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Marie-France Robbe, Yves Cariou, Michel Lepareux, Eloi Treille

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Description of the MARS small scale replica of a Fast Breeder Reactor and of the numerical models used to simulate a Hypothetical Core Disruptive Accident in the test-facility

M.F. Robbe^α, Y. Cariou^β, M. Lepareux^ξ, E. Treille^δ

^α CEA Saclay, DRN-DMT-SEMT, 91191 Gif sur Yvette cedex, France
Tel: (33) 1 69 08 87 49, Fax: (33) 1 69 08 52 42, E-mail: mfrobbe@cea.fr

^δ Novatome, NVPM, 10 rue Juliette Récamier, 69006 Lyon, France

^ξ CEA Saclay, DRN-DMT-SEMT, 91191 Gif sur Yvette cedex, France

^δ Socotec Industrie, 1 av. du Parc, 78180 Montigny le Bretonneux, France

Abstract

In case of a Hypothetical Core Disruptive Accident (HCDA) in a Liquid Metal Reactor, the interaction between fuel and liquid sodium creates a high pressure gas bubble in the core. The violent expansion of this bubble loads the vessel and the internal structures, whose deformation is important. The experimental test MARS simulates a HCDA in a small scale mock-up containing all the significant internal components of a Fast Breeder Reactor. The test-facility is filled with water topped by an argon blanket and the explosion is generated by an explosive charge.

This paper describes the MARS test-facility and presents two numerical modelings used to simulate the test with the CASTEM-PLEXUS code. In the first model, the main internal structures are described with a classical shell model. The second model represents, in addition, the heat exchangers and pumps by means of a porosity model homogenizing the components with the surrounding fluid.

1 Introduction

In case of a Hypothetical Core Disruptive Accident (HCDA) in a Liquid Metal Reactor, the interaction between fuel and liquid sodium creates a high pressure gas bubble in the core. The violent expansion of this bubble loads the vessel and the internal structures, whose deformation is important.

During the 70s and 80s, the LMFBR integrity was studied with codes specially devoted to the analysis of transient loads resulting from a HCDA: PISCES 2 DELK [1], REXCO [2], MICE, ICECO, ICEPEL, STRAW and SADCAT [3], SURBOUM [4], SEURBNUK/EURDYN [5] [6] [7], ASTARTE [8], CASSIOPEE [9], SIRIUS...

In order to validate these codes, experimental programmes and benchmarks were undertaken by several countries: COVA [10] [11] [12] [13] [14], APRICOT [15], WINCON [16], STROVA [17], CONT [18], MARA...

The french code SIRIUS [19] [20] [21] was validated on the french experimental programme MARA [22] [23]. Based on a 1/30 scale model of the Superphenix reactor, the French programme MARA involved ten tests of gradual complexity due to the addition of internal deformable structures:

- MARA 1 and 2 considered a vessel partially filled with water and closed by a rigid roof [21],
- MARA 4 represented the main core support structures [24],
- MARA 8 and 9 were closed by a flexible roof [25],

- MARA 10 included the core support structures (CSS) and a simplified representation of the above core structure (ACS) [26].

The MARS test [27] rested on a 1/20 scale mock-up including all the significant internal components.

As other codes using a Lagrangian approach, SIRIUS needed rezonings during calculation because the internal structure presence caused high distortion of the fluid meshes. Finite differences were used for the sodium and the roof and finite elements for the thin vessel. As the argon and the bubble were not meshed, a law related volume to pressure.

At the end of the 80s, it was preferred to add a specific HCDA sodium-bubble-argon tri-component constitutive law [28] to the general ALE fast dynamics finite element CASTEM-PLEXUS code. The HCDA constitutive law was qualified [29] on the CONT benchmark.

In order to demonstrate the CASTEM-PLEXUS capability to predict the behaviour of real reactors [30] [31], axisymmetric computations of the MARA series were confronted with the experimental results. The computations performed at the beginning of the 90s showed a rather good agreement between the experimental and computed results for the MARA 8 and MARA 10 tests even if there were some discrepancies [32]. On the contrary, the prediction of the MARS structure displacements and strains was overestimated [33].

This conservatism was supposed to come from the fact that several MARS non axisymmetric structures like core elements, pumps and heat exchangers were not represented in the CASTEM-PLEXUS model. These structures, acting as porous barriers, had a protective effect on the containment by absorbing energy and slowing down the fluid impacting the containment. For these reasons, we developed in CASTEM-PLEXUS a new HCDA constitutive law taking into account the presence of the internal structures (without meshing them) by means of an equivalent porosity method [34] [35].

Moreover, as the process used for dealing with the fluid-structure coupling was improved since then and as it was shown in [36] and [37] that this process improved the precision of the results for the tests MARA8 and MARA10, it was undertaken another comparison between the experimental results of the MARS test.

This paper presents a description of the MARS test-facility as well as the two numerical models used to simulate the test with the CASTEM-PLEXUS code. In the first simulation, the main internal structures are described with a classical shell model and uses the new process for the fluid-structure treatment. The second simulation represents, in addition, the heat exchangers and pumps by means of an homogenization model.

2 Description of the MARS test-facility

The primary circuit of the Superphenix reactor (Fig. 1) is a "pool" design [38]. The whole core, primary pumps and intermediate heat exchangers are enclosed in the main reactor vessel which is made of stainless steel and welded to the roof slab. The main reactor vessel is encased in a safety vessel also made of stainless steel.

The MARS experiment (Fig. 2) was realised at the CEA-Cadarache in order to simulate a HCDA in a 1/20 scale mock-up of the Superphenix reactor block. The main vessel (1 m diameter and 1 m height) includes all the significant internal components of the reactor [27].

The main vessel, of variable thickness (0.8 to 1.6 mm), was an assembly of a cylindrical part and of a two part torospherical bottom. The cylindrical part was made of 316L stainless steel whereas the bottom was made of 304L stainless steel. The two inner vessels were modelled, as well as the anti-convecting device and the main vessel cooling system.

The core cover plug was a rather complicated structure, despite simplifications compared with the reactor geometry: the model included the top plate, the in-pile shell with its pipes, the spacer plates and the heat-insulation. The core catcher was composed of the catcher plate, support structure, vertical flanges, chimney and spacing feet.

The lateral neutron shielding was represented by four radially split shells and their supporting structures. The mass of the unmelted part of the core was simulated by a mixing of aluminium cylinders and steel hexagons fixed into two AG3 aluminium plates. The strongback and the diagrid support were respectively represented by a non-axisymmetric ring and a cylinder.

The roof slab was constituted by two circular plates of different thicknesses to simulate the reactor roof stiffness. Openings were drilled to enable the passage of the large components and the two rotating plugs were concentrically off as in the reactor.

The main components inserted through the roof slab were modelled: four primary pumps, eight intermediate heat exchangers, four emergency cooling exchangers and two integrated purification devices. The various supporting rings (roof slab, core support structure, large components) and joining rings (between the roof slab and the rotating plugs) were represented.

The mass deficit of the mock-up cover simulation was compensated by lead plates providing additional weights on the cover. The safety vessel, the dome, the biological shield plates and the handling machine were represented only by their inertia using lead plates. Rubber-ring bands simulated the heat-insulating material between the roof and the main vessel and the gas intervals of the roof slab.

The thin structures (inner vessels, baffles, lateral neutron shielding, main components, emergency heat exchangers, core cover plug, core catcher, core, joining and supporting rings) were mainly made of 304L stainless steel in order to simulate the austenitic steel of the reactor structures. The massive structures and those made of heterogeneous materials (roof slab, rotating plugs, core support structure, diagrid support) were made of A5 aluminium. The top plate of the core cover plug was made of A42 aluminium.

The sodium coolant at operating conditions was simulated by water at 20°C. The cover gas of the mock-up was the same as in the reactor (argon).

The test was fired using a 80 g low density low pressure explosive charge of L54/16 composition [39]. The charge mass was chosen to simulate the 800 MJ full scale mechanical energy release used in the reference HCDA in the Superphenix reactor. The explosive charge was supported by the base of the core cover plug.

The whole test was well instrumented with:

- 19 pressure transducers fitted on the roof slab and the rotating plugs,
- 5 accelerometers placed on the reactor cover,
- 24 strain gauges attached on the main vessel, roof slab support ring and cover joining rings,
- 3 high speed cameras used to obtain displacements of the main vessel, roof slab and large plug, small plug and core cover plug,
- residual deformations were evaluated by measuring, before and after the firing, mesh sizes of the grid drawn on the different structures.

3 Numerical modeling of the test-facility

CASTEM-PLEXUS [40] [41] [42] [43] is a general fast dynamics finite element code devoted to the analysis of problems involving fast transients. It can deal with fluids and structures with a possibility of coupling. A specific CDA constitutive law was implemented in the code in order to be able to represent precisely this kind of explosion [36].

Owing to the symmetry of the mock-up, an axisymmetric representation was chosen for the numerical simulation of the MARS test-facility with the CASTEM-PLEXUS computer code. In a first simulation, the external structures were modeled by shells or massive structures and the main internal structures were described with a classical shell model. The second simulation represents, in addition, the heat exchangers and pumps by means of a porosity model homogenizing the components with the surrounding fluid.

The models of both simulations include a representation of the main vessel with three thin shells of different thickness and made of different materials for the cylindrical part and the torospherical part of the vessel. The top of the test-facility is described by massive elements for the roof, the small rotating plug and the large rotating plug. The massive fixings hanging the test-facility to the rigid frame are represented by a cylindrical shell at the extremity of the roof.

The top closure is assimilated to an axisymmetric structure for the needs of the numerical simulation. The openings in the roof for the passage of the components (pumps, heat exchangers) are simply accounted for by the mass they remove to the roof. Local masses on the top of the roof and of the small and large rotating plugs are added to consider the mass of the instrumentation and of the lead plates compensating the mass deficit of the MARS mock-up in relation to the real reactor. The additional local mass at the centre of the roof top also includes the mass of the internal components (pumps, heat exchangers, purification devices). Another local mass is placed at the edge of the roof to simulate the lead plates used in the test-facility to describe the inertia of the safety vessel, the dome, the biological shield plates and the handling machine.

The core cover plug was simplified. The upper part is modeled by the top plate and three plates simulate the heat and neutronic insulation. The in-pile shell and the three spacer plates are also meshed. The pipes are assimilated to two cylinders. The external shell surrounding the plug is also represented.

The joining rings between the roof slab and the three plugs are formed, in the experiment, by two concentric and cylindrical plates linked by a bridle at their top extremity. They are represented with thin shells made of aluminium and joining the top of the massive structures. Complementary shell elements made of rubber and joining the base of the massive structures were added to prevent the going up of argon in the free slit.

The heat-insulating material between the roof and the main vessel is represented by an horizontal rubber-ring band joining the roof base to the main vessel and preventing the upwards motion of argon in the empty slit. The main vessel, hung to the roof in the MARS test-facility, is fixed rigidly to the roof in the numerical model.

In the centre of the test-facility, the strongback, the neutron shielding support, the support of the baffles and of the internal vessel being fitted together, they are described by a single rigid structure, that we will call the Core Support Structures (CSS). This structure is assimilated to an axisymmetric shell of constant thickness, allocating to it an equivalent mass corresponding to the mass of all the structures. The CSS is supposed to be rigid and to transmit the totality of the forces to the structures fixed on it. The CSS is attached to the vessel by a cylindrical collar.

The diagrid support is represented by a thin shell. The core is not meshed: it is simply taken into account by an added mass spreaded along the diagrid. The diagrid support is fixed to the core support structure by a swivel link. Concerning the four shells schematizing the neutron shielding in the MARS mock-up, only the central one is modeled. This shell governs the fluid port between the core cover plug and the neutron shielding. The three other shells are taken into account by a local added mass located at the base of the first neutron shielding shell.

The baffles surrounding the outer neutron shielding are assimilated to an axisymmetric structure and represented by a vertical shell. The internal vessel is composed of two shells. Only the central one is meshed; the second one is simply described by an additional local mass at the base of the meshed internal vessel. The shielding, the baffle shell, the internal vessel are embedded on the core support structure.

The core catcher is not meshed because its complex geometry would impose a lot of shells of small dimensions and therefore a very fine local meshing, not compatible with the rest of the model. Consequently, the core catcher is represented by an added mass spreaded along the bottom of the main vessel.

The behaviour of the structures previously quoted is generally described with isotropic elastoplastic constitutive laws. However elastic laws are used to describe the rubber elements of weak resistance joining the different parts of the roof and the plugs, the internal and medium cylinders schematizing the pipes of the core cover plug whose compartment is approximated by means of an homogenization of the non-axisymmetric structures. The core support structure behaviour is also supposed linear elastic.

The presence of the internal components (pumps and heat exchangers) is taken into account in a global way in both models. In the first model, the components are represented by a pressure loss applied along a cylinder located at the average radius of the components. This pressure loss coefficient is estimated from [44] and by supposing that a cylindrical obstacle partially blocks up the port. The surface of this obstacle is given by the ratio between the solid section and the total section for a 1 radian angle.

In the second model, the components are represented by a porosity model consisting in homogenizing the structures with the surrounding fluid [34] [35] in order to take into account the structure presence simply. The fluid elements comprised between the extreme radii of the peripheral components are selected and homogenized with the structures. The structures are described by their volumic filling rate (47 %). Even if the model allows to take into account a pressure loss by friction, this possibility is not used in this simulation.

The figure 3 presents the mesh used for both simulations of the MARS test. The figures 4 and 5 show the structures for the first simulation with the pressure loss and the second simulation with the porosity model. In particular, one can see on the figure 5 the presence of a trapezoidal area between the internal vessel and the roof corresponding to the porous zone.

In case of a HCDA, the internal fluids are sodium, argon and a gas bubble. In the MARS test, the sodium and bubble are respectively replaced by water and an explosive charge. Water and argon are initially at the atmospheric pressure whereas the explosive charge induces an initial pressure of 288 MPa in the bubble area.

The characteristics taken into the numerical model are:

- Water : $\rho = 998.3 \text{ kg/m}^3$ sound speed = 1550 m/s $p^{(0)} = 10^5 \text{ Pa}$
- Argon : $\rho = 1.658 \text{ kg/m}^3$ $c_p/c_v = 1.67$ $p^{(0)} = 10^5 \text{ Pa}$
- Explosive charge : $\rho = 400 \text{ kg/m}^3$ polytropic coef. = 1.322 $p^{(0)} = 2.8810^8 \text{ Pa}$ $c_p/c_v = 1.24$

In CASTEM-PLEXUS, the fluids and solid structures can be described with an Eulerian, Lagrangian or A.L.E. (Arbitrary Lagrange Euler) approach. In the models, all the structures are represented with the lagrangian description and the mesh follows the deformation of the structures. The bubble zone is kept fixed. Indeed if the bubble grid was ALE, the mesh would deform very much because of the expansion of the bubble gas at a very high initial pressure and this large deformation would entail numerical difficulties to carry out the computation. Moreover, the fixed bubble grid is used as a reference for the updating of the ALE surrounding mesh. In the first simulation, the water and the argon are described with an ALE modeling: the fluid grid is updated according to the deformation of the neighbouring structures.

In the second simulation, the water and the argon are described with the ALE grid evolution, apart from the homogenized zone. As the porosity model developed in CASTEM-PLEXUS is only available for the eulerian description, the homogenized zone must be eulerian. Consequently two element layers next to the internal vessel are let out of the homogenized zone to operate the fluid-structure coupling. As the porosity model is not available in ALE, the structures in the centre of the test-facility (the four lines of neutron shielding, the core assemblies and the core catcher) cannot be represented by this process.

Two kinds of fluid-structure coupling are available in the CASTEM-PLEXUS code. Their main differences lie in the definition of the local normal vector used to write the coupling relations between the freedom degrees of the fluid and the solid. The first fluid-structure coupling (FS2D instruction) requires the definition of coupling elements by the user and imposes to the fluid

nodes to have the same displacements as the structure nodes. However, there is no automatic actualisation of the ALE grid for the elements other than the ones on the coupled lines.

The second coupling (FSA instruction) goes without coupling elements; the code considers directly the fluid and solid nodes in contact and writes relations allowing a possible tangential movement of the fluid in relation to the structure. The FSA coupling is well adapted to complex geometries but it often implies a user intervention to pilot the displacements of the fluid ALE grid.

The FSA coupling was adopted for the MARS test because the presence of the internal structures involves large local displacements of the fluid grid. In the previous CASTEM-PLEXUS computations [33], the FS2D coupling was used because the FSA coupling was developed later. However, in the current model, a FS2D coupling persists in a local area.

As the diagrid is merely put down on the core support structure and as both structures are not rigidly linked, the diagrid extremity is linked to the CSS by a swivel contact. Consequently, there are two different structure nodes at the same location (the one pertaining to the diagrid and the other to the CSS) whereas there is only one fluid node facing the two structure ones. This configuration cannot be processed by the FSA coupling. Therefore a FS2D coupling was settled down at the connection between the diagrid, the core support structure and the fluid between the radial shield and the CSS.

The boundary conditions are:

- Complete blocking of the base of the fixing shell hanging the mock-up to the rigid frame,
- No rotation of all the nodes of the top closure at the intersection between the massive structures and the shells: links between the roof slab, the small and large rotating plugs and the joining rings, links between the roof and the main vessel, the heat-insulating material between the roof and the main vessel and the fixing shell,
- No horizontal displacement and no rotation of the structure nodes located on the symmetry axis (core cover plug, diagrid, vessel) and of the nodes of the plates simulating the heat and neutronic insulation of the core cover plug,
- No horizontal displacement of the fluid nodes on the symmetry axis,
- No horizontal displacement of the core support structure,
- Vertical displacement of the core support structure equal to the vertical displacement of the point at the intersection between the collar and the vessel,
- Same vertical displacement for the four plates simulating the heat and neutronic insulation of the core cover plug.

To link a shell to a massive structure, it is necessary to impose identical displacements for the nodes of the shell extremity and of the massive structure facing each other. Are concerned the diagrid and the CSS, the roof and the fixing shell, the roof and the main vessel, the joining rings of the top closure.

The FSA coupling cannot be used for the nodes at the top extremity of the neutron shielding and the baffle because the code cannot define the local normal vector in an opened medium. Therefore the FSA coupling is used all along both shells except at the top extremity. Identical displacements are then imposed for the solid node at the top edge of the shell and the facing fluid node.

In order to help the code to calculate correctly the ALE mesh updating in the areas of high fluid speed or high pressure variations, the user has to define relations governing the local displacement of the mesh. Three governing lines were set up.

The first line imposes to the fluid nodes between the lower plate of the core cover plug and the neutron shielding top to stay aligned between both structure nodes during the displacement of the structures. This relation prevents a large deformation of the ALE grid due to the huge flow of the fluid going out from the central zone. Besides, this line is used as a reference for the updating of the fluid in the central zone.

Two lines impose to the fluid nodes between the lateral shielding top and the baffle and between the baffle and the internal vessel to stay aligned between the structure nodes. These lines prevent a distortion of the fluid mesh due the large local motions of the structures in that area.

Inside the core cover plug, there is no fluid-structure coupling defined between the internal structures of the plug and the fluid because the fluid can cross the pipes simulated by vertical cylinders. No fluid coupling is defined between the upper part of the external shell surrounding the plug and the fluid because this shell was perforated in the test-facility and fluid could pass from the plug to the rest of the mock-up. Consequently, in order to preserve a regular meshing inside the core cover plug, the fluid nodes on the vertical lines between the lower plate simulating the heat and neutronic insulation and the upper spacer plate has to stay aligned between the structure nodes of both plates.

4 Conclusion

In that paper, we describe the MARS test-facility representing a small scale replica of a Fast Breeder Reactor. This mock-up contains all the significant internal structures of the reactor block of the Superphenix reactor: core, core support structures, diagrid and diagrid support, neutron shielding, baffles, internal vessel, core catcher, core cover plug, pumps, heat exchangers... The external geometry of the reactor was also represented precisely: roof slab including openings for the passing of the components, rotating plugs, main vessel of variable thickness...

The MARS mock-up was used to simulate a Hypothetical Core Disruptive Accident in a Liquid Metal Fast Breeder Reactor. In case of HCDA, the interaction between fuel and liquid sodium creates a high pressure gas bubble in the core. The violent expansion of this bubble loads the vessel and the internal structures, whose deformation is important. The fluids intervening in the real accident are sodium, argon and a bubble gas composed of the molten core. In the experiment, the sodium is replaced by water and an explosive charge is placed in the centre of the mock-up to simulate the bubble expansion.

This paper presents a description of the MARS test-facility as well as the two numerical models used to simulate the test with the CASTEM-PLEXUS code. In the first simulation, the main internal structures are described with a classical shell model while the peripheral components are simply taken into account by means of a pressure loss. In the second simulation, the internal structures are also represented with shells apart from the peripheral components (heat exchangers and pumps) which are represented by means of a porosity model homogenizing the structure with the surrounding fluid.

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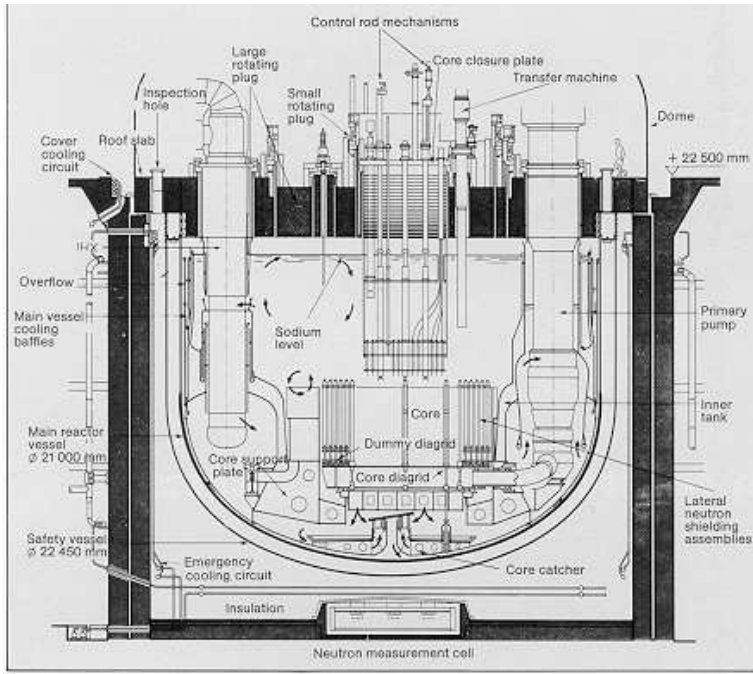


Fig. 1: The Superphenix reactor

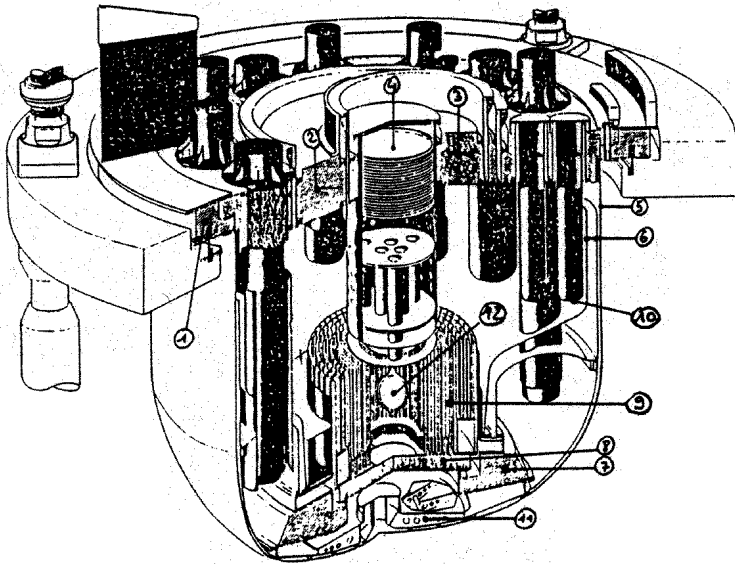


Fig. 2: The MARS test-facility

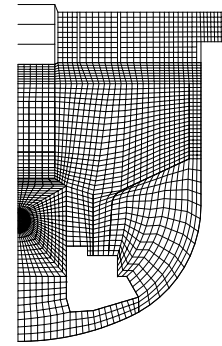


Fig. 3: Mesh of the MARS test

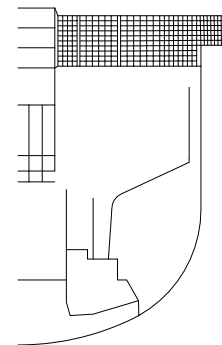


Fig. 4: Mesh of the structures with the shell model

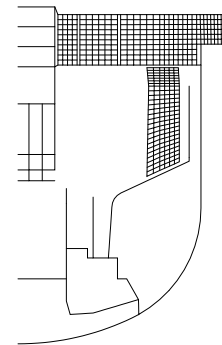


Fig. 5: Mesh of the structures with the porosity model