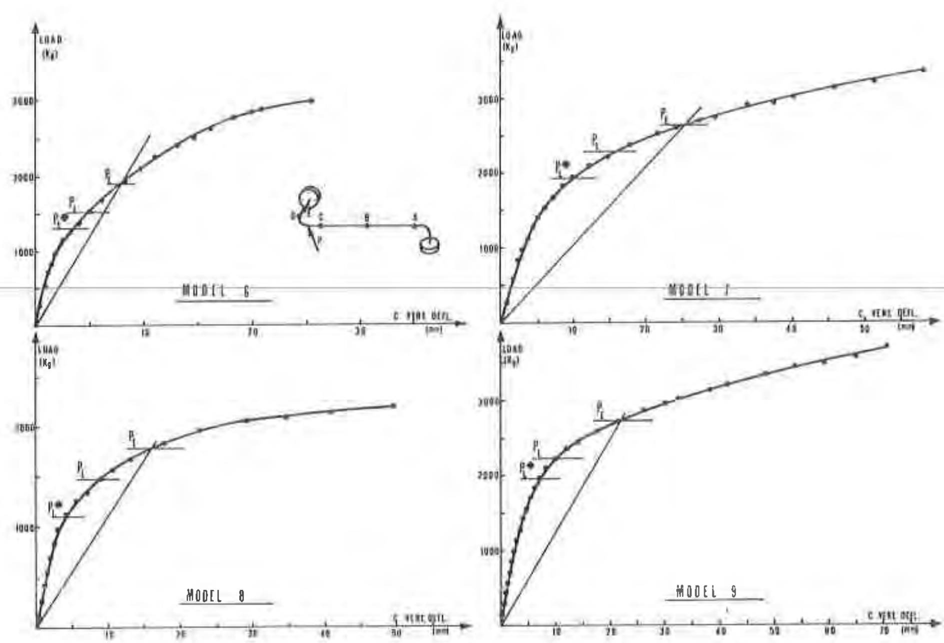

Fig. 6 - Load-deflections curves

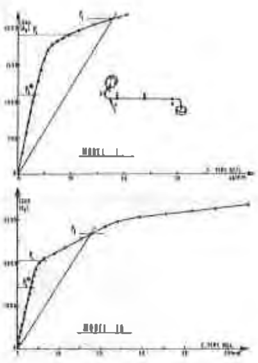

Fig. 7 - Load-deflectibns curves

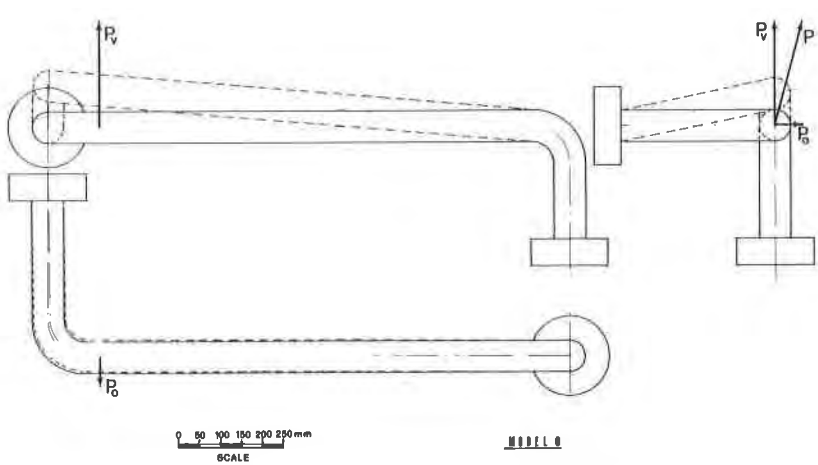

Fig. 8 - Deformed model shape

Fig. 9 - Local buckling (model 4)

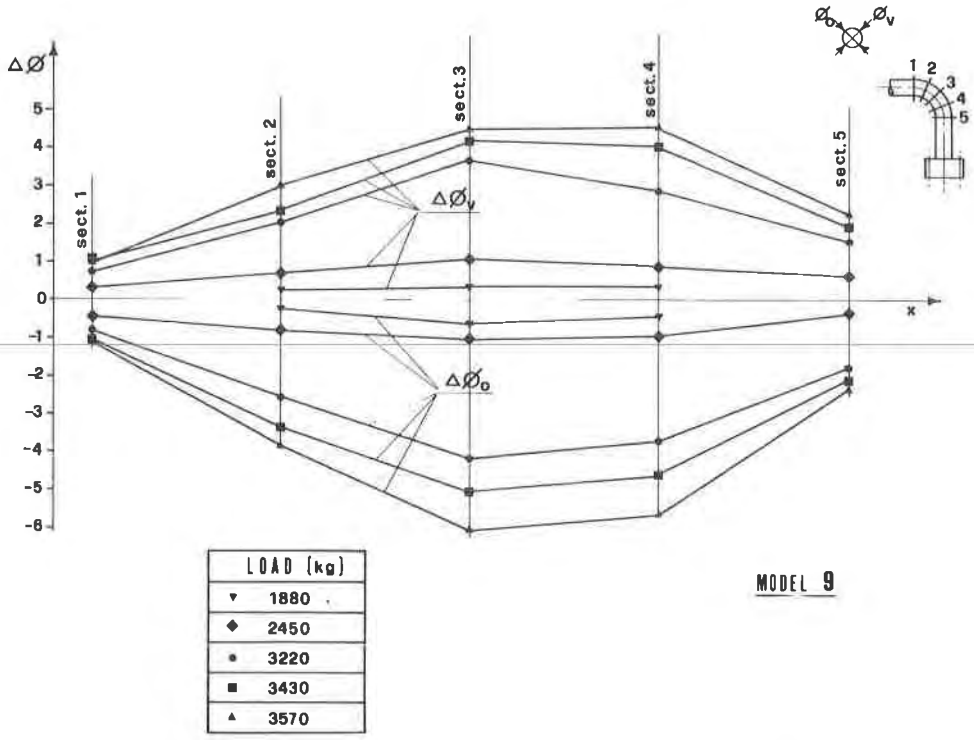

Fig. 10 - Elbow cross-section out of roundness