Feed-Backs on PEC Fast Reactor Core Design due to Seismic Conditions and Main Numerical Results

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Abstract

The paper deals with the recent numerical analysis carried out to evaluate the core seismic response of the Italian PEC fast reactor. After some notes on the improvements of the iterative procedure applied for taking into account the strong effects of the vessel-core seismic interaction, it stresses the consequences of our studies in terms of feed-backs on the design and presents the main results of the analysis carried out with up-to-date data, pointing out their use for the structural and functional verification of the shutdown system and core elements, as well as for the evaluation of reactivity insertion in an earthquake.

1. Introduction

As pointed out in ref. /1/, a considerable effort is devoted by the Fast Reactor Department of ENEA to the seismic verification of the core of the Italian fast reactor test facility (see the brief description of the PEC core in /1/). The core seismic calculations are performed by ENEA with the non-linear computer program CORALIE /2/; furthermore, a procedure which iterates the CORALIE calculations and those, linear, carried out by NIRA for the whole reactor - block is applied to take into account the strong effects of the vessel-core seismic interaction. These effects are rather strong in the case of PEC due to the large mass associated with the core and considerable flexibility of the vessel supporting structure (we remember that PEC is a semi-integrated loop-type reactor) /3/.

The first results of the calculations carried out for the analysis of the vessel-core seismic interaction were presented at the Chicago SMiRT Conference /3/, together with the features of the iterative procedure, while the methods of CORALIE are described in the paper of ref. /2/, presented at the Paris SMiRT Conference. Moreover, both subjects are summarized in paper /1/, presented at this Conference. Thus, this work will deal with the continuation of the numerical analysis of ref. /3/, stressing the consequences in terms of feed-backs on the design ; then, it will present the improvements applied to the iterative procedure to reduce the number of iteration steps; finally, it will report the main numerical results of the analysis carried out with up-to-date data, pointing out their use for relevant experimental tests.

2. The iterative procedure

A simplified flow-chart of the iterative procedure applied to take into account the effects of the vessel-core seismic interaction is shown by Fig. 1/3/. This figure indicates that a linear core model has to be defined at each iteration step in order to allow the linear reactor-block calculations to be performed. The model for the second and subsequent iterations is obtained by linearizing the transfer functions between the diagrid acceleration and reaction loads transmitted by the core to the vessel, which are calculated on the basis of the CORALIE results as described in ref. /3/.

With regard to the first iteration linear core model, rough assumptions have to be made , due to lack of precise information on the core response at such an iteration step: the effects of these assumptions will be discussed in the following sections.

3. Calculations with preliminary data

The calculations of ref. /3/ had been carried out referring to earthquake TSS (corresponding to the American SSE /1/) and using preliminary data with regard to the geometry, vibrational behaviour and shock data of the core elements. Furthermore, only the case that the test channel is replaced by a group of seven elements had been analysed (see /1/) . Such calculations had been performed for both the case of unrestrained core (corresponding to the original design solution), and those of a single restraint ring at the level of the contacting pads (located close to element midplane) and a double restraint, i.e. a design solution with a second restraint ring at about 2.5 m from element base. In the case of double restraint a second set of thick pads had been also applied to the reflecting and neutron shielding elements at the upper pad level. The restrained core solutions had been analysed in order to investigate the possibility of improving core response by limiting core element motions (the clearances between the rings and the core were small but not zero for handling reasons).

The aforementioned calculations have been subsequently completed refining the analysis of the double restraint solution, and extending the study to the case of a single restraint at the upper level /4/.

All these calculations have demonstrated the adequacy of the iterative procedure in both the case of unrestrained core and those of restraints /3,4/. However, a large number of iterations (nine, at least) was necessary in the presence of the upper restraint (Tab. I). Furthermore, the results of the analysis of ref. /3/ show that a single restraint located close to element midplane does not improve core seismic response, while those of the study of ref. /4/ demonstrate that the upper restraint has a positive effect on the response of the elements to which a second set of pads is applied (the lower ring of the double-restraint structure appears useless again : in fact, no contact has been detected in /4/ between this ring and the core) .

4. Improvements of the iterative procedure

Due to the fact that the design solution with a core-restraint ring located close to core element top had appeared to be that most promising for limiting core seismic motions, a study has been carried out to reduce the large number of iterations which was necessary in such a case to reach convergence. This study, described in detail in ref. /5/, has demonstrated that the reason of the slow convergence in the calculations of refs. /3,4/ lies in the assumption made in these calculations for the definition of the first iteration linear core models:these, in fact, led to very conservative results in the first iteration runs with CORALIE (Tab.I). It has been found that first iteration results which are much closer to the convergence solution (Tab. I) can be achieved with the following procedure :

(a) Two calculations of the whole reactor-block are performed with the two first iteration linear core models of Fig. 2 (the first one with free elements and the second with elements hinged to one another at the two pad levels and to the diagrid at the restraint level). In these first iteration calculations increased values of the fractions of critical damping , η_e= 15%, have to be assumed, instead of those used in the CORALIE runs (η= 5%, see /1/).

(b) The two acceleration time-histories obtained according to item (a) are averaged at each time t, providing the excitation to be applied in the CORALIE first iteration run.

We note that the increase of damping in the first iteration reactor-block analysis simulates shock effects on frequency response, while the core stiffening due to impacts against the restraint ring is approximated by the mentioned average of time-histories.

It has been verified that, with the above cited methods the convergence procedure becomes much faster: in fact, as shown by ref. /5/ and Tab. I, only 4÷5 iterations are necessary, instead of the previous 9÷11.

5. First modifications of the design

Due to the results of the preceding paragraphs, modifications have been applied to the PEC design. More precisely, a restraint ring (with a distance of 9.3 mm from the external core elements) has been inserted in the vessel at about 2.6 m from element base (i.e. very close to the axial level assumed in the preliminary calculations); furthermore, a second set of pads has been applied to all core elements at the restraint level /1/. Such modifications have been decided mainly to limit displacements of the control-rod guide-elements to values compatible with scram requirements /6/. The upper pad design has been such as to reduce internal gaps (i.

e. the seismic motion inside the restraint ring) as much as possible without any risk of handling problems : in fact, the thicker pads (providing gaps among assemblies of 0.5 mm) have been applied to the reflecting and neutron shielding elements, while those on fuel elements were thinner (gaps of 1.9 mm).

Furthermore, all element feet have been modified, in order to eliminate the stress peacks detected in the previous calculations /4/ and guarantee that upset limits are satisfied in the case of earthquake ½TSS /1,7/.

6. Calculations at TSS with up-to-date data

In 1984, the calculations for the PEC core seismic verification were repeated, for the previously mentioned restraint solution, with up-to-date data. More precisely, beside taking into account the design modifications described in § 5 :

(a) isostatic double contact restraints have been assumed in the feet of all core elements, together with corrections of the stiffness values of the feet and (for reflecting elements) zones of the internal tubes containing the nickel blocks, according to our experimental results on single elements at the highest excitation levels /8,9/;

(b) the added mass effects due to sodium have been partially (but conservatively) taken into account by increasing element linear mass in such a way as to reduce maximum frequency core response to 80% the value corresponding to absence of sodium (see ref. /1/);

(c) the shock model has been corrected to account for shock stiffness values according to 3D static calculations, and shock damping /1/.

The iterative procedure has been applied, again only for TSS, making use of the improved techniques described in § 4. Damping values η = 5% have been mantained in the CORALIE runs according to /1/. Also in this case, only four iterations have been necessary to reach convergence (Tab. II and Fig. 3): this confirms the adequacy of the improvement applied to the iterative procedure.

7. First calculations for ½ TSS

Referring to the convergence solution obtained for TSS with up-to-date data, some first calculations have been also performed for excitations appearing close to ½TSS. More precisely, this earthquake has been simulated assuming 60% the TSS diagrid acceleration, according to previous studies with the assumption that the linear core model is independent of excitation level /5/. This has led to the first iteration results of Tab. III.

8. Use of the previous results

The analysis described in § 6 and § 7 has allowed the excitation time-histories for the seismic experiments of the shutdown system to be determined for both TSS and ½TSS /6/. Furthermore, the excitation for the most recent seismic experiments on core elements could also be evaluated /10,11/, together with a first set of data (maximum displacement and shock force values) recently used in the tests for the structural and functional verification of the core elements /7/ (we note, about shock forces, that these are considerably increased by the presence of the restraint). Finally, the study on neutronic-seismic interaction could be started.

It is worth citing that the analysis of § 6 and § 7 had to be limited to the single central row with hexcan flats normal to excitation direction /1/ (Fig. 4).: this was due to urgency of starting the experiments.

9. Conservatism of the results obtained for TSS

Further calculations have been carried out for TSS, after those of § 6, in order to check the conservatism of the previous results, especially with regard to displacements of the control-rod guide-elements (the excitation applied to the experiments of the shutdown system referred to adjacent elements, because no control-rods are present in central rows /1/). More precisely, the response of core element rows parallel to the central one and containing control-rods has been evaluated, together with that of the central row with excitation normal to hexcan corners (Fig. 4). These calculations have confirmed the adequacy of the central row analysis, as Tab.III indicates for the control-rods.

10. Vessel-core seismic interaction for ½ TSS

In order to evaluate the conservatism of the results previously obtained for ½ TSS, the vessel-core seismic interaction effects have been determined correclty also for this earthquake. The iteration has been started from the CORALIE response obtained with the assumption of 60% the TSS diagrid acceleration (§ 7). Only two further iterations have been necessary to achieve convergence (see Fig. 3 and Tab. III).

It is worth noting that the convergence solution obtained for ½TSS corresponds to a seismic response which is considerably lower than that obtained in the first runs of § 7. This conclusion has been confirmed by the results of further calculations, performed for other core element rows, as for TSS (Tab. III).

11. Most recent design modifications

Very recently, further modifications have been applied to core elements, to reduce reactivity insertion in an earthquake to an acceptable level.This has been decided on the basis of the results of dynamic calculations, carried out as usual for the single central row /12/. These have shown that in the case of TSS a complete compaction of the fuel elements occurs in this row at both pad levels, due to the presence of the restraint ring. Thus, the thickness of the contacting pads has been considerably increased in the fuel elements (especially at the upper level, at which the new gaps are 0.5 mm). Furthermore, hexcan stiffness of the fuel elements has been considerably increased at upper pad level, in order to minimize the contribution of hexcan deformation to element compaction. Finally, the upper pad thickness has been reduced on neutron shielding elements, because of the negative effect of such pads on core compaction, detected in the calculations /12/ (small pads, providing gaps of 2 mm, have been mantained in order to guarantee the conservatism of the experiments performed for the shutdown system and core elements /6,7/; see Tab. III).

12. Most recent calculations

Calculations based on the previously described final core element geometry have been started. A detailed description of this analysis will be provided in a future paper. Thus, only a few remarks are reported here.

(a) Shock parameters. In the most recent calculations experimental values /7/ are used for defining shock stiffness (for more details see /1/).

(b) Number of modes. Two modes have been found to be sufficient, as shown by Figs. 5 and 6.

(c) Effect of the neglected modes. The correction of shock stiffness to account for shock induced excitation has been found to lead for PEC to very uncorrect results, especially as concerns shock forces (see ref. /1/ and Figs. 5 and 6).

(d) Vessel-core seismic interaction. Some further iterations had to be performed to take into account the effects of the last modifications. Also the effects of recent correction of vessel schematisation according to /13/ have been considered.

(e) Added mass effect. The assumption made on added mass due to sodium (§ 6) has been found to lead to conservative results (see ref. /1/ and Fig. 7).

(f) Test channel. Calculations for the core configuration with the test channel have been initiated, starting from the final excitation obtained in the case core without test channel. Iterations have to be performed, because the linear core model features appear to be considerably affected by the presence of the test channel.

(g) Element displacements. The maximum displacements of core elements appear to be rather lower than those previously evaluated (see, for instance, those of the control-rod guide-elements in Tab. III). This demonstrates the reliability of the experimental results obtained with data based on the previous geometry, with regard to scram feasibility and element foot integrity.

(h) Shock forces. Due to higher stiffness, larger shock force values have been calculated for fuel elements at upper pad level. However,further experiments on the new hexcans have been positively concluded /7/.

(i) Reactivity insertion. A specific discussion of this topic is contained in ref. /12/. Some remarks are also reported in /1/.

13. Conclusions

The developments of the numerical analysis carried out for the PEC core seismic verification have been shortly described,pointing out the consequences of such analysis in terms of feed-backs on the design, and the use of results for relevant experiments. It has been shown that the data applied in these experiments are adequate inspite of the recent further modifications applied to core elements.

References

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/7/ NERI,P., et al., "Experimental Tests for Structural and Functional Verification of PEC Fast Reactor Core Elements with Seismic Loadings", This Conference (EK2/8).

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/10/ BONACINA,G., et al., "Response to Impacts of Fast Reactor Core Elements during Seismic Excitation", Paper presented at this Conference (EK2/4).

/11/ BONACINA,G., et al., "Dynamic and Seismic Response in Air and Water of Prototypic Models of PEC Fast Reactor Core Elements", Paper presented at this Conference (EK2/5).

/12/ ARTIOLI,C., et al., "Evaluation of the Neutronic-Seismic Interaction Effects in the PEC Fast Reactor Core Analysis", Intl. Topical Meeting on Fast Reactor Safety, Knoxville , U.S.A., 1985.

/13/ DESCLEVES,P., MARCHAND PASQUIER,B., MARTELLI,A., MARESCA,G., "Comparison between a Beam and a Shell Model for the Seismic Analysis of a Reactor Vessel", This Conference (K9/11).

Tab.I: Effects of the iterative procedure on PEC core element maximum displacements (mm) calculated for TSS at top level in the case of a core-restraint at 2.5 m from element base. Calculations with <u>preliminary data</u>

Tab.II: Maximum top displacements (mm) computed according to <u>first modifications</u>

	Original procedure											Improved procedure					Case of TSS						Case of ½TSS		
ITERATION INDEX	1.	2.	3.	4.	5.	6.	7.	8.	9.	10	11	1.	2.	3.	4.	5.	1.	2.	3.	4.	5.	6.	1.	2.	3.
Central fuel elem	31	30	18	17	16	17	23	19	16	15	15	20	20	17	15	15	46	35	36	36	35	35	32	26	25
Forced fuel elem	36	39	26	24	21	21	25	24	21	22	22	27	23	22	22	22	49	35	36	38	37	37	31	25	25
Normal refl. elem	37	41	27	25	22	23	25	24	23	22	22	26	24	23	22	22	52	33	34	35	33	33	28	23	23
Neutron shield. el	30	26	23	16	16	15	19	15	14	15	15	21	18	18	15	15	42	27	27	28	27	27	22	18	18
Fuel elem. in decay	24	26	28	15	15	13	16	14	13	14	14	16	17	16	14	14	47	24	25	26	25	25	20	17	17

Tab.III: Maximum displacements of control rods at upper pads (mm) referring to both the first and final design modifications. Comparison with the values applied to the TSS and ½ TSS shutdown experiments

		first design modifications						final modifications
EARTHQUAKE LEVEL	EXCITATION DIRECTION	EXCITATION NORMAL TO HEXCAN FLATS					TRANSVERSE EXCITATION	EXCITATION NORMAL TO HEXCAN FLATS
		central row (shutdown exp.)	row index from core center					
			1.	4.	5.	6.	central row	central row
TSS	positive	31	26	27	25	30	24	27
	negative	not calculated	26	24	22	26	not calcul.	25
½ TSS	positive	25	11	16	12	15	18	16
	negative	not calculated	13	14	14	12	not calcul.	16

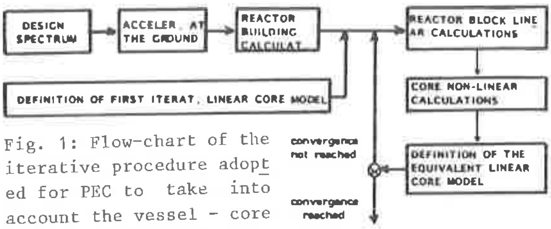


Fig. 1: Flow-chart of the iterative procedure adopted for PEC to take into account the vessel - core seismic interaction

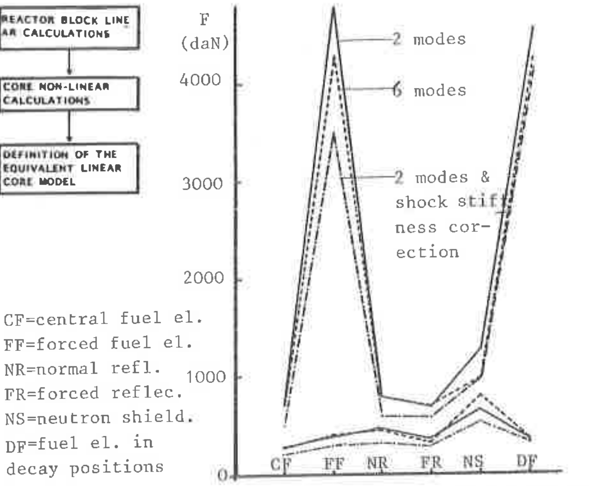


Fig. 5: Maximum shock forces computed at TSS for the various element types with refined (not final) data

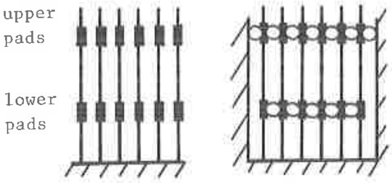


Fig. 2: First iteration linear core models assumed for PEC reactor-block

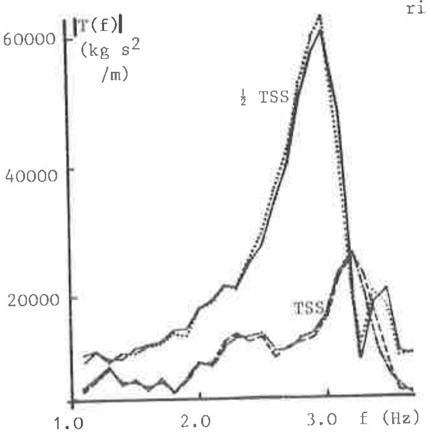


Fig. 3: Transfer functions at last two iterations (first design modifications) (core reaction force / diagrid acceleration, TSS and ½ TSS, amplitudes)

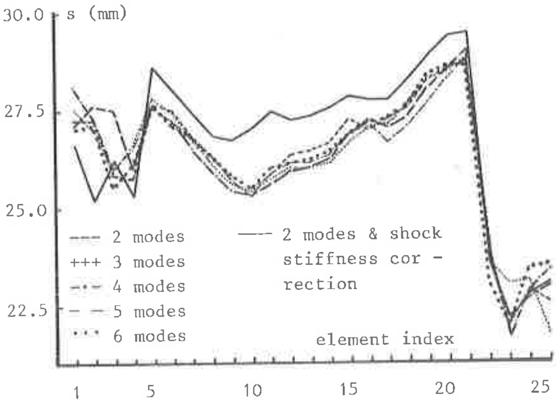
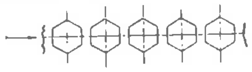


Fig. 6: Maximum displacements computed for TSS at upper pads (refined -not final- data, central row)

(a) Excitation normal to hexcan flats



(b) Excitation normal to hexcan corners

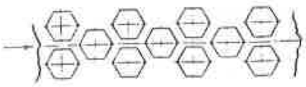


Fig. 4 : Single rows of core elements assumed in the PEC core calculations with the computer program CORALIE

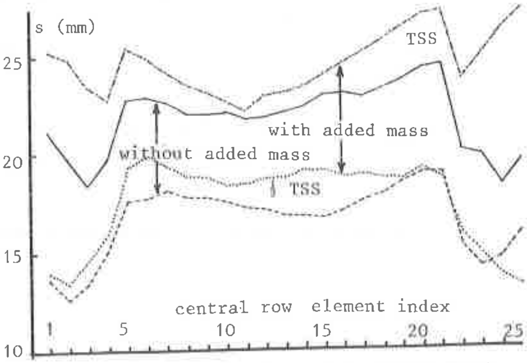


Fig. 7: Upper pad max. displacements (final data)