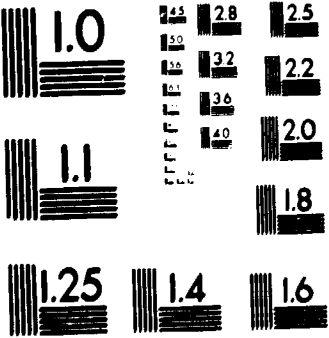

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

ISSN/0393-6287

RT/FUS/87/35

A. PIZZUTO, R. CERRETA, E. DI PIETRO

STABILITY OF A STIFFENED TOROIDAL SECTOR UNDER UNIFORM EXTERNAL PRESSURE

IT8900005

COMITATO NAZIONALE PER LA RICERCA E PER LO SVILUPPO DELL'ENERGIA NUCLEARE E DELLE ENERGIE ALTERNATIVE

ISSN/0393-6287

COMITATO NAZIONALE PER LA RICERCA E PER LO SVILUPPO
DELL'ENERGIA NUCLEARE E DELLE ENERGIE ALTERNATIVE
Associazione EURATOM-ENEA sulla Fusione

STABILITY OF A STIFFENED TOROIDAL SECTOR UNDER UNIFORM EXTERNAL PRESSURE

A. PIZZUTO, R. CERRETA, E. DI PIETRO
ENEA - Dipartimento Fusione, Centro Ricerche Energia Frascati

RT/FUS/87/35

Testo pervenuto nel luglio 1988
Progetto Enea: Realizzazione macchina Tokamak FTU (DB)

This report has been prepared by: Servizio Studi e Documentazione - ENEA, Centro Ricerche Energia Frascati, C.P. 65 - 00044 Frascati, Rome, Italy.

This Office will be glad to send further copies of this report on request.

Summary This paper presents the results of a stability analysis on a sector of the FTU (Frascati Tokamak Upgrade) toroidal vacuum vessel.FTU is an experimental machine, now under construction, mainly devoted to the study of the effects of lower hybrid radiofrequency heating on plasmas in reactor relevant conditions. Its vacuum chamber is a stainless steel structure completely welded with a major radius of 0.935 m and a minor radius of 0.335 m consisting of 12 toroidal thin sectors joined together by thick ribs.This structure is loaded by compressive electromagnetic forces both in toroidal and in radial direction that can create instability conditions. One of the major problems in its design is to determine the points where this phenomenon is likely to occur in order to avoid dangerous buckling situations. Theoretical analysis of the stability behaviour of one of these sectors has been conducted by means of the ABAQUS finite element code. The critical load has been determined by a classical algorithm and by the modified Riks method. Both methods have given similar results in an elastic analysis. Furthermore the second one has been applied also using an elastoplastic model of the material to determine the critical load and the post buckling behaviour of the structure. Experimental tests have been conducted on a full scale model of the toroidal sector. The model has been placed in a large tank filled with water where the pressure has been gradually increased up to the collapse of the structure. The theoretical and experimental results have been compared and a good agreement has been found between them.

Riassunto Questo lavoro presenta i risultati di una analisi di stabilità di un settore della camera da vuoto del Tokamak FTU (Frascati Tokamak Upgrade). FTU è una macchina sperimentale, attualmente in costruzione, destinata allo studio degli effetti del riscaldamento mediante radiofrequenza su di un plasma in condizioni quasi reattoristiche. La camera da vuoto di FTU è una struttura toroidale in acciaio austenistico saldata: ha un raggio maggiore di 0.935 m e un raggio minore di 0.335 m suddivisa in 12 settori sottili uniti mediante settori spessi recanti gli accessi per le diagnostiche, il sistema di pompaggio ecc. Questa struttura è sottoposta a carichi elettrodinamici di compressione agenti sia in direzione toroidale che radiale i quali possono creare condizioni di instabilità. Uno dei problemi più critici della sua progettazione è quello di determinare le condizioni in cui la struttura diventa critica in modo da evitare situazioni di collasso. L'analisi teorica del comportamento di questa struttura è stata condotta mediante il codice ABAQUS. I carichi critici sono stati determinati usando sia gli algoritmi classici sia il metodo di Riks modificato. I due metodi hanno dato risultati analoghi in regime elastico. Inoltre il secondo è stato usato per fare una più realistica analisi elasto-plastica. I valori così calcolati sono stati confrontati con quelli ricavati da una prova sperimentale su di un modello scala 1:1 eseguito dentro un serbatoio pressurizzato con acqua. I risultati teorici e quelli sperimentali sono in ottimo accordo.

1. INTRODUCTION

Components of fusion nuclear reactors are loaded by heavy electromagnetic compressive forces that can generate instability phenomena in the structures.

One of the major elements in these machines is the vacuum chamber used to contain the plasma and assure the existence of vacuum within the tokamak.

This paper regards the study of instability in FTU (Frascati Tokamak Upgrade) vacuum chamber.

This machine, now under construction, is mainly devoted to the following scientific objectives [1]:

a) the study of confinement at reactor relevant conditions with medium high plasma density in presence of strong additional radiofrequency (RF) heating;

b) the study of RF heating in reactor conditions of electron-ion coupling;

c) the study of plasma-edge physics close to reactor conditions;

d) the study of RF current drive at relatively high density.

The vacuum chamber (Fig. 1) is a stainless steel structure completely welded with a major radius of 0.935 m and a minor radius of 0.335 m consisting of 12

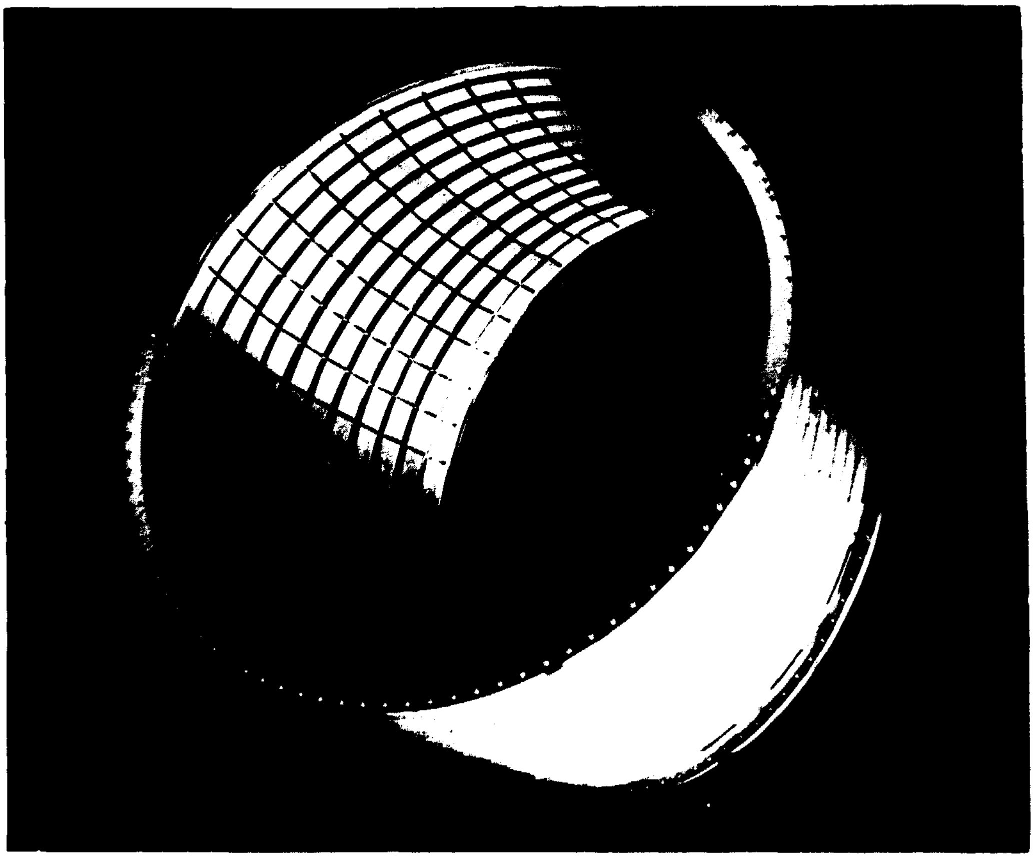

Fig. 1 FTU vacuum chamber sector

toroidal thin sectors joined together by thick rigid sectors which incorporate 6 equatorial ports alternated to 6 full tees

In the following pages behaviour of one thin sector of this chamber has been analyzed. The sector has been considered of an isolated structure closed by two circular thick plates fixed to the end flanges. This component is loaded by an external uniform pressure that can generate buckling phenomena.

The study has been carried out by means of the following steps:

☐ an analytical evaluation on a straight pipe with the same geometrical dimensions of the sector;

☐ a theoretical approach by ABAQUS finite element code with a classical eigenvalues algorithm;

☐ a further study by the same code using Riks algorithm;

☐ an experimental investigation on a full scale model loaded by hydrostatic pressure.

2. CALCULATION MODEL

The sector is formed by a two millimeter thick shell stiffened by twelve circular ribs spaced by a 2° angle about the vertical axis of the torus. Furthermore at both ends two thicker ribs are present to allow the coupling to the other sectors of the tokamak (Fig. 1).

The presence of two thick circular plates at both ends of the sector has been simulated with a very large increase of the rigidity of the external ribs.

This component has been modelled by means of a mesh consisting of by 8-node shells and 2-node beams.

The shells are doubly curved thin semi-Loof elements (2). The beams are classical Euler-Bernoulli elements whose cross-section is assumed not to be deformed in its plane, or warp out of its plane, and to remain normal to the beam axis. These elements give satisfactory results for thin structures.

The mesh has been made by the pre-processor *COCO* belonging to the *CASTEM* family of calculus codes and is illustrated in Fig. 2.

It is useful to emphasize that the sector has a thermal shield in its interior to avoid dangerous thermal stresses during operation. This inner wall has a large number of cuts and its contribution to the stiffness of the structure is negligible. On the other hand its mass is not negligible so that it has been modelled by lumped masses placed in the nodes of the ribs.

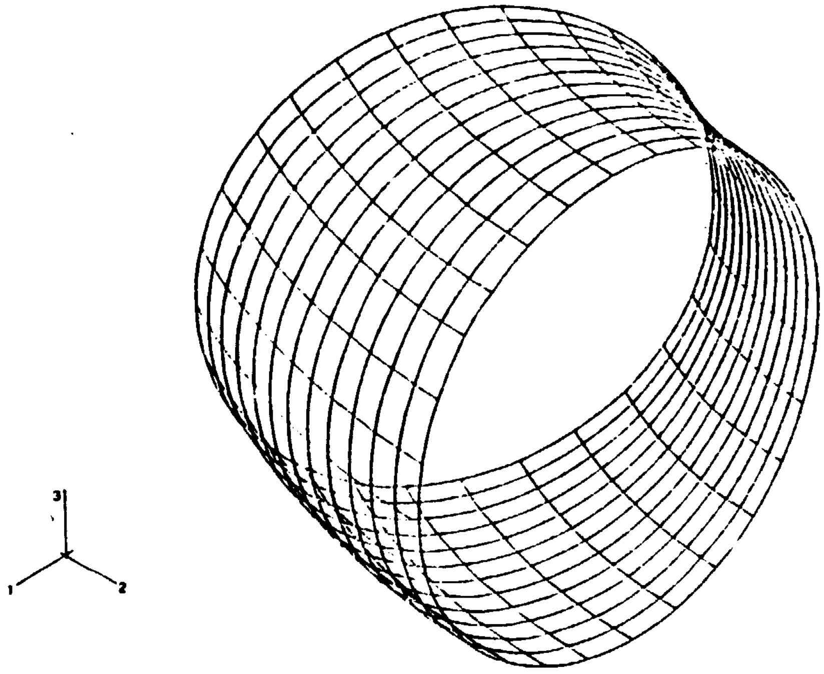

Fig. 2 FTU vacuum chamber mesh

In the first evaluations, the material (AISI 304 LN) has been assumed elastic while the following calculations, carried out by the Riks method, have been performed taking into account plasticity both with and without hardening.

The following properties have been assumed:

a) Young's modulus = 210 GPa
b) Poisson coefficient = 0.30
c) yield strength = 270 MPa
d) first hardening slope = up to 390 MPa, 0.035 strain
e) second hardening slope = up to 435 MPa, 0.07 strain

The stress-strain curve is shown in Fig. 3.

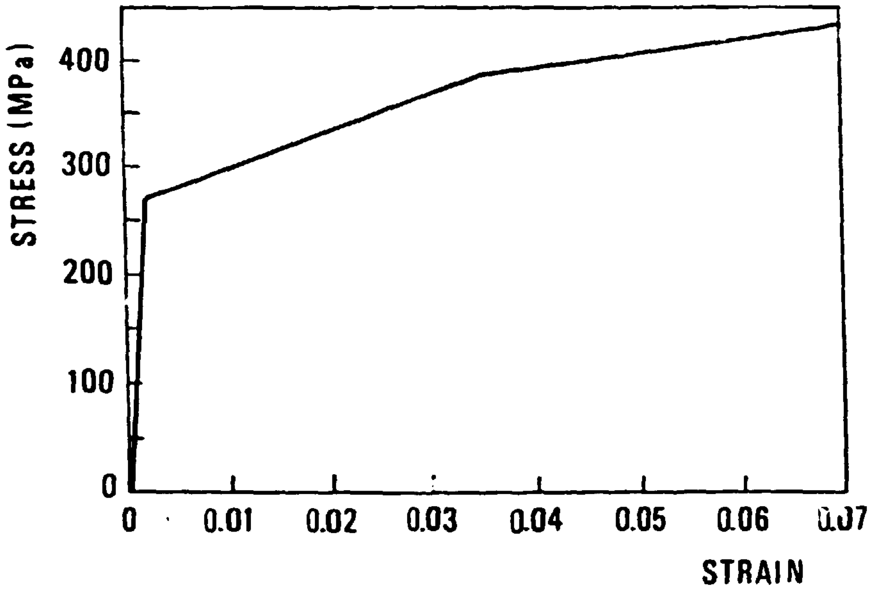

Fig. 3 AISI 304 LN stress-strain curve

3. THEORETICAL RESULTS ON A STRAIGHT PIPE CLOSED AT THE ENDS LOADED BY UNIFORM EXTERNAL PRESSURE

The calculation has been carried out following the approach of Timoshenko [4]. It is based on the combination of the differential equations of equilibrium of a cylindrical shell under separated axial load and uniform lateral pressure pipe is. reinforced by equally spaced (pitch 32.6 mm) circumferential ribs. The end plates are supposed simply suppported by the pipe.

The method consists in changing the flexural rigidity along the axial direction with the aim to consider the presence of ribs. This operation permits to solve the problem in the same manner as a simple cylindrical shell.

Different combinations of the number of half-waves in the axial direction and in the circumferential direction have been supposed and, for each one of them, the buckling load has been calculated. The lowest pressure, obviously the most dangerous one, has been evaluated equal to 280 MPa. This value resulted lower than the critical load evaluated in the next paragraph by means of a FEM code on a toroidal model of the vacuum chamber sector. This is a consequence of the increased global rigidity of the toroidal shape with respect to a straight pipe.

4. FEM RESULTS IN ELASTIC DOMAIN

The first calculations by the finite element code ABAQUS have been performed with an elastic model of the material. This study usually gives a critical load higher than the experimental value but it provides an idea on the role of the plasticity during the buckling by comparison with the exact solution. The calculation has been carried out by two different algorithms.The first one is the resolution of a classical eigenvalues problem and the latter (the Riks method) allows to follow the load/displacement path during the application of the load.

We give now some further informations about these two types of procedures.

a) Eigenvalues prediction. This evaluation provides the calculation of the dead state and the live loads of the structure [2].

The first one consists in the determination of the linear stiffness matrix of the structure when loads are not applied in the initial configuration.

The live loads are, instead, the nominal loads that can cause instability phenomena.

The problem consists in the determination of the factor that multiplied by the nominal load gives the critical load. In the load state the elastic stiffness can be written:

$$KT = KD + KL$$

where:

KD = elastic tangential stiffness of the structure in the initial configuration

KL = the change in stiffness from the initial configuration to the loaded one.

After the calculation of KT, the essence of the linearized buckling analysis is the solution of the equation (5)

$$\det (KD + \lambda KL) = 0$$

where the eigenvalue λ is the unknow multiplier of the of the nominal loads that cause the buckling.

This approach is based on the assumption that the change in stiffness varies linearly with the magnitude of the live load. This could be not valid for our case as our structure can be flexible , that is it can exhibit considerable non-linearity in its behaviour prior to buckling.

b) Riks method. This method allows to obtain non linear static equilibrium solutions for unstable problems where the loads and/or the displacements may decrease as the solution evolves.

The algorithm is based on the discovery of a single equilibrium path in a space defined by the nodal variables and the loading parameter. This is a factor that multiplies all load magnitudes along the equilibrium path and represents the unknow value of the problem.

Development of the solution requires that we move along this path as far as required. The basic algorithm is the Newton method, and therefore at any time there will be a finite radius of convergence. In ABAQUS a modified Riks algorithm [2] it has been implemented. This is done by moving a given distance along the tangent line to the current solution point, and then searching for equilibrium in the plane that passes through the obtained point and that is orthogonal to the same tangent (see Fig. 4).

The calculus by the eigenvalue algorithm has provided a critical pressure equal to 350 MPa that is much higher than the experimental buckling load of 158 MPa. This result evidences the fact that the structure is object of deformations in plastic field that decrease the rigidity of the structure.

To confirm this interpretation and to have an indipendent check of the used procedure, the same calculation has been repeated by the Riks method.

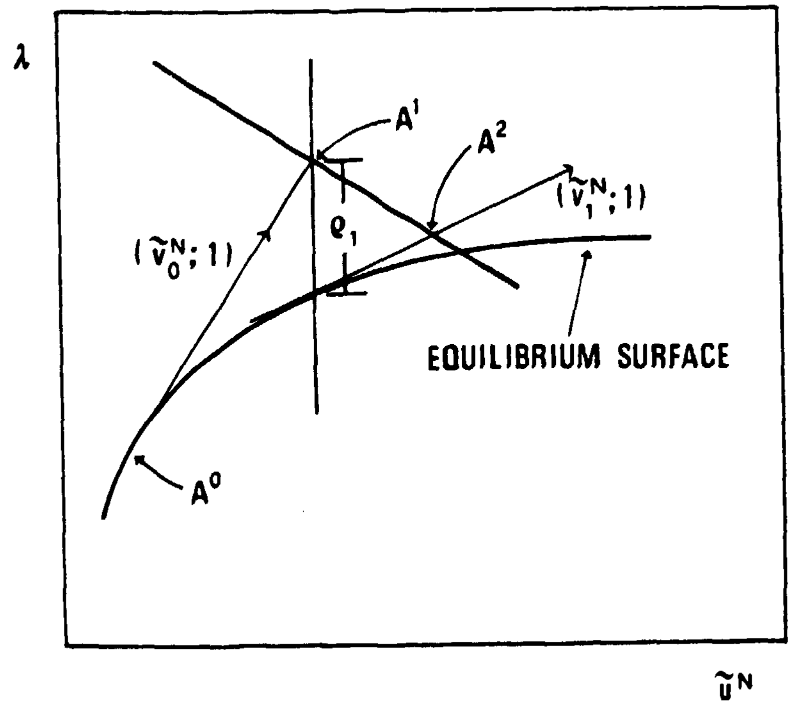

Fig. 4 Riks algorithm

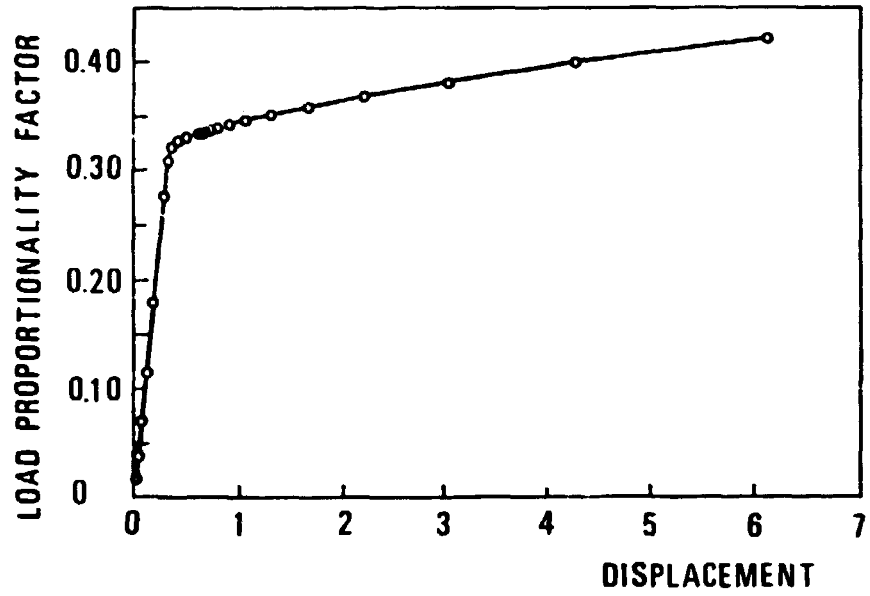

Fig. 5 Load-displacement history with Riks method and elastic material. *The load is obtained by multiplying the load proportionality factor by 100 MPa*

This algorithm has permitted to calculate a critical hydrostatic pressure of about 340 MPa (see Fig. 5).

5. RESULTS IN ELASTO-PLASTIC DOMAIN

The successive calculations have been performed in the hypothesis that the material is both elasto-perfect plastic and elasto-plastic with hardening as already indicated in Fig. 3 .

The responses of the Riks method are illustrated in Fig. 6 and Fig. 7 while the deformed shapes are shown in Figs. 8 - 9.

By the comparison between them, some considerations can be made:

- the critical loads are very similar in both approaches. In fact in the elasto-perfect plastic case and in the elasto-plastic one the critical loads are respectively equal to 160 MPa and 174 MPa;
- the post buckling phase has not presented snap-through phenomena in the analyzed range of displacements;
- the deformed shapes in both calculations are quite similar and show, as expected, that the largest deformations occur at points where the radial distance from the axis of the torus is maximum;

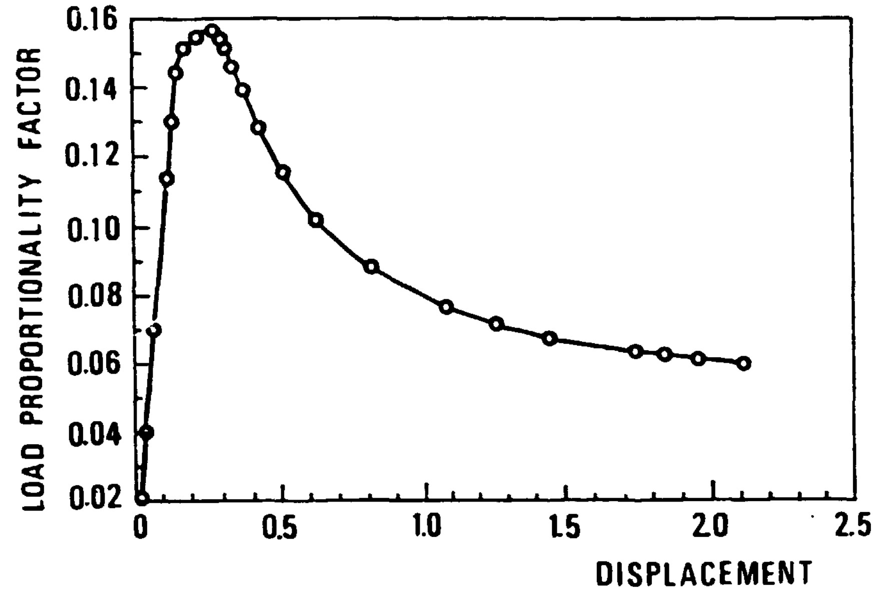

Fig. 6 Load-displacement history with Riks method and elastic-plastic material without hardening. The load is obtained by multiplying the load proportionality factor by 100 MPa

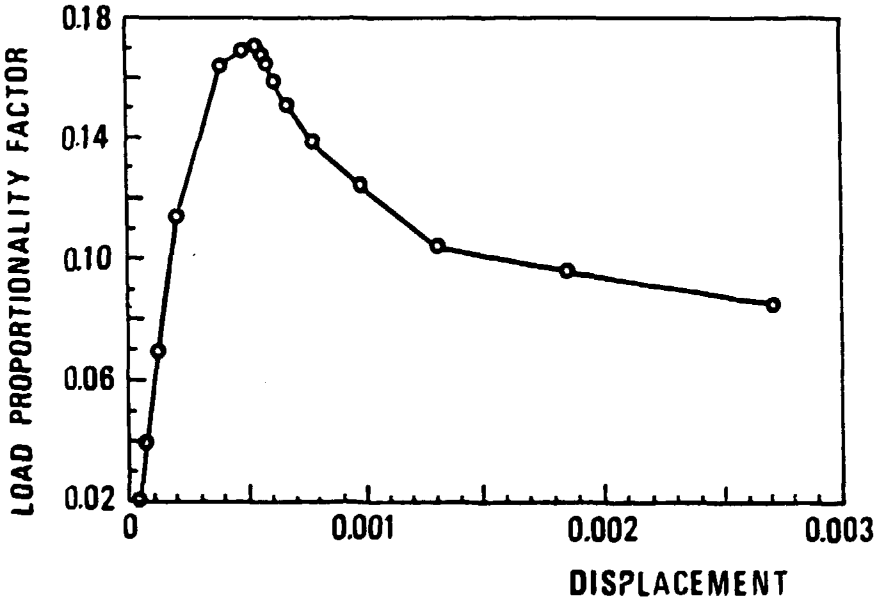

Fig. 7 Load-displacement history with Riks method and elastic-plastic material with hardening. The load is obtained by multiplying the load proportionality factor by 100 MPa

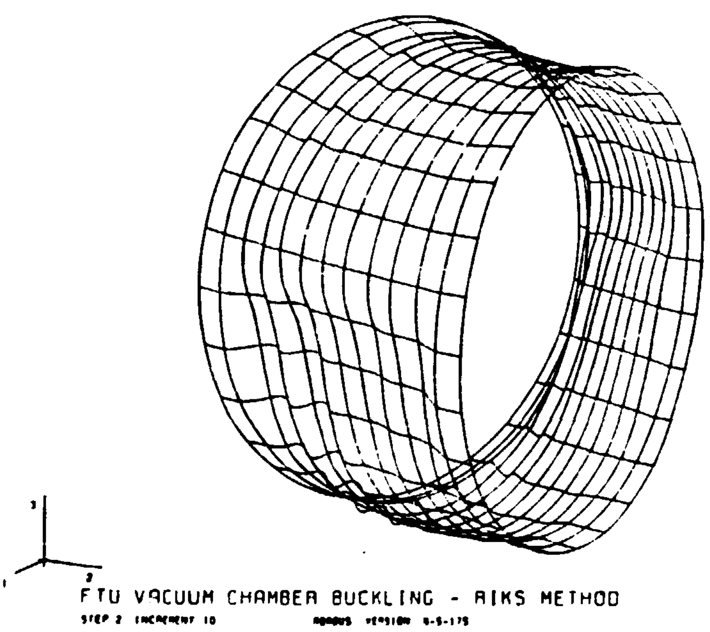

Fig. 8 Deformed shape of the toroidal sector (First viewpoint)

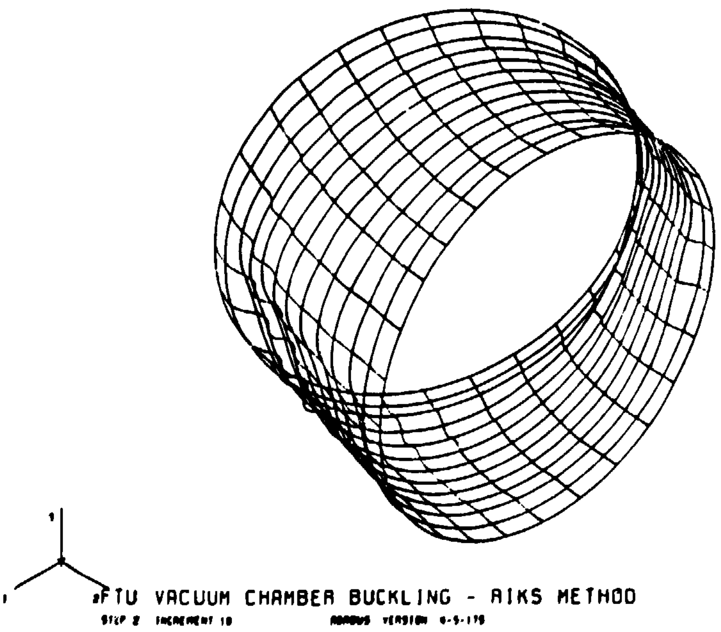

Fig. 9 Deformed shape of the toroidal sector (Second viewpoint)

- the collapse seems to be generated from local instabilities in the shell structure that produce further instabilities in the ribs;
- the hardening of the material plays only a marginal role in the buckling;
- deformed shapes show the buckling not to be localized in a perfectly centered position with respect to the flanges as expected considering the type of load and the structure symmetry.

6. EXPERIMENTAL TESTS

The experimental tests have been carried out on a full scale model that has been made to collapse under uniform external pressure in a large tank filled with water.

The equipment is schematically shown in fig.10 and is essentially composed by:

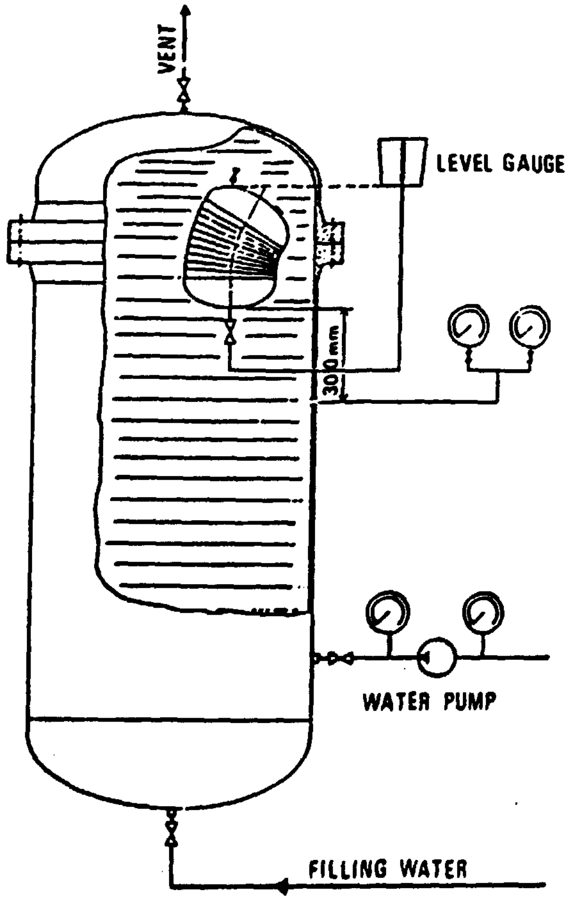

Fig. 10 Schematical view of the experimental facilities

- a large pressure vessel;
- two pressure gauges;
- a water pump;
- a level gauge.

The sector, closed by two circular discs, has been fixed on two diametral beams welded to the interior of the tank. At first it has been filled with water like the whole vessel where the pressure has been gradually increased till the collapse of the structure. When the buckling has begun the valve on the top of the level gauge has suddenly opened proving the failure of the sector.

Measurements have been made both on the pressure in the tank and on the change of the internal volume of the sector.
The results are showed in Table I. . The largest damages are in the area where the calculations have foreseen the buckling to begin.

TABLE I - Experimental results

No.	Pressure (MPa)	Cumulated time (s)	Height level gauge (mm)
1	0.	0.	0.
2	10.	45.	20.
3	20.	65.	35.
4	30.	130.	40.
5	40.	210.	44.
6	50.	303.	49.
7	60.	393.	54.
8	70.	480.	59.
9	80.	563.	63.
10	90.	652.	69.
11	100.	742.	75.
12	110.	831.	83.
13	120.	937.	88.
14	130.	1039.	95.
15	140.	1144.	106.
16	150.	1257.	117.
17	158.		133.

IMPLOSION

7. CONCLUSIONS

In Table II are summarized the results of the calculations and the experimental data.

TABLE II - Comparison among the calculated critical loads and the experimental result
A. : *analytical approach according to Timoshenko*
E. : *eigenvalue approach*
R. : *Riks method*

Case	Theoretical load (MPa)	Experimental load (MPa)
1 Elastic (A)	[illegible]	
2 Elastic (E)	[illegible]	
3 Elastic (R)	340.	158.
4 Elastic-plastic without hardening	[illegible]	
5 Elastic plastic with hardening	174.	

The accordance between the results of the Riks method and the experimental tests is very good. This fact points out the potentiality of this method in all the problems regarding instability

The influence of the plasticity in the material model is very strong and the purely elastic calculations provide results that are about twice larger than the experimental tests.

REFERENCES

[1] "The Frascati Tokamak Upgrade (FTU)" Report 82.49, Associazione EURATOM-ENEA, CRE., Frascati (October, 1982)

[2] ABAQUS - Theory Manual by Hibbit, Karlsson and Sorensen (September, 1984)

[3] K. J. Bathe - Finite Element Procedures in Engineering Analysis - Prentice Hall (1982)

[4] Timoshenko ang Gere - Theory of elastic stability - McGraw Hill Book Company

[5] F. Cesari - Comportamento non lineare delle strutture col metodo degli elementi finiti - Pitagora Editrice Bologna (1985)

Edito dall'ENEA, Direzione Centrale Relazioni.
Viale Regina Margherita, 125 - Roma
Finito di stampare in settembre 1988

Fotoriproduzione e stampa
a cura della «Arti Grafiche S. Marcello»
Viale Regina Margherita, 176 - Roma

Questo fascicolo è stato stampato su carta riciclata