Structural aspects related to the Decay Volume of the SHIP Project

Working group

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- Structural concept and design
- Safety verifications
- Optimizazion of the structure
- Prototypes proposal for different tests

Castaldo Spa

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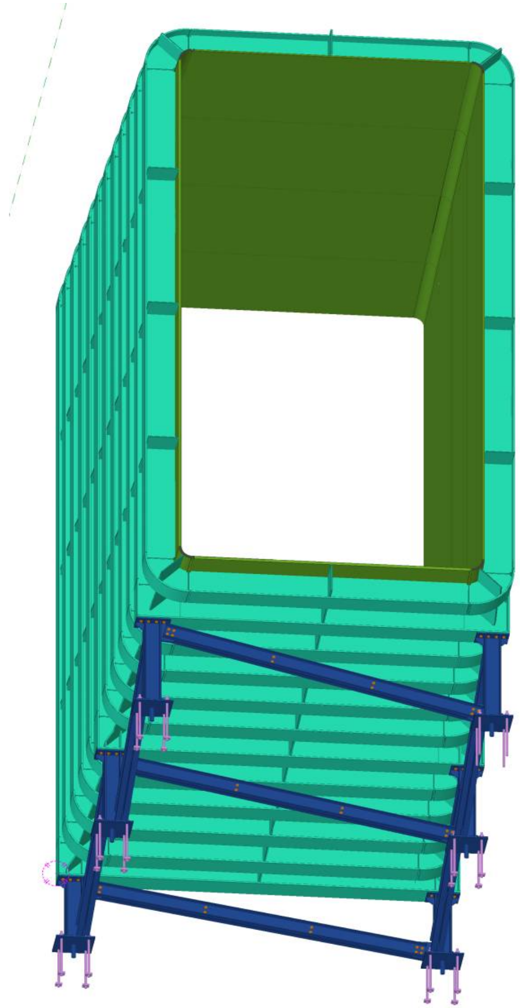
- Constructive method
- Execution
- Transportation
- Quality control
- Prototypes production for physical and mechanical tests

Critical items related to the structural design of the Decay Volume

Highlights:

- ➢ ***How to optimize the current structural solution?***
- ➢ ***Interaction of the structural solution with the LS***
- ➢ ***Weldings techniques and assembly procedures***
- ➢ ***Prototypes required before the one/two full rings***
- ➢ ***Building Information Modeling for the decay volume***

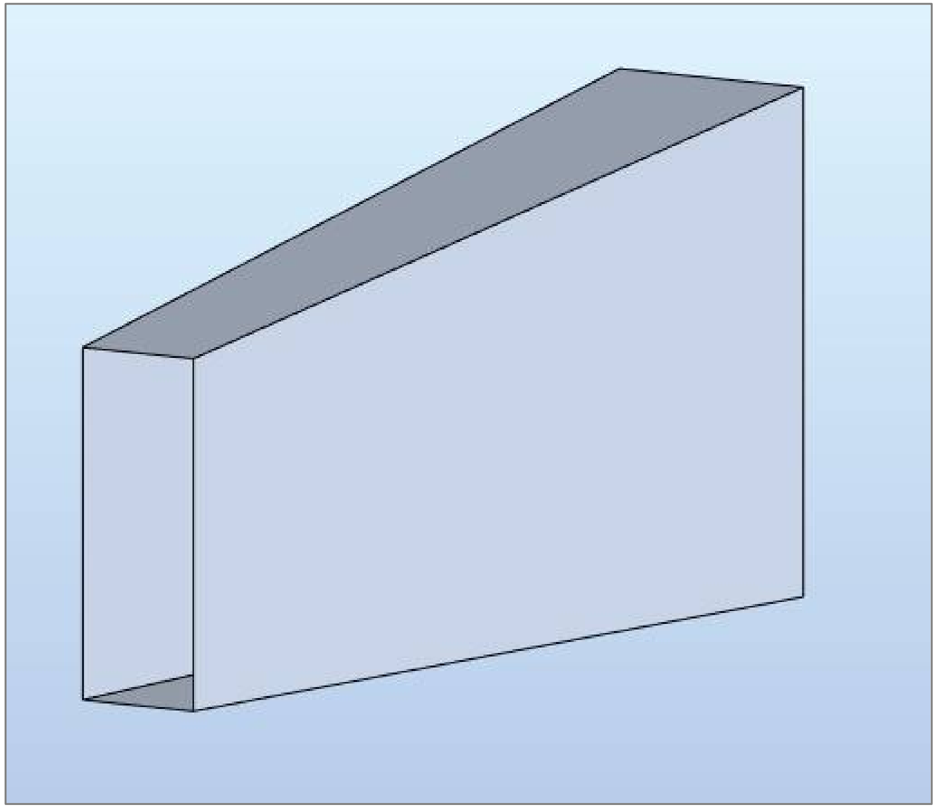


Draft version of the structural model – February 2021

How to optimize the current structural solution?

The current design of decay volume is done using ***S355JO(J2/K2)W Corten steel*** elements:

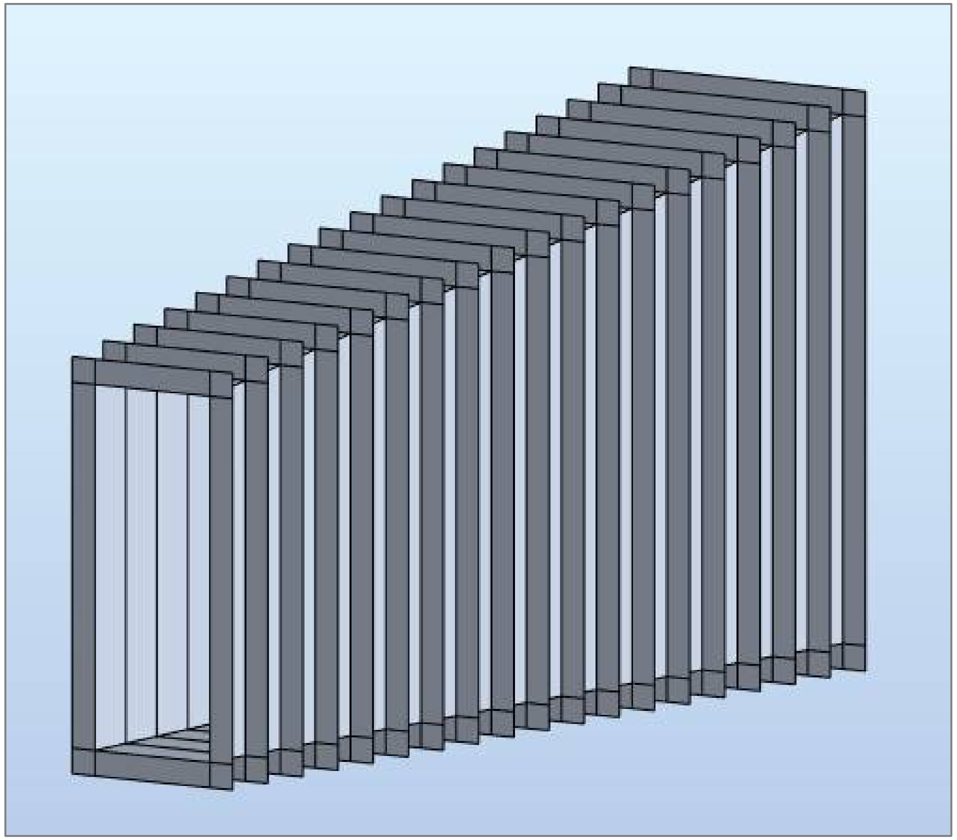
- Inner and outer steel sheets with thickness of 20 mm (with the exception of the last 16.4 meters in which the thickness is 30mm);



How to optimize the current structural solution?

The current design of decay volume is done using ***S355JO(J2/K2)W Corten steel*** elements:

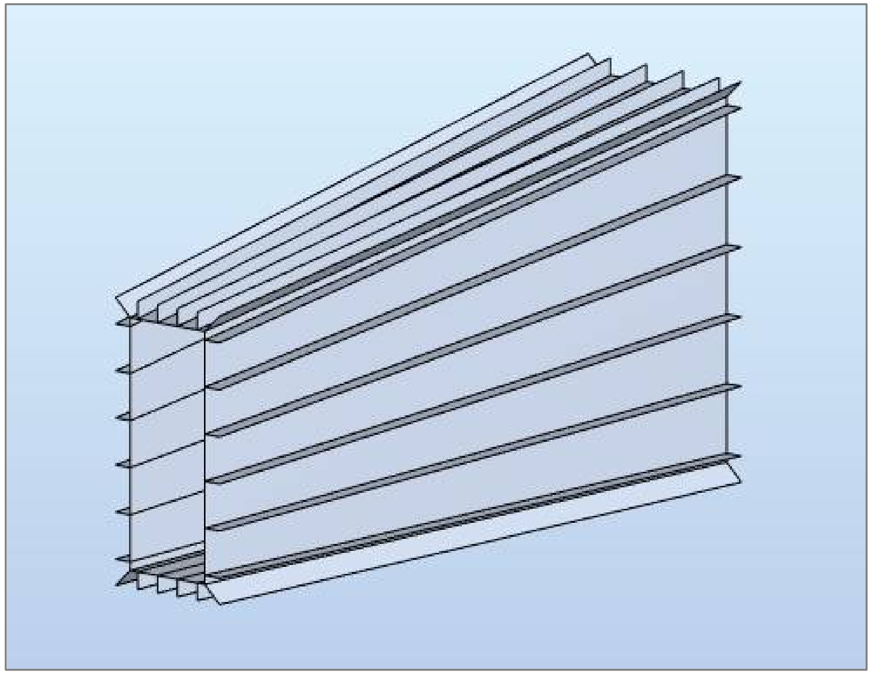
- Vertical stiffening members spacing 800 mm, with a thickness of 10 mm and an height of about 400 mm.

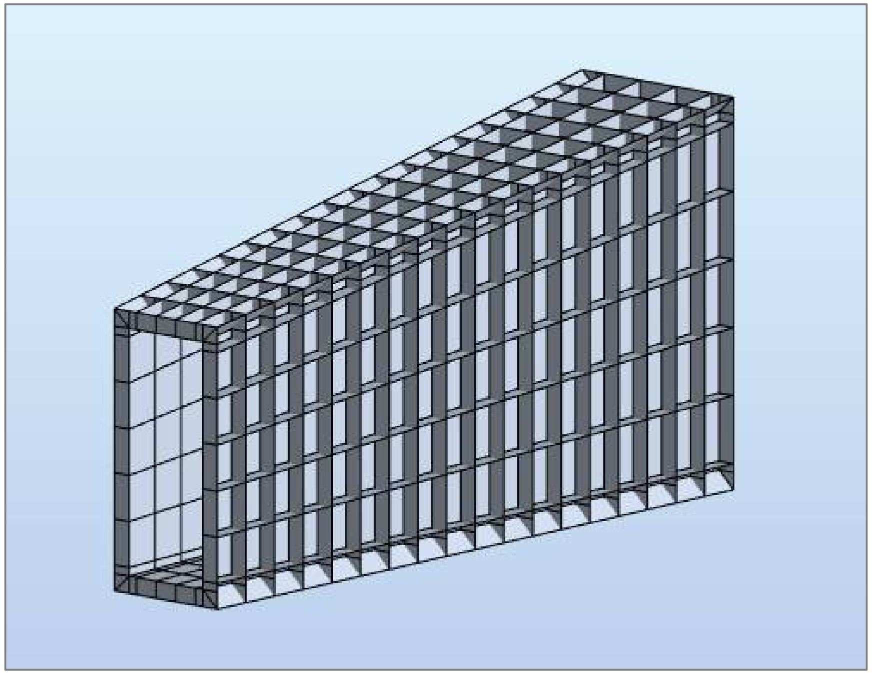


How to optimize the current structural solution?

The current design of decay volume is done using ***S355JO(J2/K2)W Corten steel*** elements:

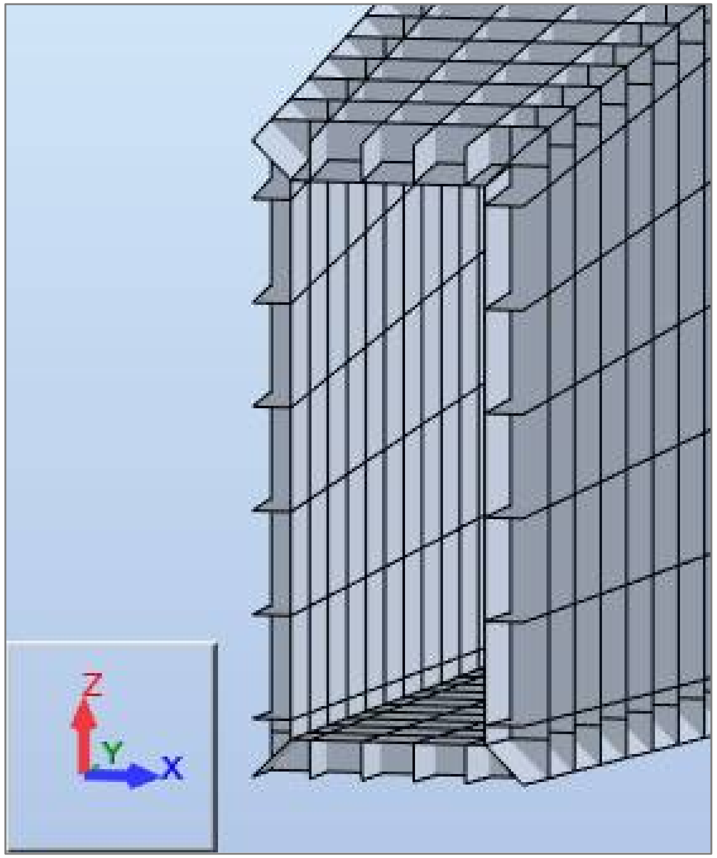
- Longitudinal stiffening elements, with thickness of 10 mm and spaced with in a range of 804 - 1702 mm for the lateral walls.

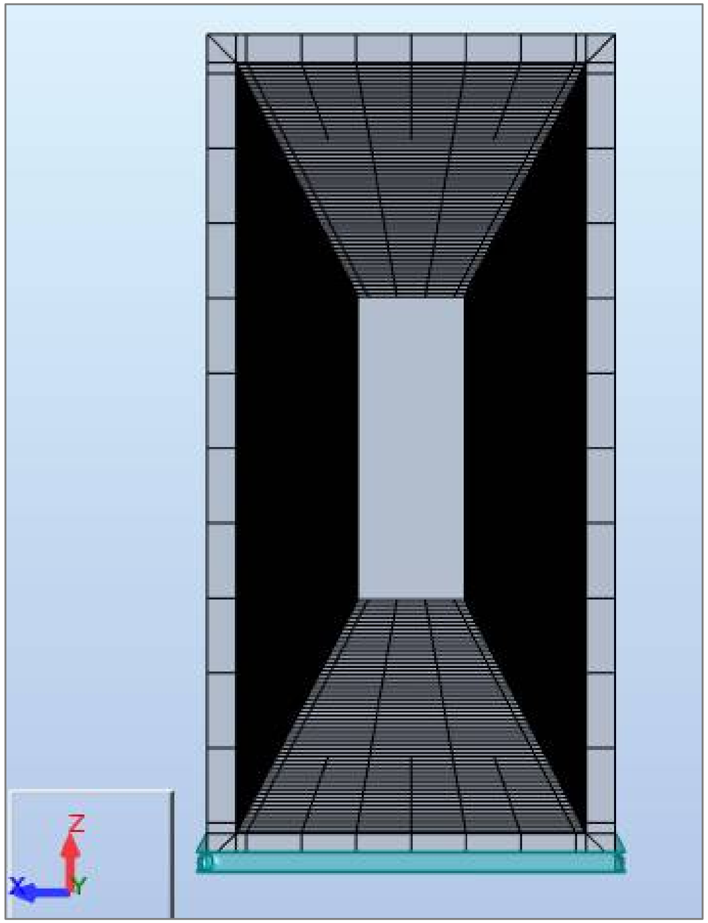




How to optimize the current structural solution?

Dimensions of the ***initial and final sections***: *a) initial section: 1.52 x 4.32 meters (internal steel sheet)* and about ***2.20 x 5.00 meters*** *(external steel sheet); b) final section: 5 x 11 meters (internal steel sheet)* and about ***5.90 x 11.90 meters*** *(external steel sheet).*





How to optimize the current structural solution?

Current structural solution design-Safety checkings

Standard references

- ***Eurocode 0: Basis of structural design***
- ***Eurocode 1: Actions on structures***
- ***Eurocode 3: Design of steel structure***
  - **Part 1-1: General rules and rules for buildings;**
  - **Part 1-5/6 : Plated structural elements.**
- ***Eurocode 8: Design of structures for earthquake resistance***
  - **Part 1: General rules, seismic actions and rules for buildings.**

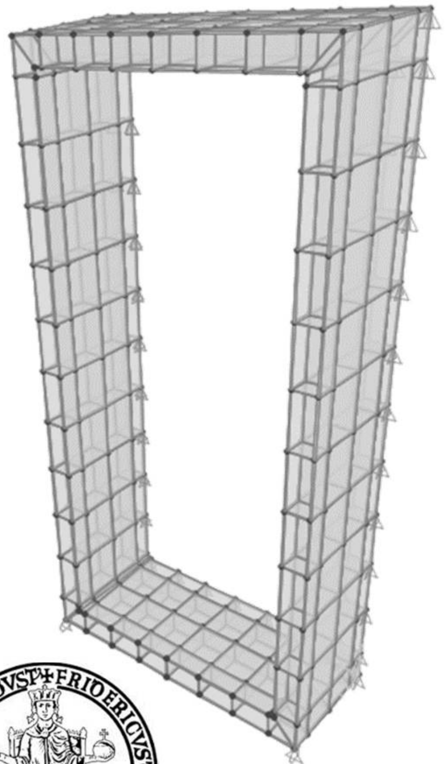
Additional requirements

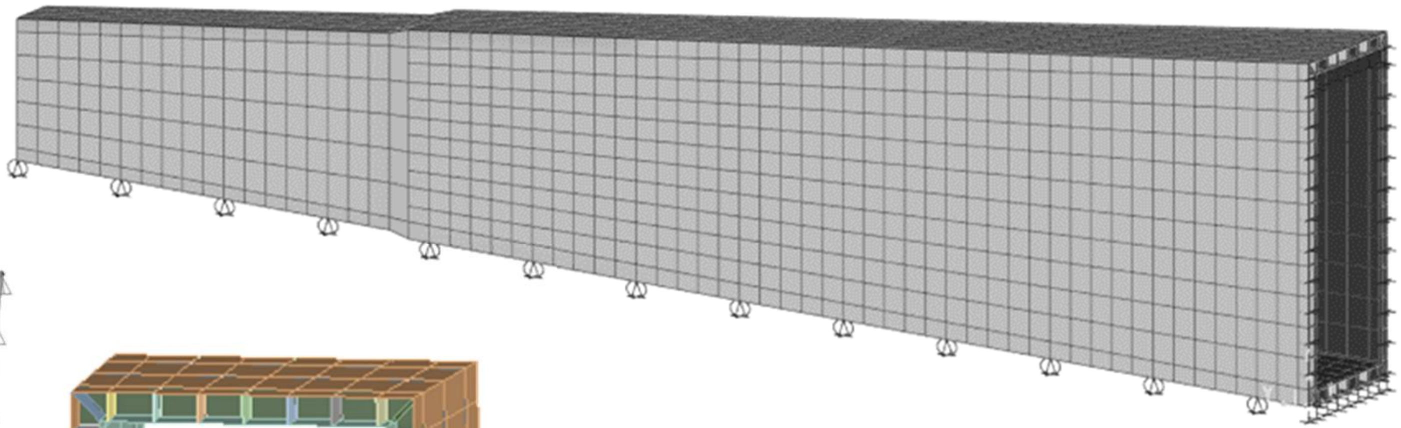
- ***EN 13445 Part 3-Section 8***

How to optimize the current structural solution?

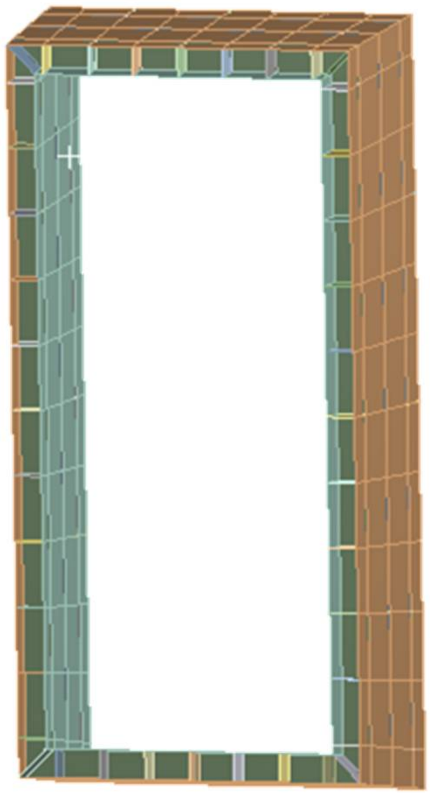
FEM modelling approach

2,4m ring model
(SAP2000)





Complete DV model (SAP2000)



2,4m ring model (ANSYS)

Current structural solution design-Verifications

Instabilty

$$\sigma_{cr,p} = k_{\sigma,p}\, \sigma_E$$

$$\sigma_E = \frac{\pi^2\, E\, t^2}{12\left(1-\nu^2\right) b^2}$$

Resistance

$$\sigma_e = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \left(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_y\right) + 3\left(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2\right)}$$

	Plate	El mean	Averaged	Unaveraged
instability	Ext	0.10	0.13	0.22
	Int	0.09	0.14	0.19
	Trasv	0.16	0.20	0.18
	Long	0.37	0.70	0.70

	Plate	El mean	Averaged	Unaveraged
resistance	Ext	0.45	0.69	0.84
	Int	0.45	0.69	0.86
	Trasv	0.41	0.43	0.50
	Long	0.86	0.94	0.98

Current structural solution design-Verifications

	Plate	El mean	Averaged	Unaveraged
instability	Ext	0.10	0.13	0.22
	Int	0.09	0.14	0.19
	Trasv	0.16	0.20	0.18
	Long	0.37	0.70	0.70

Checks summary table (Instability, Maximum Demand/capacity ratio)

Checks summary table (Von Mises equivalent stress, Maximum Demand/capacity ratio)

	Plate	El mean	Averaged	Unaveraged
resistance	Ext	0.45	0.69	0.84
	Int	0.45	0.69	0.86
	Trasv	0.41	0.43	0.50
	Long	0.86	0.94	0.98

	Plate	El mean	Averaged	Unaveraged
most binding verification	Ext	resistence	resistence	resistence
	Int	resistence	resistence	resistence
	Trasv	resistence	resistence	resistence
	Long	resistence	resistence	resistence

Checks summary table (comparison)

Current structural solution design-Verifications

	Plate	El mean	Averaged	Unaveraged
most binding verification	Ext	resistence	resistence	resistence
	Int	resistence	resistence	resistence
	Trasv	resistence	resistence	resistence
	Long	resistence	resistence	resistence

Checks summary table (comparison)

Based on this outcome, we can think to a new optimization of the sections, for example changing the resistance class of the steel to reduce the mass in all the members types how much as possible. However, if the thickness of the members becomes too small, we need to face and solve possible local instability issues for the members.

More advanced trials are requested.

Current structural solution design-Verifications

	Plate	El mean	Averaged	Unaveraged
most binding verification	Ext	resistence	resistence	resistence
	Int	resistence	resistence	resistence
	Trasv	resistence	resistence	resistence
	Long	resistence	resistence	resistence

Checks summary table (comparison)

Alternatively, we can think to widen a little bit the step among the vertical stiffening members by conserving the same thickness of the members. In addition, we can better investigate the nodal zones in which we have the maximum tensional level.

More advanced trials are requested.

Interaction of the structural solution with the LS

How to fill the 2000 cells of the decay volume with the Liquid Scintillator?

Option under investigation:

- The filling process is planned in strips of vertical cells for the lateral walls.
- The filling process is planned in horizontal aligned cells for the floor and the ceiling.

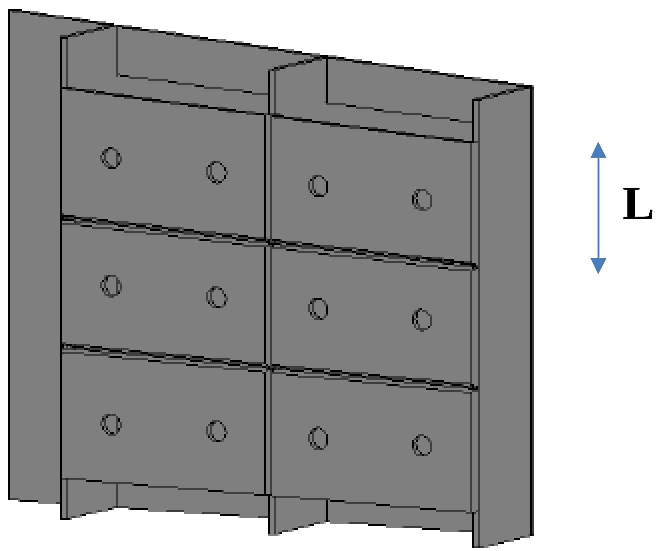
Additional structural verifications:

- The proposed configuration for the lateral walls needs a more in depth evaluation to guarantee that the lateral walls can resist to the different condition of the hydrostatic pressure.
- It is probable that a small increment of thickness of the stiffening members can be required to satisfy the verifications.

Interaction of the structural solution with the LS

Initial proposal to be validated form all the interested stakeholders

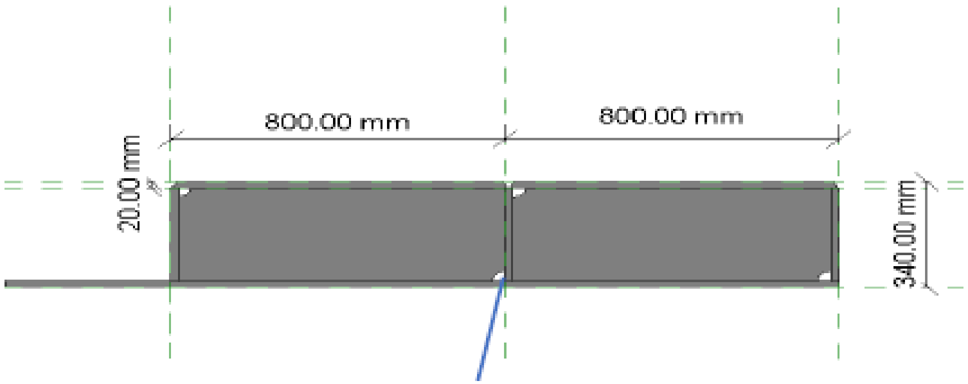
Upper panel: 2 holes whit a diameter 7 cm on singol panel at L/2 distance

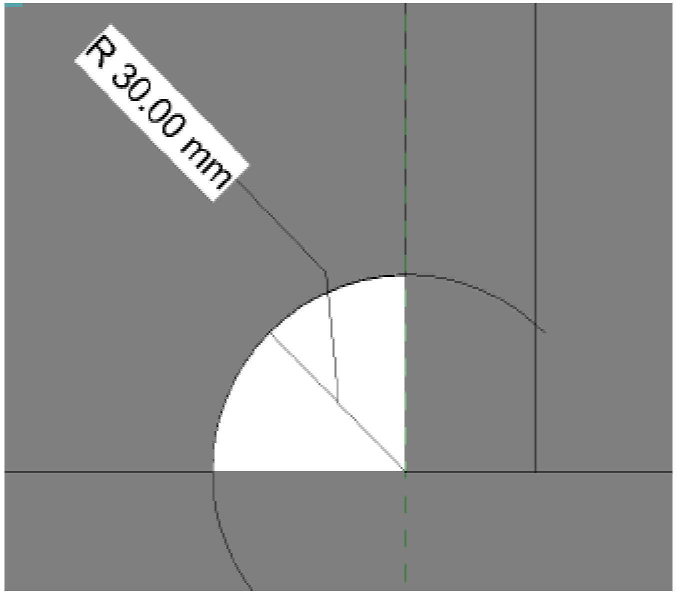


Interaction of the structural solution with the LS

Initial proposal to be validated form all the interested stakeholders

Holes semicircular on edge of the transversal stiffening whit radius 3cm.

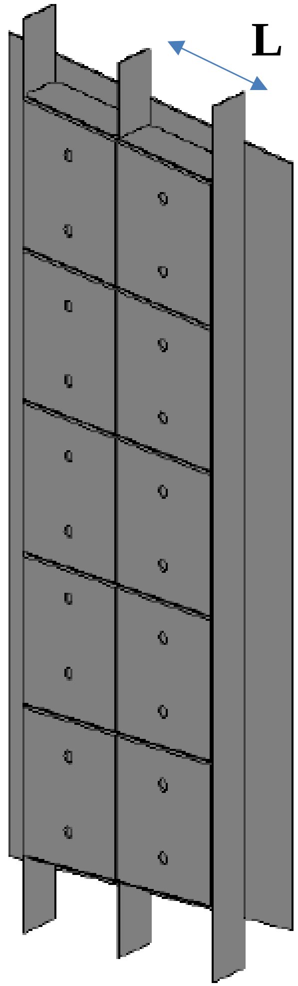




Interaction of the structural solution with the LS

Initial proposal to be validated form all the interested stakeholders

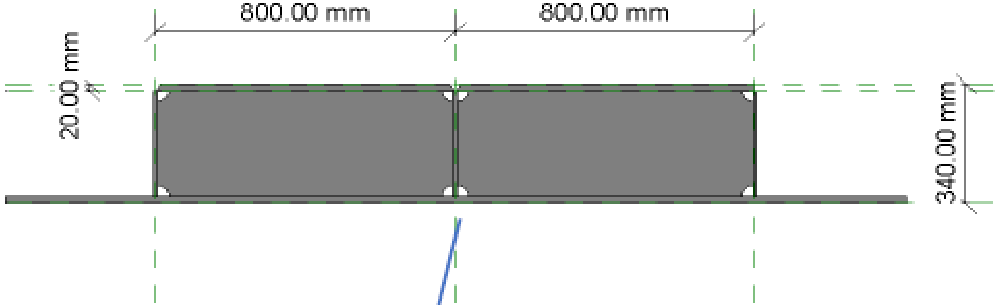
Vertical panel: 2 holes whit a diameter 7 cm on singol panel at L/2 distance

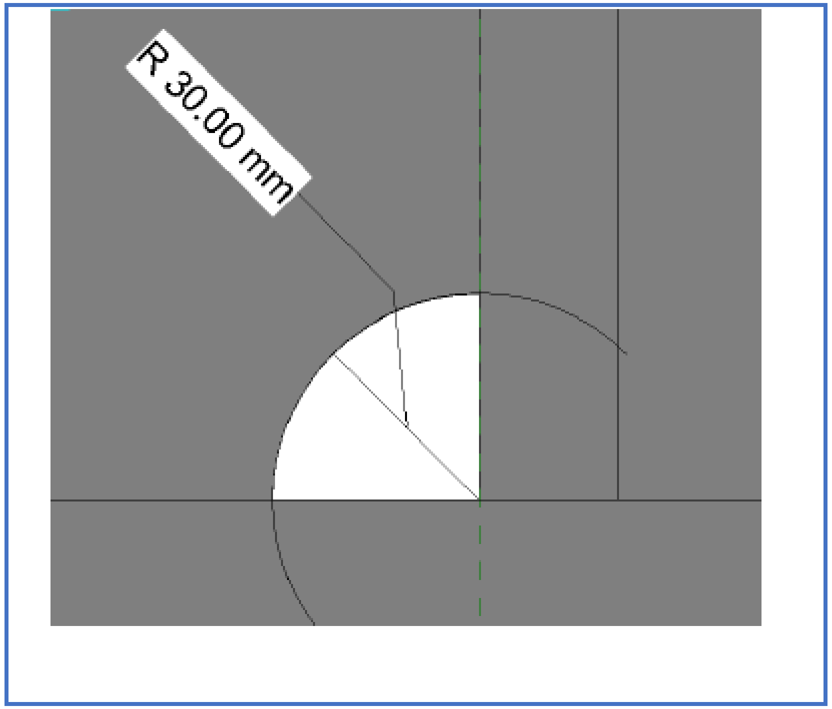


Interaction of the structural solution with the LS

Initial proposal to be validated form all the interested stakeholders

Holes semicircular on edge of the transversal stiffening whit radius 3cm.





Welding techniques and assembly procedures

Realization process

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

Clauses	EXC1	EXC2	EXC3	EXC4
7 – Welding				
7.1 General	EN ISO 3834-4	EN ISO 3834-3	EN ISO 3834-2	EN ISO 3834-2
7.4 Qualification of welding procedures and welding personnel				
7.4.1 Qualification of welding procedures	Nr	See Table 12 and Table 13	See Table 12 and Table 13	See Table 12 and Table 13
7.4.2 Qualification of welders and operators	Welders: EN 287-1 Operators: EN 1418	Welders: EN 287-1 Operators: EN 1418	Welders: EN 287-1 Operators: EN 1418	Welders: EN 287-1 Operators: EN 1418
7.4.3 Welding coordination	Nr	Technical knowledge according Tables 14 or 15	Technical knowledge according Tables 14 or 15	Technical knowledge according Tables 14 or 15
7.5.1 Joint preparation	Nr	Nr	Prefabrication primers not allowed	Prefabrication primers not allowed
7.5.6 Temporary attachments	Nr	Nr	Use to be specified Cutting and chipping not permitted	Use to be specified Cutting and chipping not permitted
7.5.7 Tack welds	Nr	Qualified welding procedure	Qualified welding procedure	Qualified welding procedure

Welding techniques and assembly procedures

Realization process

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

Table 12 — Methods of qualification of welding procedures for the processes 111, 114, 12, 13 and 14

Method of qualification		EXC 2	EXC 3	EXC 4
Welding procedure test	EN ISO 15614-1	X	X	X
Pre-production welding test	EN ISO 15613	X	X	X
Standard welding procedure	EN ISO 15612	X [a]	-	-
Previous welding experience	EN ISO 15611	X [b]	-	-
Tested welding consumables	EN ISO 15610			
X Permitted				
- Not permitted				
[a] Only for materials ≤ S 355 and only for manual or partly mechanized welding.				
[b] Only for materials ≤ S 275 and only for manual or partly mechanized welding.				

Welding techniques and assembly procedures

Realization process

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

Clauses	EXC1	EXC2	EXC3	EXC4
7.5.9 Butt welds 7.5.9.1 General 7.5.9.2 Single side welds	Nr	Run on/run off pieces if specified	Run on/run off pieces Permanent backing continuous	Run on/run off pieces Permanent backing continuous
7.5.17 Execution of welding			Removal of spatter	Removal of spatter
7.6 *Acceptance criteria*	EN ISO 5817 Quality level D A1 *deleted text* A1	EN ISO 5817 Quality level C generally	EN ISO 5817 Quality level B	EN ISO 5817 Quality level B +

Welding techniques and assembly procedures

Realization process

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

Table 17 — Additional requirements for quality level B+

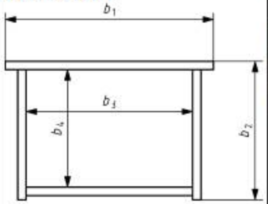
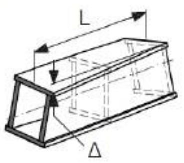
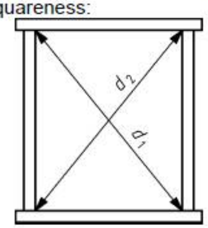
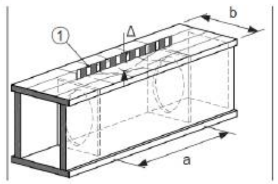
Imperfection designation		Limits for imperfections [a]
undercut (5011, 5012)		not permitted
internal pores (2011 to 2014)	Butt welds	$d \leq 0,1\ s$, but max. 2 mm
	Fillet welds	$d \leq 0,1\ a$, but max. 2 mm
solid inclusions (300)	Butt welds	$h \leq 0,1\ s$, but max. 1 mm $l \leq s$, but max. 10 mm
	Fillet welds	$h \leq 0,1\ a$, but max. 1 mm $l \leq a$, but max. 10 mm
linear misalignment (507)		$h < 0,05\ t$, but max. 2 mm
root concavity (515)		Not permitted

Welding techniques and assembly procedures

Welding techniques

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

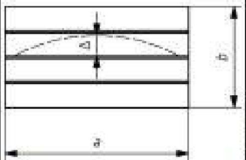
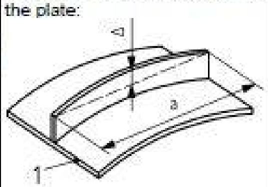
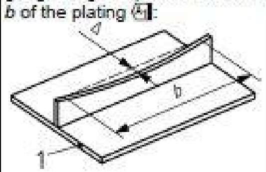
D.2.4 Functional manufacturing tolerances – Welded box sections

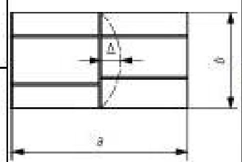
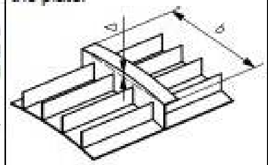
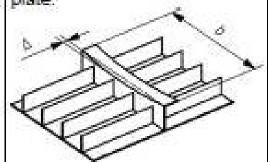
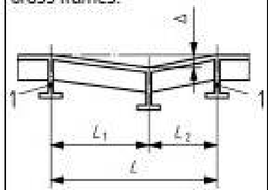
No	Criterion	Parameter	Permitted deviation Δ Class 1	Permitted deviation Δ Class 2
1	Plate widths: 	Deviation in internal or external dimensions: A1) $b \le 900$ mm (A1 900 mm < A1) $b \le 1\ 800$ mm (A1 $b > 1\ 800$ mm where $b = b_1, b_2, b_3$ or b_4	Δ = ± 3 mm Δ = ± b/300 Δ = ± 6 mm	Δ = ± 2 mm Δ = ± b/450 Δ = ± 4 mm
2	Twist: A1)  (A1	Overall deviation Δ in a piece of length L	Δ = ± L/700 but 4 mm ≤ |Δ| ≤ 10 mm	Δ = ± L/1 000 But 3 mm ≤ |Δ| ≤ 8 mm
3	Squareness: 	Difference Δ between diagonal dimensions at diaphragm positions: $\Delta = \|d_1 - d_2\|$	Δ = (d_1+d_2)/400 but Δ ≥ 6 mm	Δ = (d_1+d_2)/600 but Δ ≥ 4 mm
		Where d_1 and d_2 are significantly different: $\Delta = \left\| (d_1 - d_2)_{actual} - (d_1 - d_2)_{intended} \right\|$		
4	Out of plane imperfections of plate panels between webs or stiffeners, general case: A1)  **Key** 1 straight edge gauge of length a (A1	Distortion Δ perpendicular to the plane of the plate: if $a \le 2b$ if $a > 2b$	Δ = ± a/250 Δ= ± b/125	Δ = ± a/250 Δ= ± b/125

Welding techniques

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

D.2.11 Functional manufacturing tolerances – Stiffened plating

No	Criterion	Parameter	Permitted deviation Δ	
			Class 1	Class 2
1	Straightness of stiffeners: Longitudinal stiffeners in longitudinally stiffened plating  Key 1 plate	Deviation Δ perpendicular to the plate: 	Δ = ± a/400	Δ = ± *a* / 750 but |Δ| ≥ 2 mm
2		Deviation Δ parallel to the plate measured relative to a gauge length equal to the width *b* of the plating: 	Δ = ± *b* / 400	Δ = ± *b* / 500

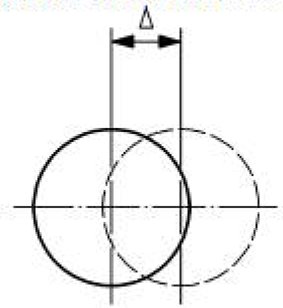
3	Straightness of stiffeners: Transverse stiffeners in transversely and longitudinally stiffened plating: 	Deviation Δ perpendicular to the plate: 	Smaller of: Δ = ± *a* / 400 or Δ = ± *b* / 400	Smaller of: Δ = ± *a* / 500 or Δ = ± *b* / 750 but |Δ| ≥ 2 mm
4		Deviation Δ parallel to the plate: 	Δ = ± *b* / 400	Δ = ± *b* / 500
5	Levels of cross frames in stiffened plating: Key 1 cross frame	Level relative to adjacent cross frames: 	Δ = ± *L* / 400	Δ = ± *L* / 500 but |Δ| ≥ 2 mm

Welding techniques and assembly procedures

Welding techniques

Based on the definition of the ***highest class of execution (EXC4)***, specific requirements in the realization of the different pieces have be respected (herein according to EN 1090 and EN 10025)

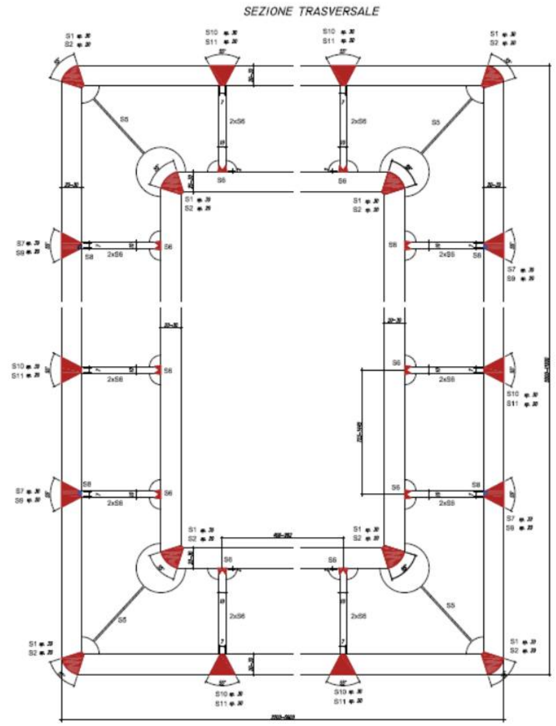
D.2.8 Functional manufacturing tolerances – Fastener holes, notches and cut edges

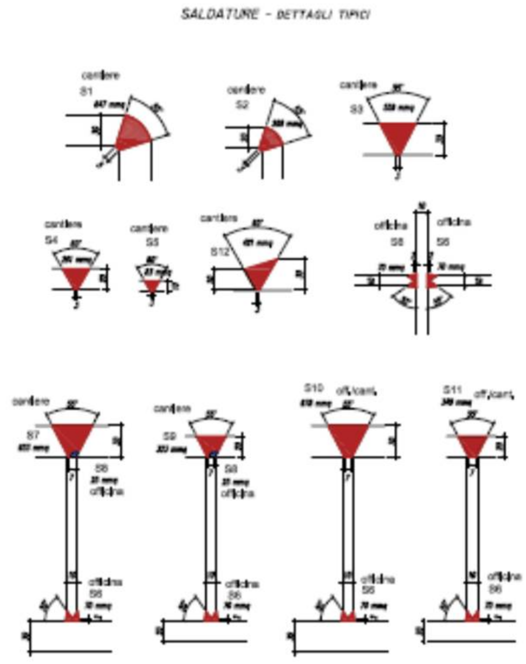
No	Criterion	Parameter	Permitted deviation Δ	
			Class 1	Class 2
1	Position of holes for fasteners: 	Deviation Δ of centreline of an individual hole from its intended position within a group of holes:	Δ = ± 2 mm	Δ = ± 1 mm

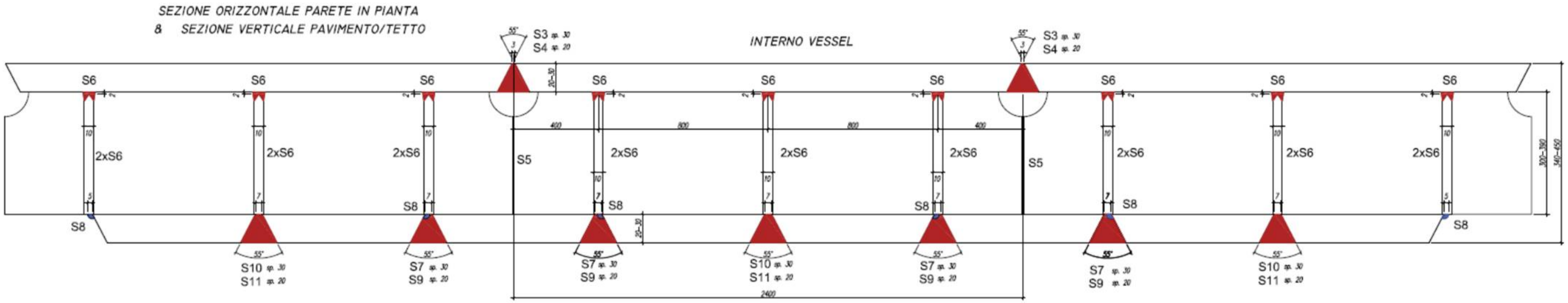
Welding techniques and assembly procedures

Weldings techniques

Scheme of the weldings for a transversal section of the decay volume



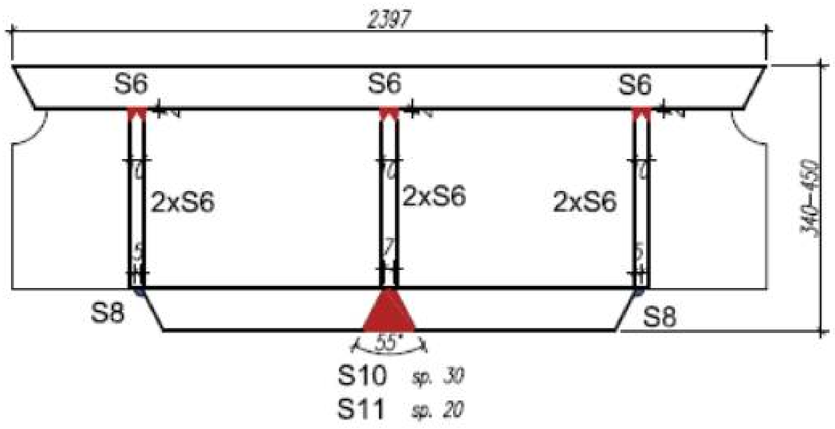




Welding techniques and assembly procedures

Assembly procedures

Standard modulus from factory (2.4 meters)



Linear meters of welding in factory: 6416

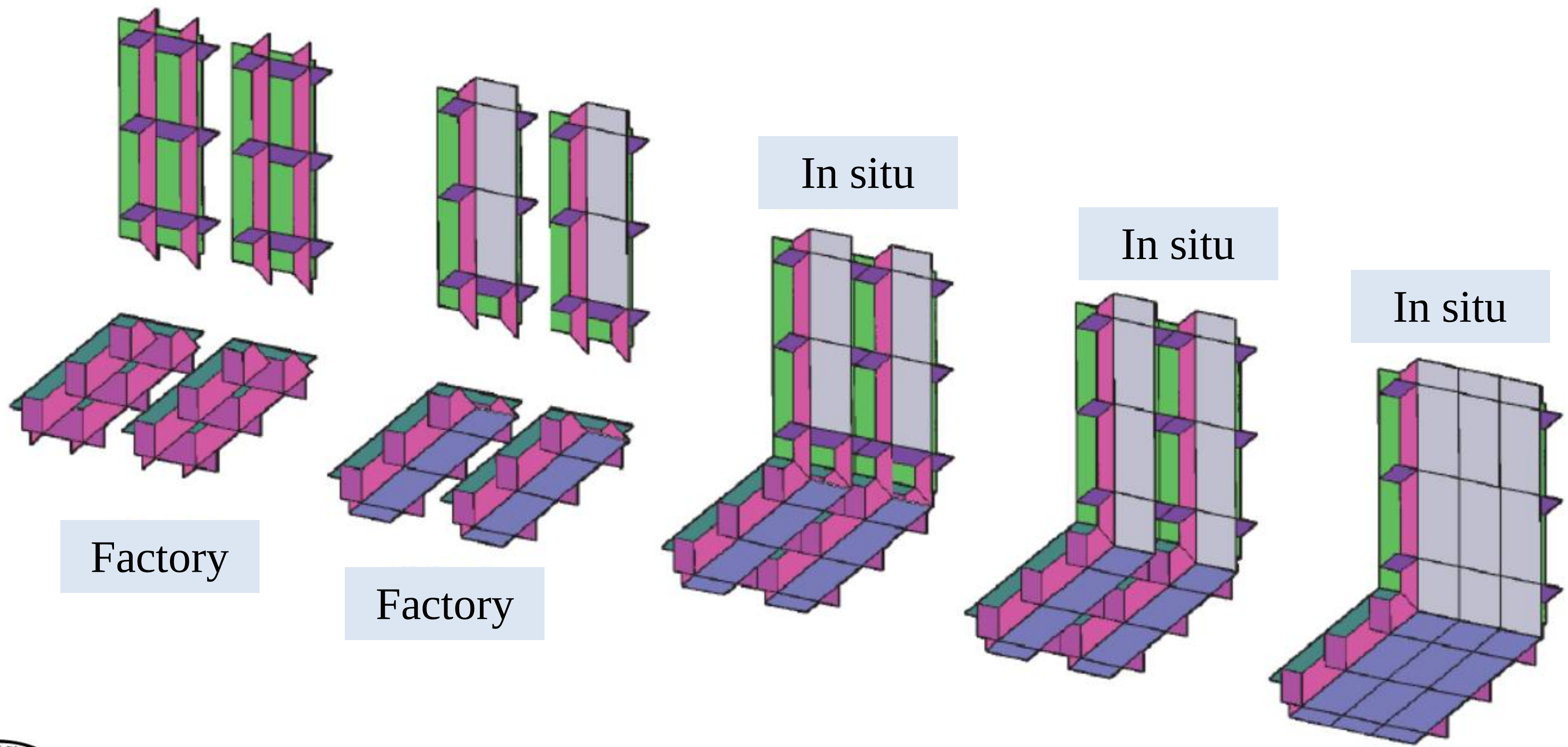
Linear meters of welding in situ: 2754

- The various panels with a width of 2.4 meters with variable height will be produced in the workshop, using numerically controlled machines with thermal break (laser etc.).
- The welding will be carried out following specific procedures and sequences that allow controlled and programmed heat inputs for the steel pieces involved in the welding process.
- Finally, the welding will be verified with appropriate techniques to check that the welding meets the required standards.

Welding techniques and assembly procedures

Assembly procedures

Production chain

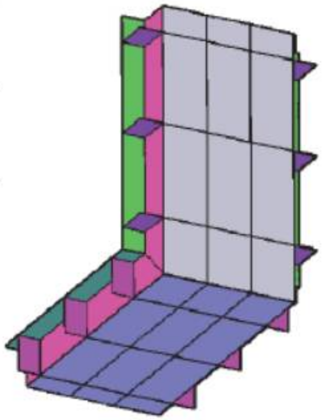


Welding techniques and assembly procedures

Assembly procedures

Production chain

In situ

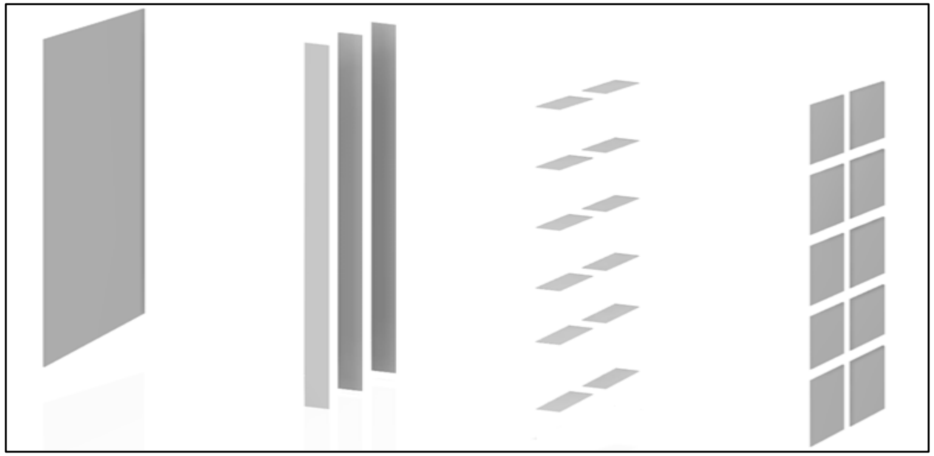


- During the assembly phase of the individual panels in the factory, such as in in situ, any potential deformations will be corrected by means of special procedures, shared and endorsed by the Italian Institute of Welding.
- These procedures have been already largely experienced from the Castaldo SpA, that is also authorized to produce structures and provide them the CE mark (European certification) up to the most severe EXC4 execution class foreseen by UNI EN 1090-2.

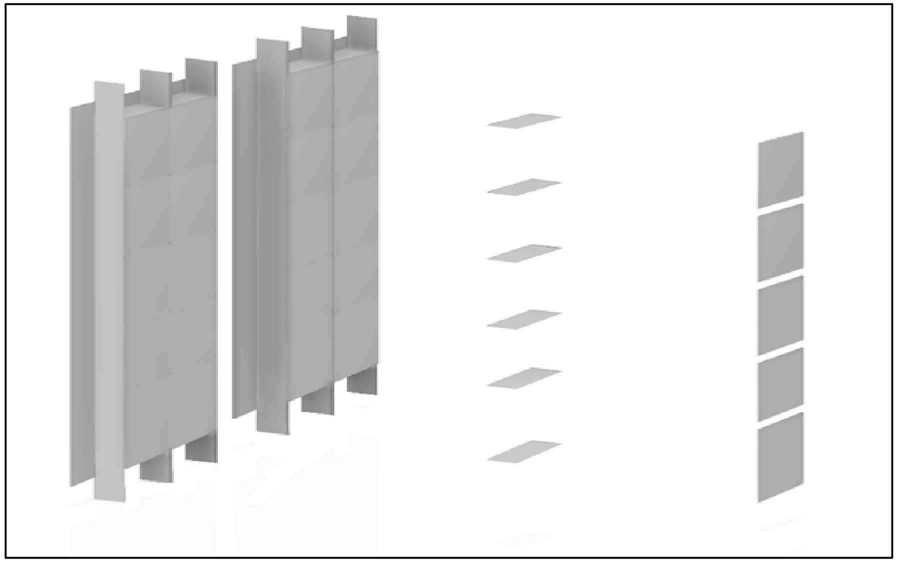
Welding techniques and assembly procedures

Assembly procedures

ASSEMBLY WORKSHOP



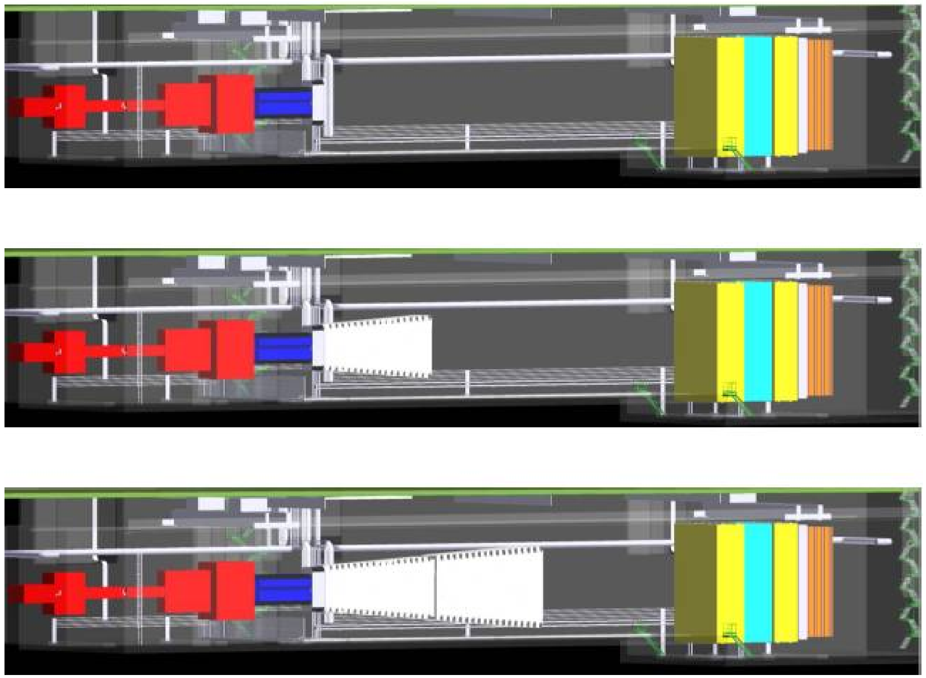
CONSTRUCTION SITE



Welding techniques and assembly procedures

Assembly procedures

- The 2.4-meter panels will be transported to the construction site to be assembled into a single panel consisting of a maximum of 6 modules.
- The decay has been divided into 4 blocks to minimize the number of welds to be made within the experimental area.
- This subdivision into macro blocks allows to increase the flatness between the various panels, which cannot be easily reached by following other procedures such as the 2.4 m ring solution, where misalignments could occur (max 1-2mm) between a ring and the other, phenomenon mitigated with the 12 m continuous sheet.



Prototypes required before the one/two full ring

Possible prototypes

➢ Required from structural design team

- Small-scale or sub-assembled specimens for structural issues:

1. Checks on the stress/deformational path
2. Checks on the tightness of the welding
3. Checks on the instability

➢ One/Two full ring test, which involves more groups

- Definition of the dimensions of the prototype (which section height are we going to choose?)
- Setup of the test
- Loads and boundary conditions
- Tests on coating/LS/hydraulics/mechanical aspects

Prototypes required before the one/two full ring

Possible prototypes

➢ Required from structural design team

- Small-scale or sub-assembled specimens for structural issues:

1. Checks on the stress/deformational path
2. Checks on the tightness of the welding
3. Checks on the instability

Experimental campaign: reliable predictions for the executive/constructive phase; all the steps (e.g., functionality, welding, execution in situ, assembly, etc.) should be tested.

Let us assume we consider a sub-assembly of few boxes in real scale. In fact, it is better to use sub-assembly than scaled portions of the decay in this phase: the scaling (1:4, 1:5 in this phase?) is quite complicated; however the advantages and disadvantages should be in depth investigated.

Prototypes required before the one/two full ring

Possible prototypes

➢ Required from structural design team

- Small-scale or sub-assembled specimens for structural issues:

1. Checks on the stress/deformational path
2. Checks on the tightness of the welding
3. Checks on the instability

Lets assume we consider a sub-assembly of few boxes in real scale:

1) Welding checks

2) Mechanical tests

3) The prototype can be used for other purposes required from different groups

Prototypes required before the one/two full ring

Possible prototypes

Let us assume we consider a sub-assembly of few boxes in real scale:

1) Welding checks:

The same typologies of welding we will in have in farm should be realized (for example external plate that closes the box etc.); for the in situ welding we can think to realize two rings in order to check the full ring welding.

The acceptance criteria required in the UNI EN 1090 should be checked. Different procedures can be used such as the use of x-ray checks, penetrating liquids checks etc.

Then, also mechanical tests can be done to check the tightness of the welding, such as a tension test on the selected sub-assembly specimen.

Prototypes required before the one/two full ring

Possible prototypes

Let us assume we consider a sub-assembly of few boxes in real scale:

2) Mechanical tests

An ad hoc setup is required to reply the same boundary conditions and the same actions/forces of the selected sub-assembly.

The design of the setup of the test becomes a critical issue during this phase (budget, facility etc in order to have a technical economic feasibility study).

C shape, top section, lateral section sub assembly can be selected and flexural test can be realized to achieve the classical deformed shape of the void and compare it with the analytical prevision.

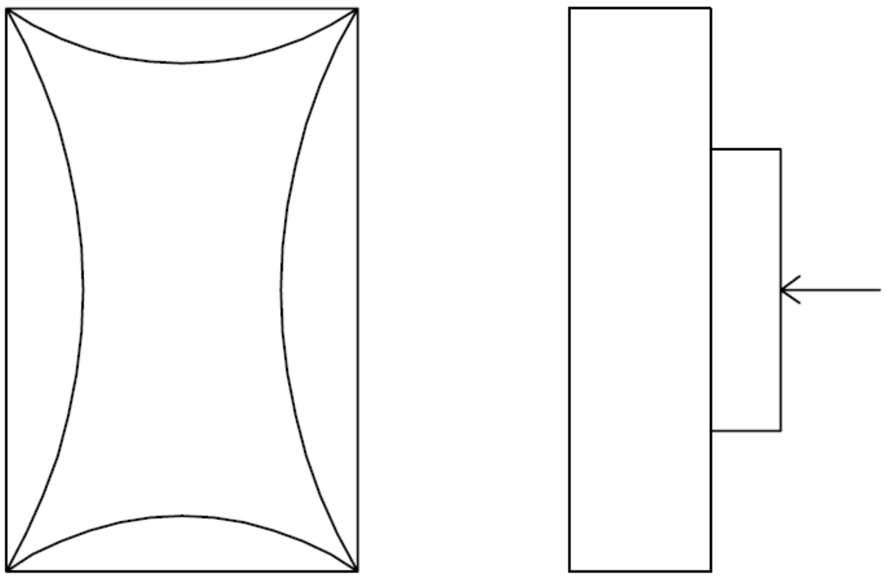
Prototypes required before the one/two full ring

Possible prototypes

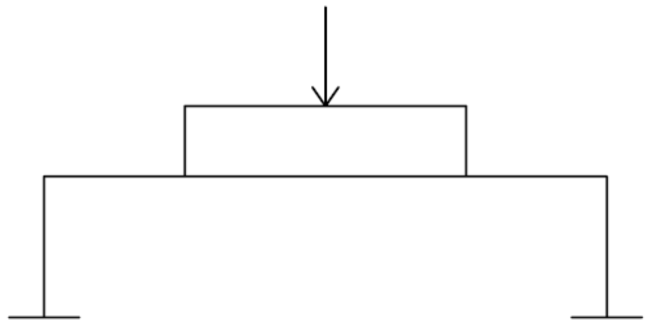
Let us assume we consider a sub-assembly of few boxes in real scale:

2) Mechanical tests

Extracted sub-assembly



Same forces path



Same boundary conditions

Prototypes required before the one/two full ring

Possible prototypes

Let us assume we consider a sub-assembly of few boxes in real scale:

2) Other conditions during the mechanical tests

The sub-assembly should be filled with LS.

The sub-assembly should be coated.

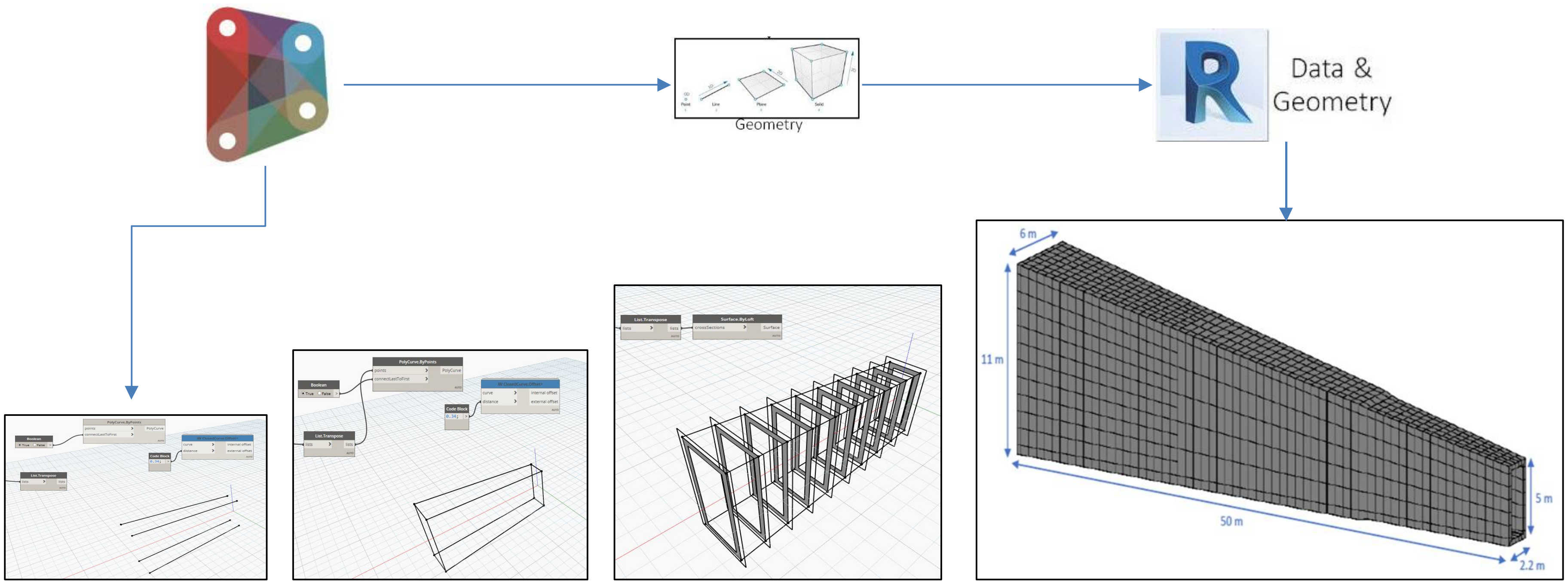
In this way, together with the simulated void pressures and with the replicate boundary conditions, we can repeat the experiment conditions.

We can consider that the other groups can do other tests on the same sub-assembly or we can go further up to failure of the members at ultimate condition to check the distance between the serviceability and ultimate conditions.

Building Information Modeling for the decay volume

New developed BIM routine

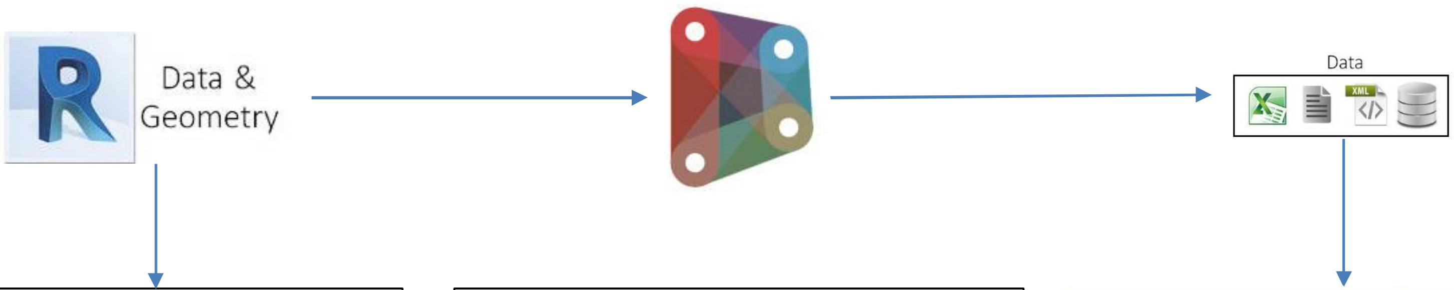
The decay volume has been designed inside a BIM framework, using Autodesk's Revit modeling software and using the open source visual platform, Dynamo, integrated directly into Revit. The reason for this choice is that the BIM computational design allows designing highly flexible parametric geometries.

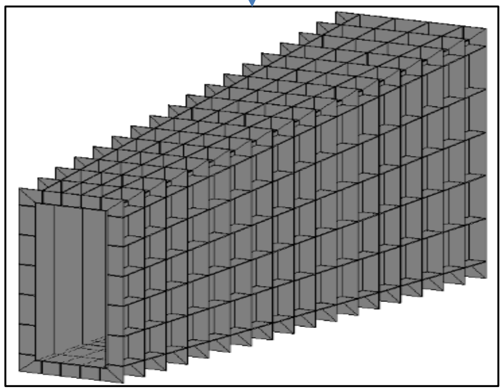


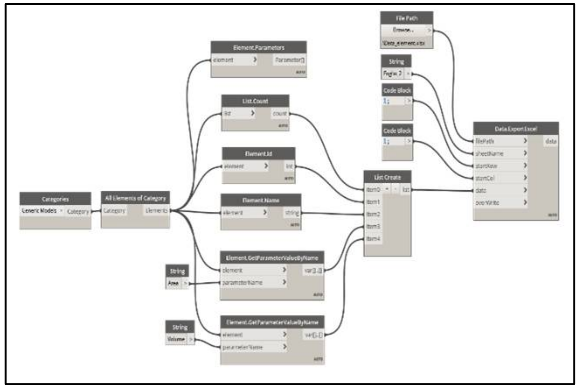
Building Information Modeling for the decay volume

New developed BIM routine

Moreover, through the use of Revit it was possible to extrapolate a series of useful information for the purposes of calculation and for the construction of the individual elements that make up the decay. For the extrapolation of data, an algorithm has been written in Dynamo to sort the data and report it directly on an excel sheet.



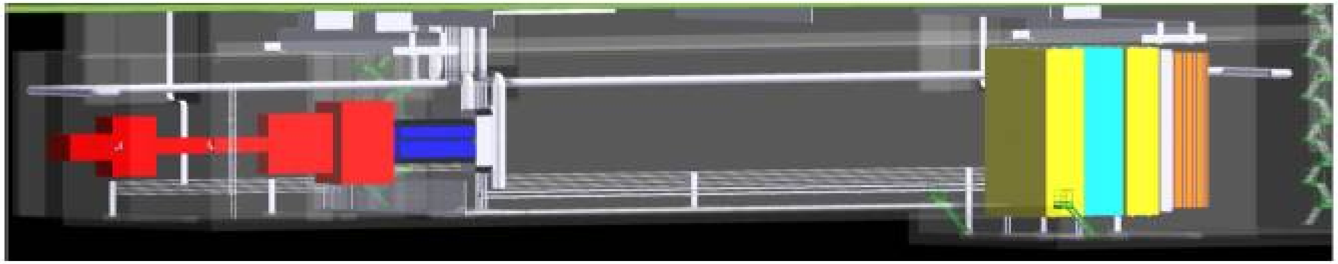


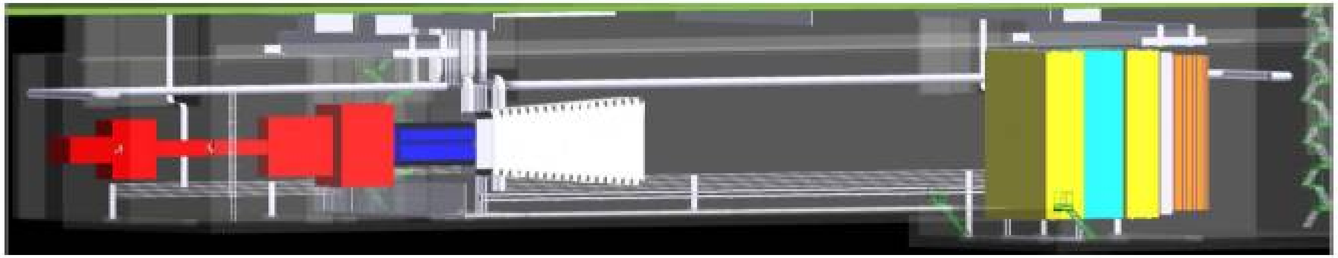


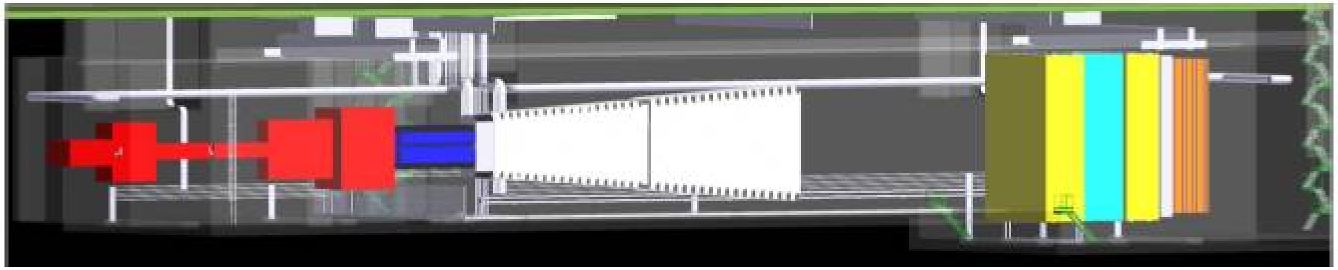
Numero totale elementi		3748	
ID elemento	Nome Elemento	Area [mq]	Volume [mc]
300519	pannello_int_DX_1	9,04	0,18
300772	pannello_int_DX_2	11,54	0,23
301263	pannello_int_DX_3	12,32	0,24
301832	pannello_int_DX_4	13,09	0,26
302334	pannello_int_DX_5	13,87	0,27
302934	pannello_int_DX_6	14,64	0,29
305528	pannello_int_SX_2	11,54	0,23
306218	pannello_int_SX_3	12,32	0,24

Building Information Modeling for the decay volume

Scheme of the assembly procedure underground

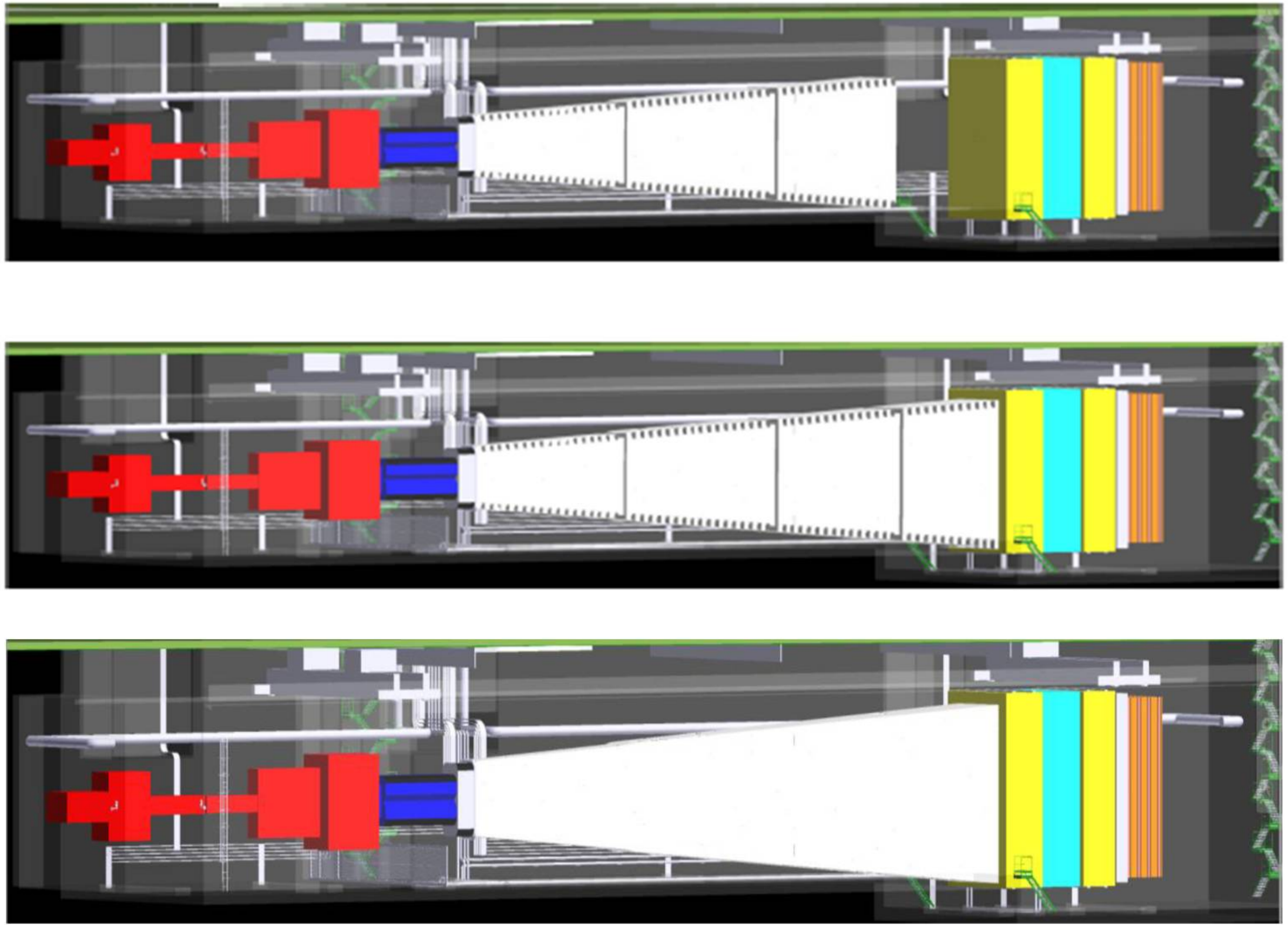






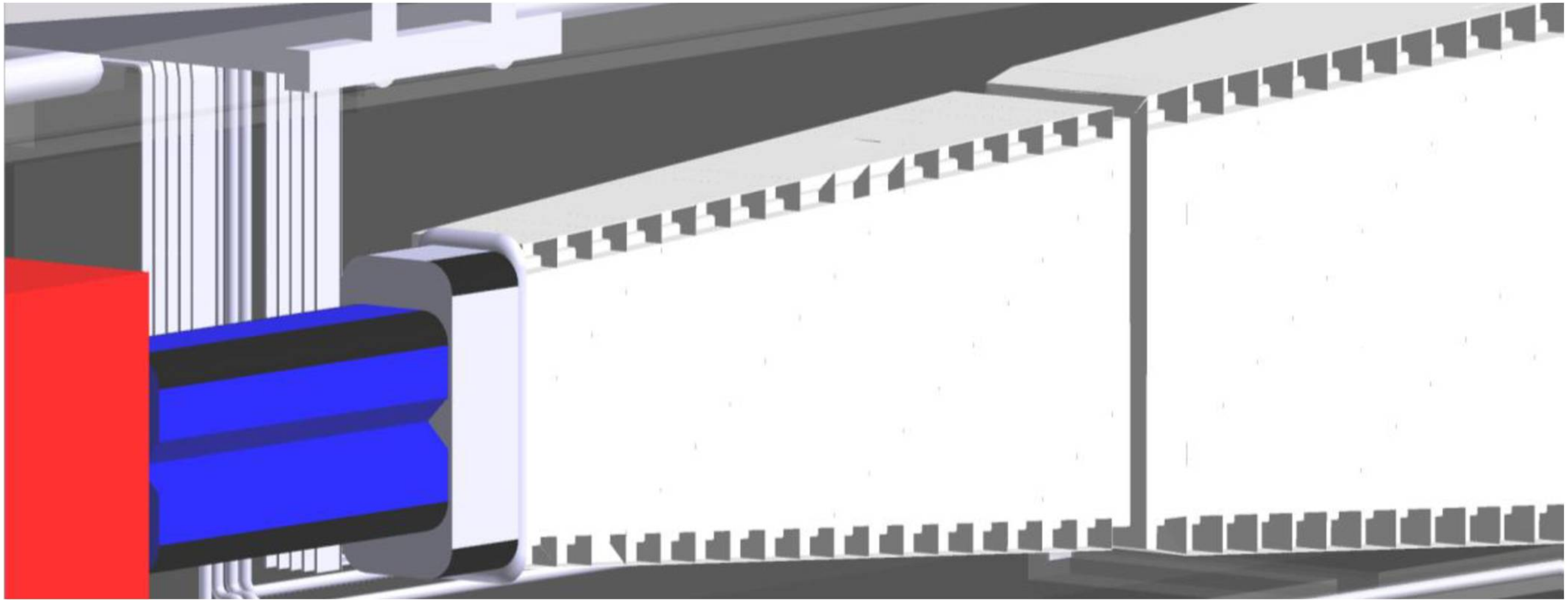
Building Information Modeling for the decay volume

Scheme of the assembly procedure underground



Building Information Modeling for the decay volume

Scheme of the assembly procedure underground



Building Information Modeling for the decay volume

Movie of the assembly procedure

Thank you for the attention