Structural response of a Tokamak first wall under electromagnetic forces caused by a plasma disruption

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1 SUMMARY AND INTRODUCTION

The plasma disruptive instabilities observed in experimental Tokamak fusion reactors exhibit quite various types of physical behaviour, but mainly two different scenarios can be identified:

- "disruptive pulse" phenomena occurring during normal operation when a critical plasma density is reached. High energy losses and increased impurity radiation are associated with the formation of unstable magnetic islands that destroy the confinement;
- "vertical instability" events occurring when the plasma position growth rate exceeds the capability of the feedback stabilisation system of the machine.

For JET (Joint European Torus [1]) reactor, systematic studies are dedicated to a better knowledge of the plasma behaviour during a disruption event (rapid energy dissipation and quenching of plasma current). Even if the plasma disruptive instabilities will be better controlled and their frequency reduced in the future, the performance of the plasma vertical stability is related to a failure condition of the machine equipment and will have to be considered in any case.

As a consequence, a serious engineering problem in fusion reactor studies is the complete knowledge of the effects of the electromagnetic-type phenomena which occur during any plasma disruption event. This accidental event creates a drastic release of a large amount of energy in the passive structures and could cause material damage and structural instability problems.

Using the advanced computerized analysis, the structural behaviour simulation of the first wall (FW) for NET (Next European Torus [2]) reactor has been undertaken with the use of computer programs such as UNISH, ADINA, ABAQUS, available at JRC-Ispra and based on the finite element technique. Due to the complexity of the structural geometry, the boundary conditions, the plasma and the magnetic field configurations, a general three-dimensional approach (3D) has been considered.

2 NET FIRST WALL DESIGN CONFIGURATION

As far as the mechanical design of the FW module structure is concerned, different versions of the NET outboard FW configuration are referred to in this report: new NET Double Null (DN) FW [2,4]; old NET Single Null (SN IIB) FW [2,3]; INTOR/NET FW [3].

The new NET DN FW is composed of 48 separated inboard and outboard stainless steel toroidal modules placed side-by-side around the plasma ring with a gap of about 2 cm between them. Each FW module consists in a thin-shell curved front-plate facing the plasma and connected by means of lateral thin walls to the back-plate structure that essentially provides mechanical support. Small cooling tubes are attached to the thin walls (front and sides) in the toroidal direction [4]. Figures 1 shows a 3D CAD (Computer Aided Design) model and a complete 3D FEM (Finite Element Method) discretization of the outboard box-like first wall.

3 ELECTROMAGNETIC TRANSIENTS ANALYSIS OF NET FIRST WALL

The numerical analysis of the transient electromagnetic phenomena generated during a plasma disruptive pulse and its effects on passive conducting structures surrounding the plasma ring can be performed using the finite element program UNISH [5] available at JRC-Ispra. The computer program calculates first the induced eddy current distribution in space and time in the structural component and then determines the electromagnetic force distribution acting on the structure and generated from the eddy current/magnetic field coupling. Previous reports [3,6,7] have already been dedicated to the application of UNISH for various versions of the NET outboard FW configuration.

As far as the upgraded outboard DN first wall is concerned, the main input parameters are as follows:

- FW equivalent thicknesses: 7 mm and 10 mm;
- FW module toroidal angle: 7.5^{o};
- FW resistivity: 0.93 E-6Ωm at 316^{o}C;
- plasma current: 10.77 MA;
- plasma current linear decay time: 20 ms;
- toroidal magnetic field: 5.0 T.

The calculated electromagnetic force and moment resultants at 20 ms are illustrated in Fig. 2. Because of their antisymmetric pattern with respect to the vertical mid-side poloidal plane and horizontal equatorial plane, bending and torsional moments are created (in R,Z,T directions: M_R, M_Z, M_T). If M_Z and M_T components are completely self-equilibrated within the FW module and balanced by the box wing stiffnesses, the first component M_R creates an overturning situation in the FW structure and must be balanced by appropriate fixed supports. In Fig. 2 the presence of violent electromagnetic loads resulting from a 20 ms plasma disruption is illustrated for different versions of the NET outboard FW. The comparative study of the three configurations indicates a substantial improvement of the last FW component design because of the drastic reduction of these extreme electromagnetic loads, which is mainly due to increased segmentation of the internal components.

Considering the mutual influence of the FW and vacuum vessel (VV) using the upgraded version of UNISH, a small decrease (10%) of the saddle eddy current densities induced in the FW has been observed. More complete information is obtained for the VV considering the screening effect of the first wall.

In Fig. 3 the variation in time of the induced tilting moment M_R in NET DN FW is illustrated in the presence of: linear plasma current decay; exponential plasma current decay; VV structure interaction. The electrical time constant for the FW structure is considerably smaller than the time constant for the VV structure characterized by toroidal symmetric eddy current loops only. In the mechanical behaviour

simulations presented in this paper, the first-mentioned situation (linear plasma current decay) has been considered because it seems to be the most conservative for the severe loading conditions.

4 VIBRATION-TYPE ANALYSIS OF FIRST WALL SEGMENT

As far as the structural/stress analyses are concerned, the complete finite element idealisation of Fig. 1 is considered with the use of ADINA [8] and ABAQUS [9,10] and takes into account the following boundary conditions:

- the FW module is supported on top to the inner wall of the vacuum vessel (VV);
- the FW module is guided in the bottom part of the VV inner surface, allowing gravity and thermal elongations.

The 5 first vibration modes/frequencies of the unloaded structure, computed for the 2 equivalent thicknesses, give (see also Fig. 6):

- Mode 1 : global shrinking/elongation mode;
- Mode 2 : principal bending mode;
- Modes 3,4,5: local twisting modes of the front/lateral walls.

These last three modes are relevant for the FW structural strength because their frequency range corresponds to the plasma current quenching period (10-20 ms). Moreover, the dominant deformed shape of the structure indicated by a linear static analysis is quite similar to the twisting vibration modes illustrated here (Fig. 4). In this case, the resonant structural behaviour needs to be investigated: resonant effects can lead to enhancement of stresses/strains by an order of magnitude and can contribute to material damage by plastic deformation and failure.

5 TRANSIENT DYNAMIC ANALYSIS OF FIRST WALL MODULE

The severe time-dependent electromagnetic loading condition represents an impulsive loading condition which can only be correctly investigated, including the inertia effects, by a complete transient dynamic analysis. The use of advanced computational procedures such as a self-adaptive time stepping algorithm for the automatic incremental solution implemented in ABAQUS [10], are successfully applied for the 3D numerical simulations.

Considering the plasma disruption time constant to be equal to 0.54 MA/ms (10.77 MA current decay in 20 ms), the global response of the FW structural component reflects the fast-transient nature of the load and contains the following information:

- the thin front shell and side walls exhibit a pronounced twisting deformation mode;
- concerning the stress results, Von Mises equivalent stresses are high in the front shell (about 130 MPa) compared with the yield stress of stainless steel at 400°C ($\sigma_{0.2}$ = 120 MPa as shown in Fig.5);
- high radial/axial forces at the nodal supports which are transmitted to the inner surface of the vacuum vessel (VV) as axial/shear forces and bending moments, as illustrated in Fig. 5.

6 LAYERED SHELL FW SECTION

The previous analysis shows that the considered FW structural type is subjected to high stresses in the plasma facing front-shell. In order

to reduce the stress level, we have considered a new type of FW structural section that could be more adapted to resist very high forces generated by electromagnetic transients. The cross-section contains two plates (front and back) including the water-cooling pipes in the poloidal direction as illustrated in Fig. 6.

The vibration analysis of the new solution has been performed by ABAQUS using the layered shell approach. The use of an equivalent layered shell model (layers of different thicknesses sequentially numbered and including different iso- or orthotropic material properties) allows us to correctly reproduce the anisotropic behaviour of the cooling tubes and the important coupling between membrane and bending deformations of the complete 3D finite element FW model. Fig. 6 shows the variation of the first five vibration modes with the different section thicknesses of the FW configuration models used. The results indicate that the increment of vibration frequencies with the cross-section reinforcement is not very important in this case. It is due to the fact that the local vibration modes of the FW segment are dominant twisting modes and, therefore, the influence of the thickness increase is not relevant.

The introduction of layered shell properties in a complete 3D FW model permits to perform in a simple and effective manner the needed transient dynamic analysis that will be illustrated during the oral presentation.

7 CONCLUSIONS

The modern computerized techniques of CAD/FEM analysis are extensively applied for the numerical simulation of the electromagnetic-mechanical coupling induced in the last design configuration of NET first wall during a plasma disruption event. A picture of the impact of the electromagnetic forces on the structural behaviour of the outboard DN first wall has been presented and an improvement of the FW structural section has been proposed. In any case, additional investigations will be performed during the long process of structural behaviour optimization of the first wall reactor components.

8 ACKNOWLEDGEMENTS

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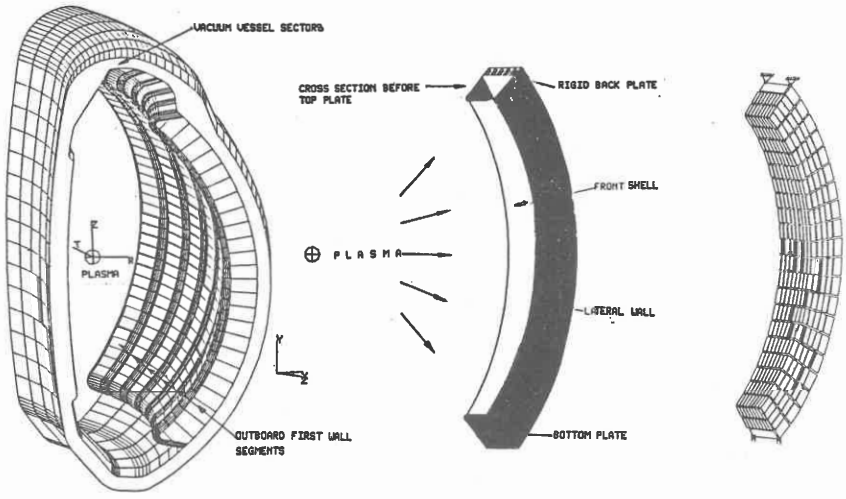
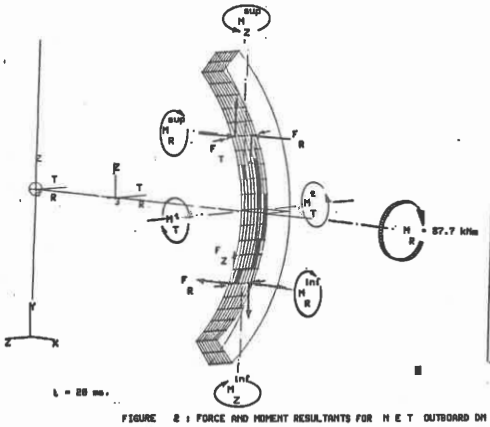


FIGURE 1 : N E T REACTOR STRUCTURAL COMPONENTS - FIRST WALL OUTBOARD SEGMENT - COMPLETE FINITE ELEMENT MODEL



VARIABLE \ FIRST WALL VERSION	INTOR/MET SOFT-13	NET SN IIB SMIRT-8	NET ON SOFT-14
NUMBER OF SEGMENTS	24	48	48
F_R (kN) (1/4 Seg.)	518	248	233
F_Z (kN) (1/4 Seg.)	158	138	81
F_T (kN) (1/4 Seg.)	n.c	n.c	27
M_R (kNm)(Tot.Model)	928	148	88

n.c : not computed

FIGURE 2 : FORCE AND MOMENT RESULTANTS FOR N E T OUTBOARD OH FIRST WALL - FORCE RESULTANTS (F_R, F_Z, F_T) & TILTING MOMENT (M_R)

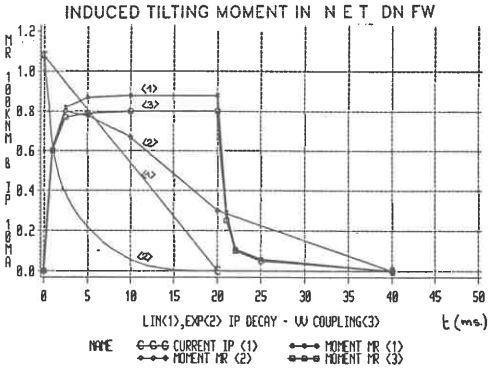


FIGURE 3 : TILTING MOMENT MR & PLASMA CURRENT IP

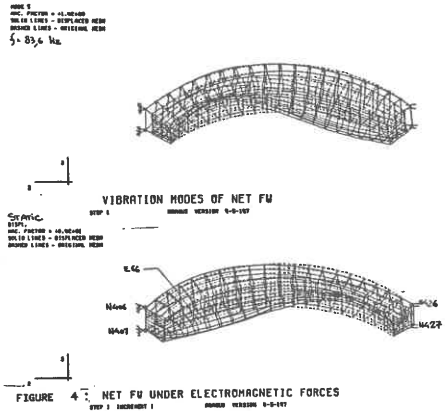


FIGURE 4 : NET FW UNDER ELECTROMAGNETIC FORCES

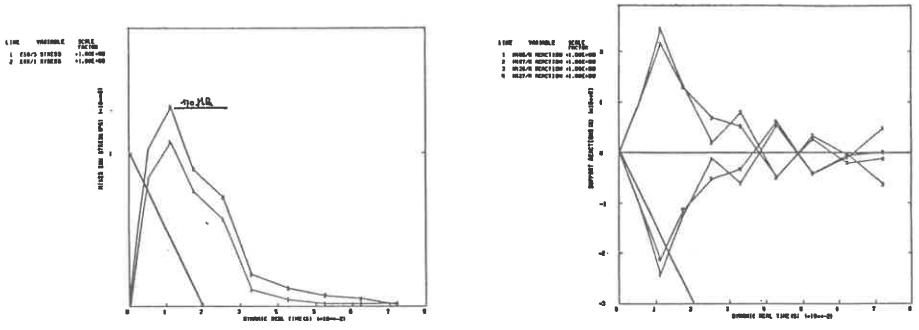
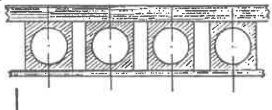


FIGURE 5 : NET FW UNDER ELECTROMAGNETIC TRANSIENTS

FINITE ELEMENT MODEL	EQUIVALENT THICKNESS t=0.007 m	t=0.010 m	LAYERED SHELL t1=0.005 m (front plate) t2=0.012 m (cool. tubes) t3=0.002 m (back plate)
M O D E S	F R E Q U E N C I E S (Hz)		
1 ELONGATION	11.75	13.35	18.23
2 BENDING	26.79	26.78	26.99
3 LOCAL	43.73	48.55	65.71
4 LOCAL	57.56	67.52	74.56
5 TWISTING	63.86	82.67	92.43

STRUCTURAL CROSS-SECTION



F I G U R E 6 : N E T FW SECTION AND VIBRATION ANALAYSIS