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Division V

DESIGN, VALIDATION AND ERECTION OF A SHIELD FOR THE VENTILATION STACK OF THE INSTITUT LAUE LANGEVIN

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ABSTRACT

The Institut Laue-Langevin is an international research centre at the leading edge of neutron science and technology. Located in Grenoble (France), the ILL nuclear reactor provides scientists with a very high flux of neutrons feeding some 40 state-of-the-art instruments, which are constantly being developed and upgraded.

Following the Fukushima accident, the safety principles of all nuclear plants were reassessed and improved. In this context, the ILL ventilation stack robustness was improved, in order to protect the new emergency control room, in the vicinity, from any risk of collapse during extreme earthquake, or following extreme flooding.

The design for protection against extreme flooding is defined with the assumption of successive collapse of the four dams located on the Drac river, resulting in a 6-meter high flood, carrying large objects such as trees or trucks.

In order to protect the ventilation stack, a steel shield was designed and build around the stack. The shield is sized to resist an impact of a 20-ton floating truck at various heights, from 2 m up to 10 m, and speeds up to 7 m/s.

The paper presents the main aspects of this project: global design, detail design, preliminary analysis, advanced analysis, validation by tests, and construction.

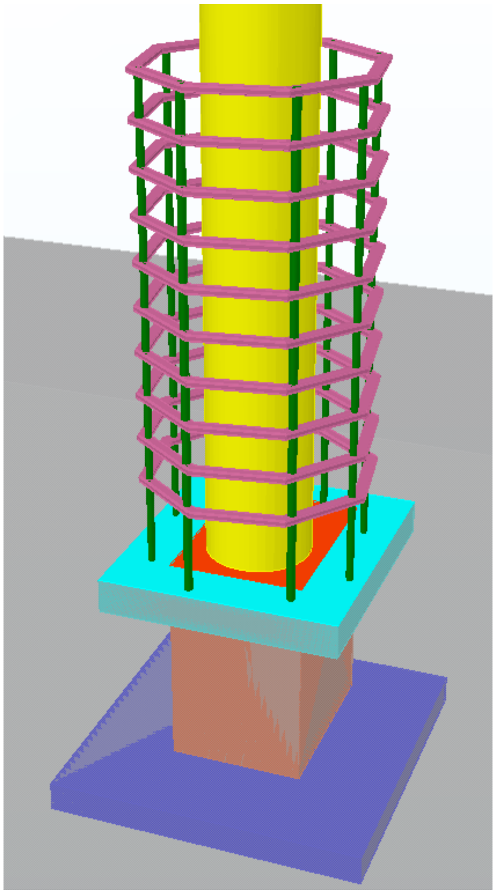


Figure 1. General view of stack shield

GLOBAL DESIGN

The first step of the design consists in defining the main sizing assumptions: maximum flood height and speed, truck mass. A hydraulic study of the flooding process was carried out by Artelia, resulting in the definition of water height and speed on ILL site, following collapse of the 4 dams on the Drac river, and their evolution over time. The results obtained at stack location show that the maximum water height is around 7.5 m, with a concurrent flow speed of 3 m/s. However, the maximum flow speed is 7 m/s with a concurrent water level up to 6.5 m. The floating truck is supposed to have a maximum mass of 20 tons, and the maximum impact height is supposed to be located 3 m above the water surface. Therefore, a 20-ton impact at speed 7 m/s is considered at level range [0; 9.5 m], and an impact at speed 3 m/s is considered at top level (10.5 m). The maximum kinetic energy is 490 kJ.

The shield is designed to balance the impacting energy by its elasto-plastic deformation. It is made of an octagonal steel frame with tubular columns and beams. The first frame level is 2 m high, whereas the others are 1 m high, so that the weakest level of the frame is the first one, regardless of the impact height. Therefore, the impacting energy is mainly balanced by the elasto-plastic deformation of the first frame level. The deformation of the other levels is small and they keep an almost vertical shape. A clear distance of 1 m is provided between the stack and the shield, allowing a large deformation of the shield without contact. The stack external diameter is 2.4 m, and the shield octagonal internal width is 4.5 m. The steel shield is anchored in a thick reinforced concrete slab linked to the stack foundation.

Preliminary hand calculations led to pre-size the frame with tubular columns Ø168x8 and beams 250x150x8 made of S355 steel. With these sections, elementary bending calculations allow to evaluate the maximum yielding force of the frame at 585 kN. Therefore, the energy of 490 kJ could be balanced with a maximum plastic displacement of around 0.85 m < 1 m.

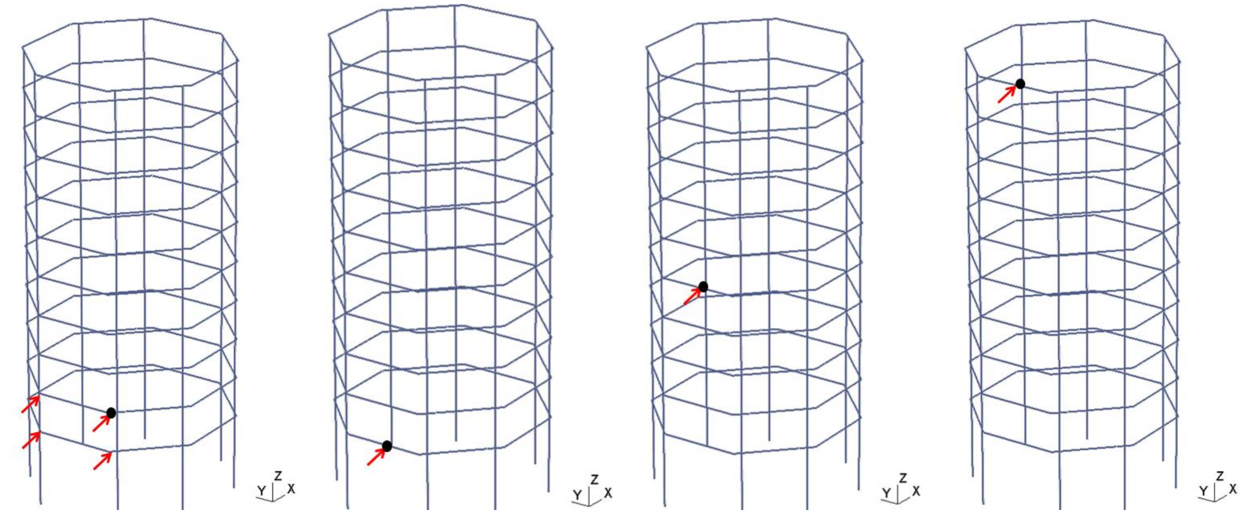
Different detailing principles are taken in order to ensure a stable plastic behaviour in a large plastic deformation domain, without the risk of brittle failure:

- Each column is made of one piece without joint overall its whole height,
- The joints between columns and beams and between beam segments are made with full penetration welds,
- The robust anchorage of columns in the foundation is achieved by sealing the column inside the concrete foundation thick slab.

The preliminary design calculations were carried out using a multi-fiber beam model of the shield, in elasto-plastic domain and large displacements and rotations range, with Code_Aster software. The columns are supposed to be perfectly embedded on the foundation slab. These preliminary calculations use static analysis, and the target displacement is obtained according to the energy balance.

The multi-fiber beams have a nonlinear elasto-plastic hardening behaviour with S355 steel properties: yield stress $f_y = 355$ MPa, tensile strength $f_u = 500$ MPa, ultimate strain $\varepsilon_u = 22\%$, Young modulus E = 210 000 MPa, hardening modulus $E_t = 700$ MPa. Four different configurations of impact are considered, at various heights and distributions (Figure 2).

For each configuration, the load is increased progressively and the nonlinear structural response is computed, until the target energy of 490 kJ is reached. This load defines the equilibrium state of the structure under impact load. The structural response is summarised by the force-displacement curve (Figure 3) and the results of interest are the deformed shapes, global force, maximum displacement, absorbed energy and maximum steel strain. These results confirm the performance of the design. The force-displacement global response is almost constant and independent from impact height. The maximum displacement varies from 720 up to 880 mm (depending on the impact height) which is less than the clear distance of 1 m. The first frame level acts well as a dissipating structure, with large deformation, and the other levels have enough over-strength so that their deformation is low. The maximum steel strain is 17 % < ultimate strain $\varepsilon_u = 22$ %. However, this large strain range is unusual in a steel frame design. Therefore, it is recommended to carry out full scale tests to validate the actual deformation capacity of the columns.



1: impact at level +2 & +3 m distributed on 4 points at beam-column intersection

2: impact at level +2 m concentrated on beam

3: impact at level +6 m concentrated on beam

4: impact at level +11 m concentrated on beam

→ Force
● Control point

Figure 2. Definition of four configurations of impact on beam model.

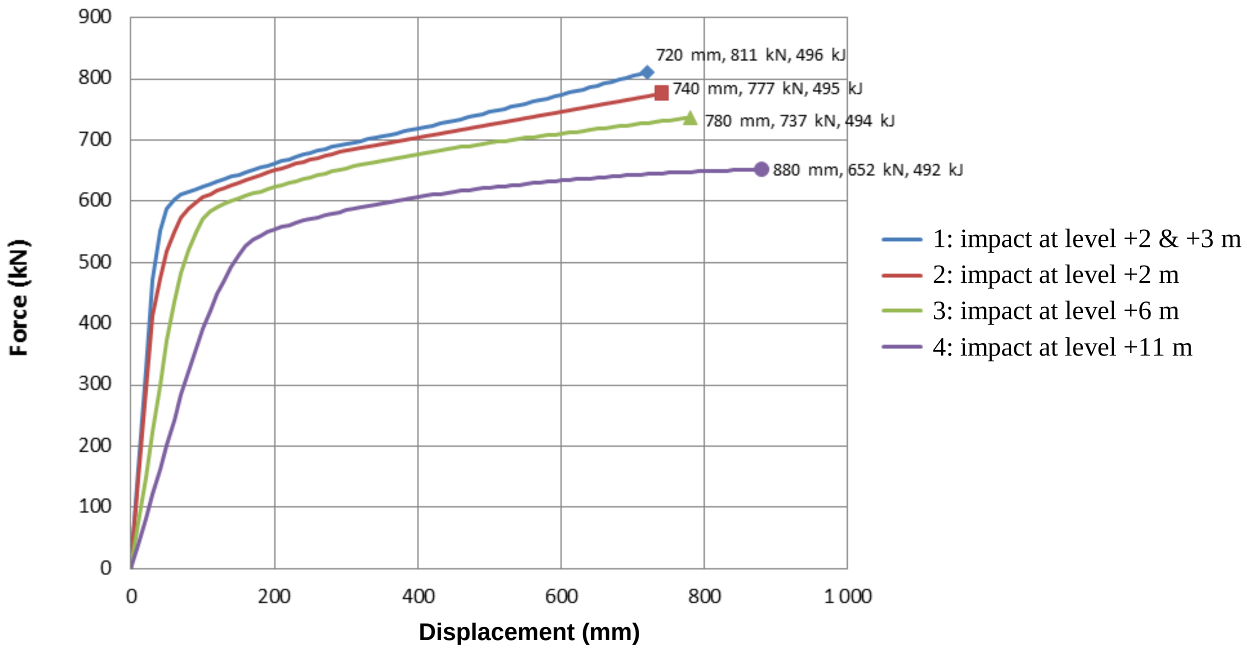


Figure 3. Force-displacement response curves of the structure for the four configurations of impact.

Table 1: Main results of interest for the 4 configurations of impact.

	Max. Global Force (kN)	Max. Displacement (mm)	Absorbed Energy (kJ)	Max. steel strain (%)
1 – Impact at level +2 & +3 m	811	720	496	17
2 – Impact at level +2 m	777	740	495	14
3 – Impact at level +6 m	737	780	494	14
4 – Impact at level +11 m	652	880	492	16

The foundation slab was pre-sized in order to withstand the forces transmitted by the columns. And the stack foundation resistance was also checked under these forces.

DETAIL DESIGN

The detail design calculations were carried out using a more refined shell model of the shield. The impact analysis is computed in fast dynamic domain using RADIOSS explicit dynamic software. This analysis aims to take into account more accurately the following phenomena:

- Dynamic response of the structure under impact;
- Local effects of impact and deformations on the tubular steel profiles: ovalisation, local buckling of walls;
- Local behaviour of embedded columns in the thick slab;
- Combination of drag forces due to water flow and impact effect.

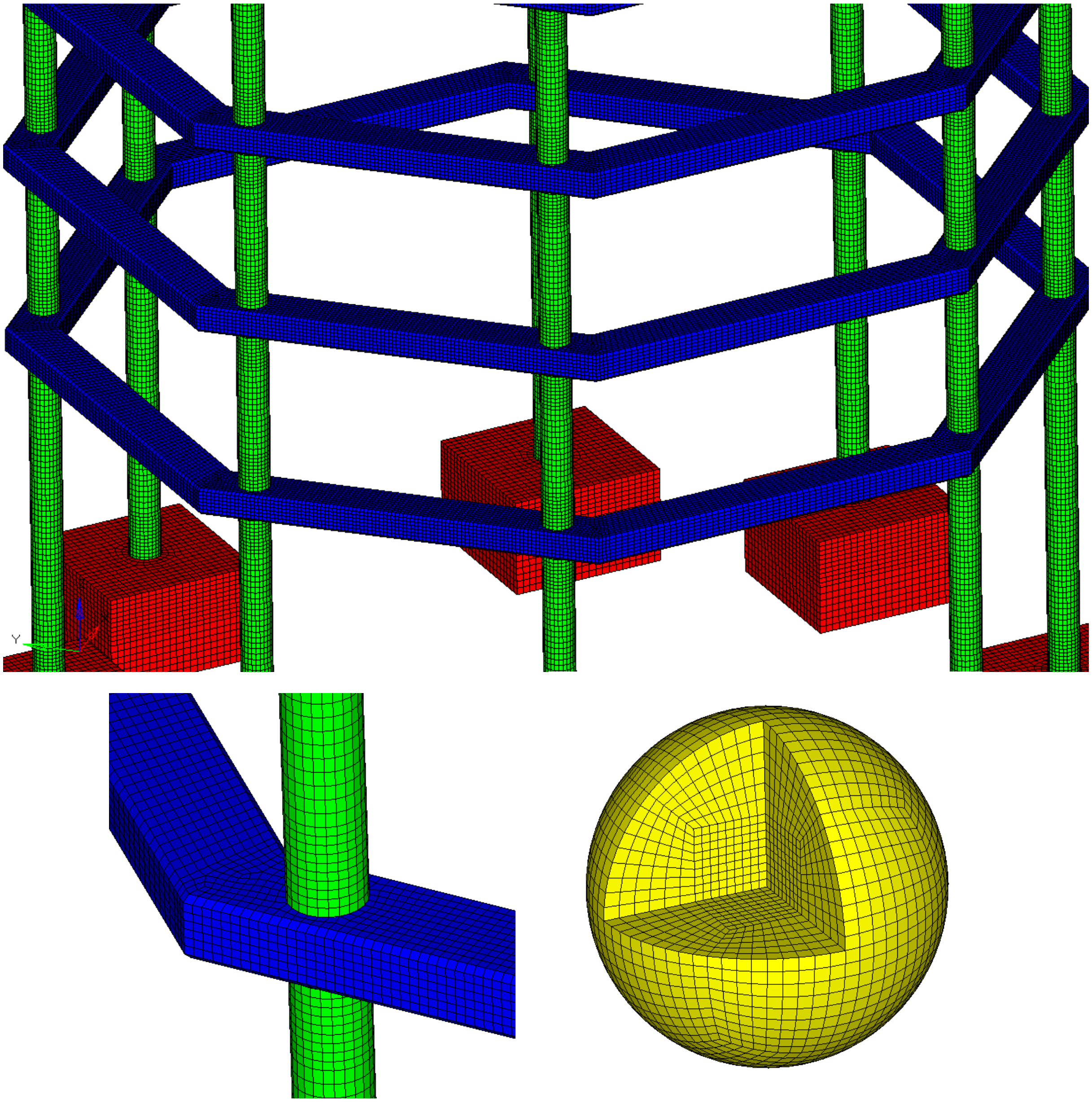
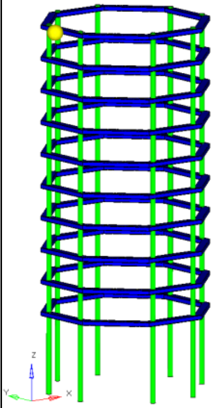
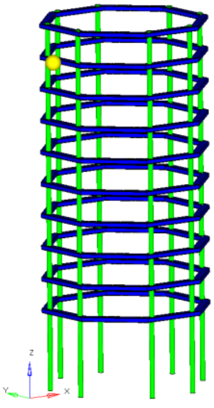
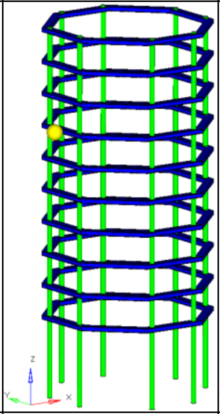
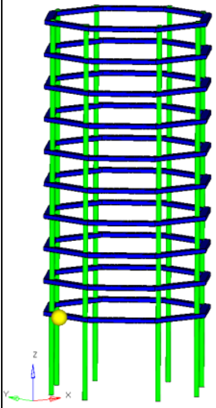
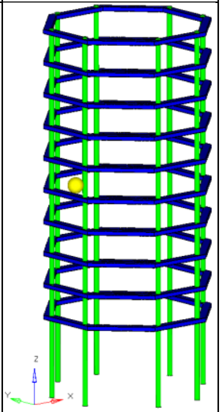


Figure 4. RADIOSS detailed model: General view and details of column-beam joint and impact sphere.

The columns and beams are modelled with 5-layered shell elements, with a mesh size of around 20 mm in the critical areas (near column-beam joints), and 30 mm elsewhere. The concrete slab is partially modelled in the vicinity of the columns' embedment. The interface between steel column and concrete slab is modelled by friction interface with a friction coefficient of 0.4. The steel behaviour law is elasto-plastic and the concrete is elastic. The lateral and bottom faces of concrete blocks are blocked.

The self-weight forces and drag forces are applied on the steel frame. The impact is modelled by a rigid sphere of 20 tons and 50 cm in diameter, impacting the shield with an initial velocity. Table 2 summarises the five studied configurations and associated main results. Deflected shapes for two configurations are shown in Figure 5.

Table 2: List of configurations studied with RADIOSS model and main results.

Configuration	1	2	3	4	5
Water level	+8 m	+7 m	+7 m	+7 m	+7 m
Impact level	+11 m on beam	+10 m on beam	+8 m on beam	+2 m on beam	+6.5 m on col.
Impact and flow speed	3 m/s	7 m/s	7 m/s	7 m/s	7 m/s
Sketch					
Max. Disp. behind impacted element	268 mm	1062 mm	983 mm	743 mm	936 mm
Max. Disp. of 1st level column	90 mm	610 mm	550 mm	600 mm	700 mm
Max. horiz. Force on foundation	575 kN	683 kN	693 kN	769 kN	668 kN

This detailed analysis confirms the performance of the global design. The maximum displacement 1062 mm is less than the exact clear distance between shield and stack (1090 mm). The global results are consistent with those of preliminary analysis. The main differences are the higher displacements and lower global forces, due to the elasto-plastic buckling of column wall, which reduces the frame strength, and is not taken into account in the preliminary beam model.

In addition, several sensitivity studies were carried out in order to validate the model robustness. The tested parameters are the type of elements (under vs fully integrated) and the concrete behaviour law (linear / nonlinear).

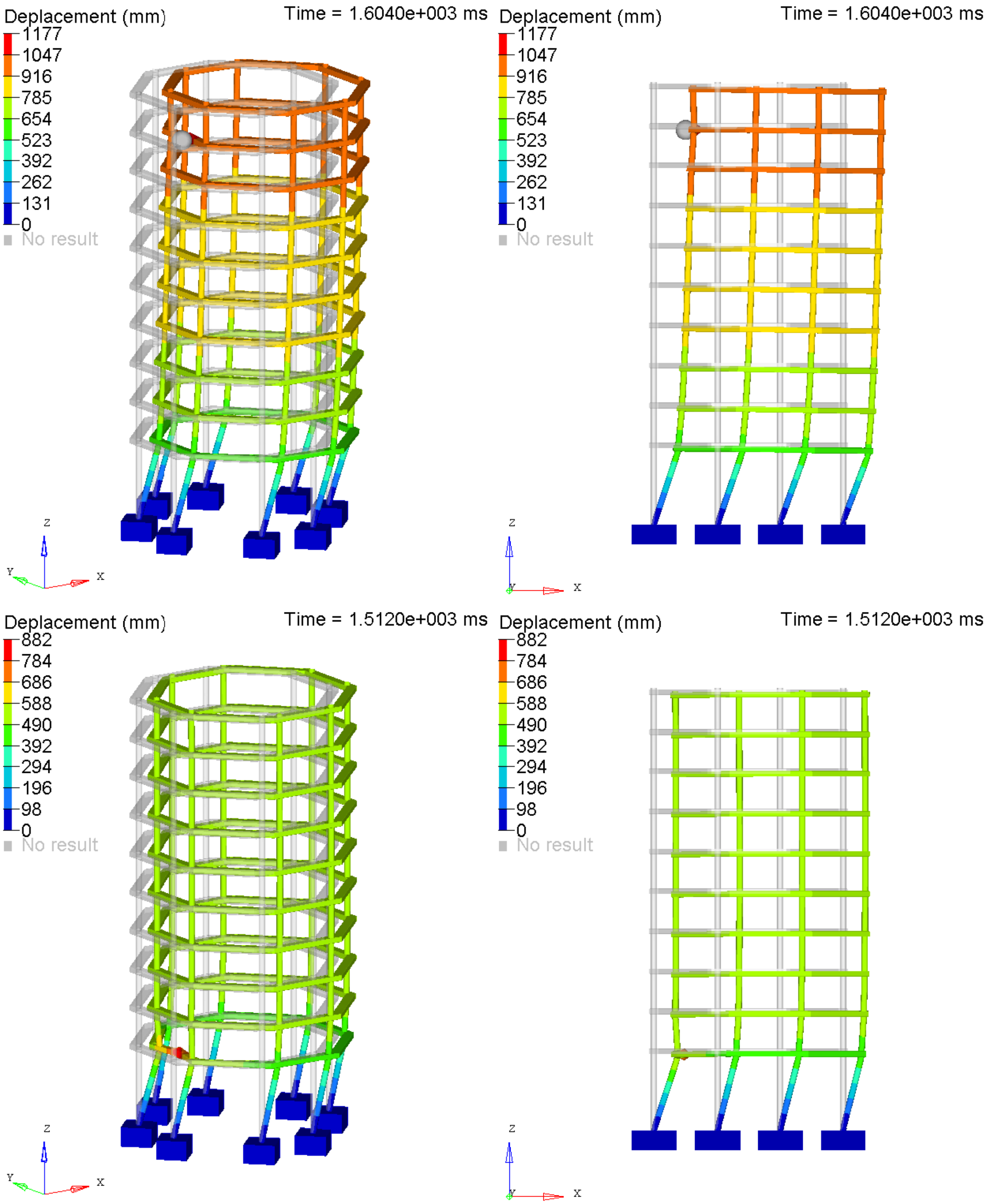


Figure 5. Deformed shapes of RADIOSS model at time of maximum displacement (config. 2 and 4).

The reinforcement of concrete foundation thick slab is designed according to transmitted forces. A robust design is achieved considering the envelop forces resulting from preliminary beam model with static analysis and detailed shell model with dynamic analysis.

The connexions between members are sized according to capacity design principles, in order to avoid any brittle failure (see details in Figure 6):

- Most of the joints between columns and beams and between beam segments are made with full penetration welds;
- However, in order to avoid welds on site, half of the beams are cut at their ¼ length which is a section with low bending, and are joined by bolted plates with a bending strength greater than beam strength;
- The robust anchorage of columns in the foundation is achieved by sealing the column inside the concrete foundation thick slab, with anchor plates. A specific local reinforcement around the columns is designed according to embedding forces.

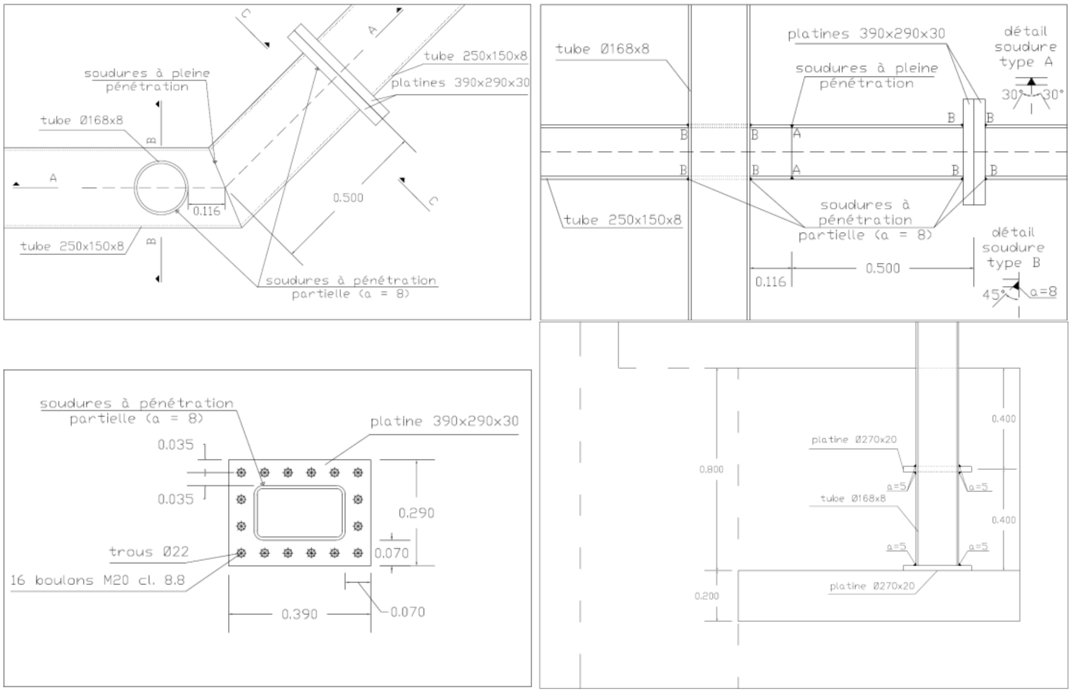


Figure 6. Details of connexions and anchorage.

VALIDATION TESTS

Due to the unusually large expected deformations of the structure, validation tests were carried out on a full-scale prototype of column, in order to check the deformation capacity of the column encased in the reinforced concrete foundation. In addition, tension tests are carried out to characterise the steel behaviour law, and check the strength of welds. All tests are done using samples of columns and beams extracted from the actual manufacturer's supply.

Two pieces of columns are embedded in a concrete slab, with the same detailing provisions than shield design. The first column is empty while the second one is full of mortar, in order to evaluate the ability to increase the column strength using a mortar filling. The columns are loaded at a height of 1 m using a 20 tons jack. A steel frame is designed to balance the jack's force, and this structure is anchored in the column concrete slab. Therefore, the system is globally balanced.

The testing columns represent the bottom half height (1 m) of the first level of the shield steel frame, with a free end at level +1 m. This is equivalent to the first level of frame columns whose height is 2 m with embedded ends at bottom and top. According to the design calculations, the maximum displacement of the first beam at level +2 m is 700 mm. As the tested column is 1 m high, its equivalent displacement is 350 mm. However, the target displacement is increased up to 500 mm which represents an equivalent displacement of 1 m at level +2 m, which is the free distance between stack and shield. The objective is to check that there is no risk of cliff edge effect (i.e. brittle failure for a small increase of displacement).

Two types of predictive models are used to analyse the test results and validate the design numerical analysis: a beam model with Code_Aster similar to the preliminary design model, and a shell model with RADIOSS similar to the detail design model. The shell model has 2 variants corresponding to the empty column and the mortar filled one.

The results of tests, reported in Figure 7, allow to validate the extreme deformation capacity of columns. The empty column supported a displacement of 600 mm without any sign of break (no visible crack or significant loss of strength). In addition, there is a good agreement between the predictive models and the actual behaviour. The two models give a good estimation of yield force. The beam model is well representative up to 300 mm displacement; for higher displacement, the strength is overestimated. On the contrary, the shell model underestimates the strength, so it is a conservative approach.

The mortar filled column has a significantly higher strength than the empty one, and also higher than the predictive models. However, the deformation capacity is significantly reduced, and a brittle failure occurs at 470 mm displacement. Therefore, this option is not recommended, and the shield is built with empty columns.

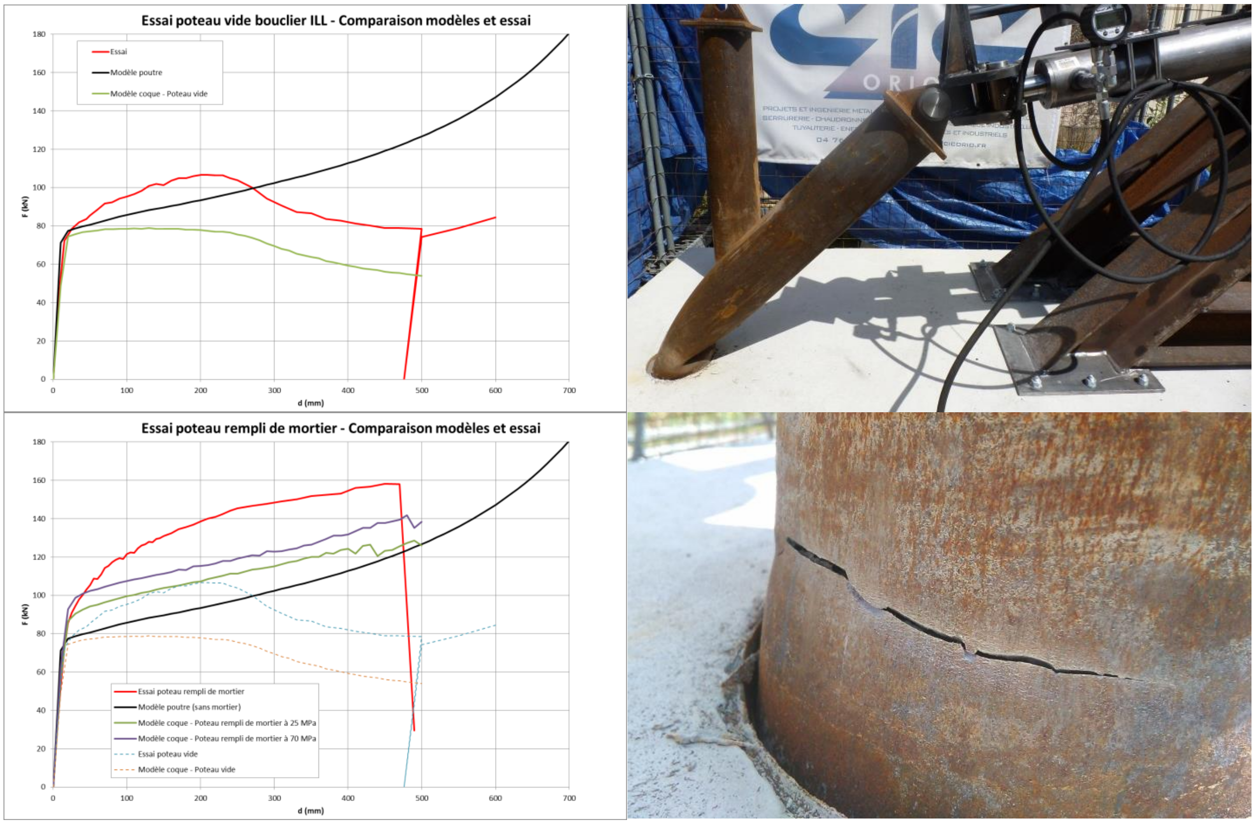


Figure 7. Results of tests: empty column (top) and mortar filled column (bottom).
Experimental data (red), Code_Aster beam model (black) and RADIOSS shell model (green)

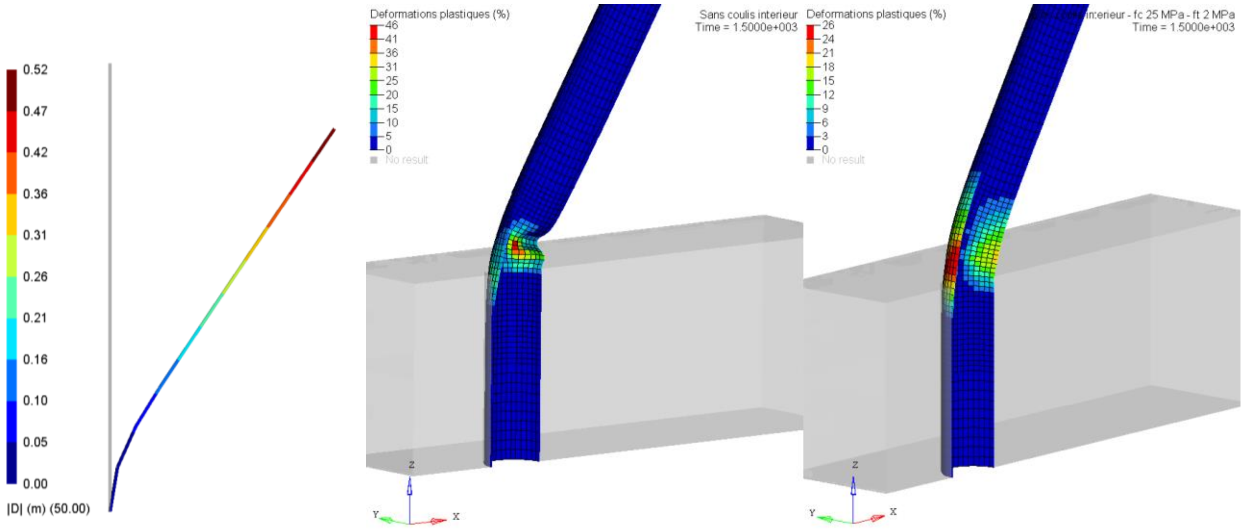


Figure 8. Predictive models: deflected shape (beam model), deflected shape and plastic strain of empty column and filled column (shell models)

In addition, the tension tests on beam and column samples, with and without welded joint, show that the welded joint is not a weak point of the structure. The welded samples have the same strength than the other ones, the break does not occur in the weld, and the ductility is similar.

CONSTRUCTION

In order to limit the operations on site, the shield was shop made in four parts (one quarter octagon each), and then shipped and assembled on site with bolted joints. The assembly was done in two stages. In a first stage, the four parts were bolted two by two in a horizontal position, so forming two half parts. In a second stage, each half part were lifted by crane and set in place around the stack. Then the two half parts were bolted. After that, the reinforcement of foundation was set up around the columns, including reinforcement bars sealed in the stack foundation, and the concrete slab was poured. Figure 9 presents an overview of different construction stages.

Figure 9. Construction of stack shield.