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Evaluation of the erosion on the CFC tiles of the ITER divertor by means of FE calculations

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ABSTRACT

In order to evaluate by finite element (FE) calculations the possibility of erosion instability on the CFC tiles of the vertical target of the ITER divertor an original methodology has been developed using the CAST3M CEA finite element code. The used approach provides a series of steady state calculation steps, the mesh being updated at each step of the iteration in order to take into account the erosion between two steps. Both physical and chemical sputtering together with sublimation have been included in the code to describe the loss of material by the thermal and particle loads envisaged for ITER normal operation regime. This model has been validated by comparison with analytical or other code results and then applied to the ITER divertor vertical target (CFC monoblock geometry). The calculations have pointed out the possibility of some erosion instabilities when a monoblock has a neighbour one with reduced conductivity or with interface defects. However it was shown that when applying normal condition loads (10 MW/m^2) for 10,000 s and then off-normal loads (20 MW/m^2) for 10 s the total erosion was 1 mm. Based on these first results no modification of the monoblock acceptance criteria is necessary. This way of calculation can be easily transposed in other FE codes and extensively used for checking various ITER operative scenarios.

1. Introduction

The CFC (carbon fibre composite) monoblocks of the ITER divertor vertical target must sustain high heat fluxes of 10 MW/m^2 during 400 s (normal operation) and 20 MW/m^2 during 10 s (off-normal event). The problem of carbon erosion is a major concern [1] since one can expect the occurrence of erosion instability in normal operation. In particular, this could happen in case of one faulty monoblock besides good ones due to the balanced rate between the various erosion mechanisms at different temperatures (sublimation due to high temperature, chemical sputtering at low temperature) [2–4]. In order to evaluate the impact of these phenomena on the acceptance criteria of the monoblocks (the monoblocks are considered thermo-mechanically compliant to a defect of given size but this compliancy could be drastically reduced by erosion instability itself) it was decided to investigate the effect on temperature distribution and erosion rate of a 20% decrease of CFC thermal conductivity or a postulated defect at the CFC/Cu bond.

2. Calculation conditions

The geometry of a monoblock is given Fig. 1. The used model for calculation is composed of one monoblock between two half-monoblocks [4]. The calculations are performed by using a 2D CAST3M CEA code model [5].

According to B2-EIRENE calculations [6], the total power load during ITER normal operation on the outer vertical target consists both in radiation from plasma and particle flux in glancing incidence: Fig. 2 gives the power distribution along the ITER divertor vertical target for the particle flux. Operation regimes where instabilities are possible correspond to a power load of about 3–6 MW/m^2 (see Fig. 3).

Nine cases have been recognized as having a potential risk of erosion instability (Table 1: assumption of 30% radiative and 70% conductive power). For each case, 3 runs have been performed, namely (a) standard value of conductivity and no defect, (b) conductivity reduced of 20% for the central monoblock, (c) defect of 90° at the CFC/Cu interface located at −30° (the glancing incidence being 3°).

The power load is applied on the upper part (with eventual penetration into the gaps between monoblocks). Forced convection in subcooled boiling is applied at the cooling tube inner surface.

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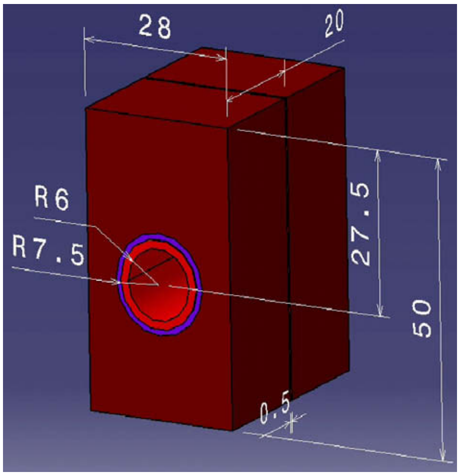

Fig. 1. Geometry of one monoblock.

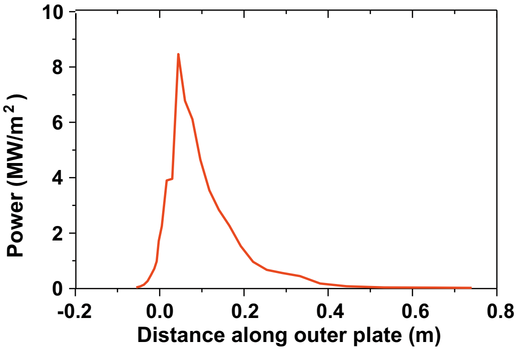

Fig. 2. Power load distribution along the outer plate.

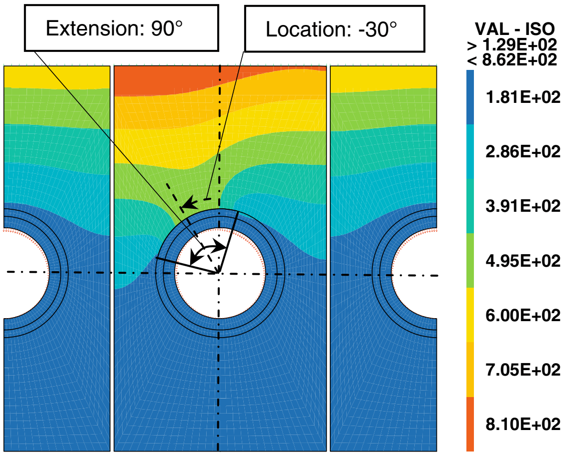

Fig. 3. Case 2c: temperature map at 10,000 s (T_{max} = 860 °C).

Table 1
Selected cases.

Case (location on the target)	Power load (MW/m^2)		Ion flux (D/m^2)	Plasma T Te (eV)	E_0 = 6.Te
	Glancing inc.	Normal inc.			
1	2.8	1.2	1,0E + 23	5	30
2	2.8	1.2	5,0E + 22	20	120
3 (x = 0.140)	2.31	0.99	7.4E + 22	20	120
4 (x = 0.117)	3.25	1.4	9.4E + 22	19	114
5 (x = 0.165)	1.75	0.75	5.7E + 22	15	90
6 (x = 0.117)	4.2	1.8	9,0E + 23	1	6
7	3.22	1.38	1,0E + 23	16	96
8	2.8	1.2	3,0E + 24	1	6
9	4.2	1.8	9,0E + 22	18	108

Cyclic boundary conditions are applied on the two half-monoblocks (left and right sides are forced to have the same temperature distribution). All the cases have been calculated for 10,000 s simulation, roughly 25 ITER pulses.

The CAST3M calculations were undertaken mainly to cross-check ANSYS calculations [4] using another methodology. The calculations are based on a series of steady states, the mesh being updated at each step of the iterations. As a consequence the heat load is updated at each step. The model was developed thanks to the routines developed since 9 years for heat load deposition on the toroidal pump limiter of Tore Supra and takes into account penetration and shadowing effects [7–9]. Indeed, the difference in height between two adjacent monoblocks can lead to a penetration of the heat load into the gap or to a shadowing effect of one monoblock on the adjacent one. This is calculated taking into account the glancing incidence angle. In case of penetration of the power into the gap, the power deposited on the edge (side part of a FE cell) is reported onto the upper surface (upper part of the FE cell).

3. Calculation validation

It was necessary to introduce 3 routines in the data language of CAST3M (GIBIANE): (i) EROSCC for the physical erosion due to carbon flux [10], (ii) SPUTDC for the physical and chemical [11] sputtering of carbon by deuterium and (iii) SUBC for the sublimation of carbon at high temperature [1–4]. Mainly chemical and physical erosions were validated against analytical equations and ANSYS calculations. Erosion calculated with CASTEM methodology is fully continuous and in agreement with analytical equations. The calculations were found also in agreement with the ANSYS transient calculations.

4. Calculation results

With this methodology the CAST3M calculations were very fast and very easy to perform. In these conditions 27 (9 × 3) runs were performed up to 10,000 s (= 25 pulses of 400 s) (see Table 2) and 6 others (1a, 1b, 2a, 2b, 3a, 3b) were redone up to 40,000 s (= 100 pulses) (see Table 3). No dramatic erosion was found, however sensitive erosion differences between monoblocks have to be pointed out (see as an example Fig. 4, where central monoblock has an erosion between 120 and 178 µm and the adjacent one between 148 and 160 µm).

5. Complementary calculations

In order to further check the possibility of the erosion instability it was decided to run one case in normal operation for 10,000 s and then to apply 20 MW/m^2 (70% conductive and 30% radiation) for 10 s. Such a result is given Fig. 5 for case 2c. At the end of 10,000 s the erosion is about 0.1 mm and it increases up to about 0.9 mm during 10 s at 20 MW/m^2. To do such a calculation it was necessary to cancel the cyclic boundary conditions that are not appropriated here. One can observe an important erosion of the

Table 2
Maximum temperature and erosion at 10,000 s.

Case number	Standard CFC			CFC conductivity −20%			90° defect at 30°		
	T_{max} (°C)	Erosion (μm)		T_{max} (°C)	Erosion (μm)		T_{max} (°C)	Erosion (μm)	
		Max	Mean*		Max	Mean*		Max	Mean*
1	670	−76	−62	850	−76	−59	861	−69	−53
2	655	−180	−155	825	−182	−155	862	−178	−140
3	522	−188	−160	624	−220	−195	678	−230	−205
4	782	−275	−250	1160	−255	−170	1070	−255	−160
5	425	−122	−88	480	−122	−102	518	−128	−105
6	1070	−32	−27	1360	−31	−17	1350	−32	−16
7	771	−270	−245	1140	−250	−165	1050	−245	−155
8	658	−135	−122	767	−148	−132	852	−141	−122
9	1040	−172	−148	1320	−68	−135	1350	−168	−134

* Mean erosion on the central monoblock.

Table 3
Maximum temperature and erosion at 40,000 s.

Case number	Standard CFC			CFC conductivity −20%		
	T_{max} (°C)	Erosion (μm)		T_{max} (°C)	Erosion (μm)	
		Max	Mean*		Max	Mean*
1	650	−275	−250	889	−272	−240
2	622	−620	−600	759	−645	−640
3	530	−670	−640	596	−800	−760

* Mean erosion on the central monoblock.

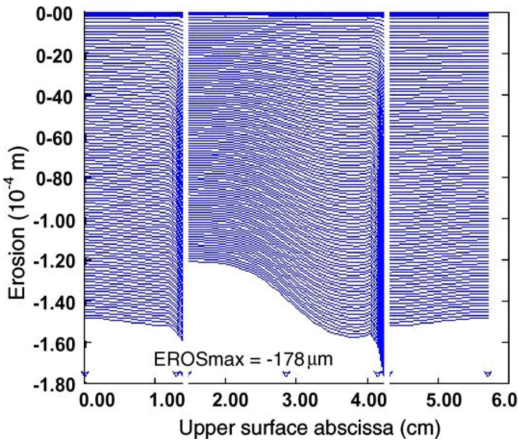

Fig. 4. Case 2c: typical erosion evolution up to 10,000 s.

faulty central monoblock (due to the high surface temperature) that leads to plasma shaping of the adjacent monoblock on the left.

6. Conclusion

This work has demonstrated the capability to run erosion calculations with CAST3M code by using a series of steady states with a mesh updating at each step as an alternative to the transient calculations performed up to now with ANSYS. These calculations have pointed out some erosion instabilities for the studied cases (neighbour monoblock with reduced conductivity or with 90° defects). However it was shown that when applying normal condition loads for 10,000 s and then off-normal loads (20 MW/m^2) for 10 s the total erosion was acceptable and limited to 1 mm.

Further investigation of critical cases should be pursued since one has now the tools for such calculations. It seems obvious that this methodology could be transposed in ANSYS.

As a consequence no modification of the acceptance criteria of the monoblocks is foreseen.

Acknowledgements

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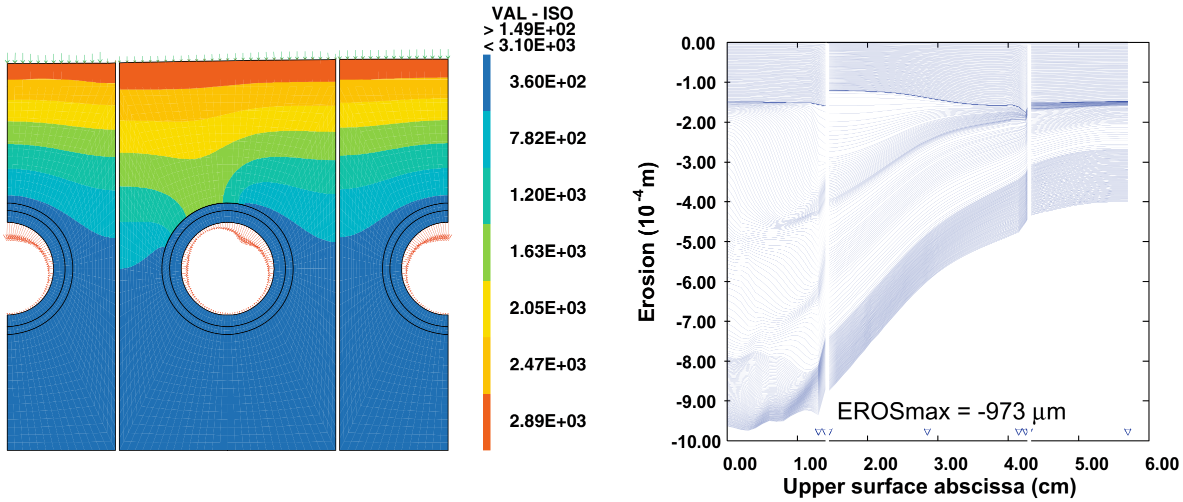

Fig. 5. Case 2c: final temperature map and evolution of the erosion during 10 s after 10,000 s of normal operation.

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