Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division V

BOLTED CONNECTIONS UNDER DYNAMIC LOADING

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ABSTRACT

The Committee on the Safety of Nuclear Installations (CSNI) under OECD/NEA organized the activity "Improving Robustness assessment of structures Impacted by missileS", called IRIS. This activity was divided into three phases. The first two phases were focused on the behaviour of concrete slabs directly affected by impact loading. The third phase was focused on the study of post-impact vibrations. During this activity, a scale model of real concrete structure with 2 installed equipment was tested. There were two different types of connections between the concrete structure and the installed equipment: bolted and welded. The test results showed a significant difference in the responses of the differently anchored equipment models. The welded connection transmits wider spectrum of vibrations including high frequencies, while the bolted connection showed a large damping of higher frequencies. At the end of the 3rd phase, a comparison between numerical models and measured response of the tested structure was presented. Most of the numerical studies were focused on the simulation of concrete structure and detail simulation of equipment connections was not the key point of these studies. Only EDF presented a simplified analytical model of a bolted connection incorporating the gap around the bolts into the connection model (see Hervé (2022)).

The aim of this paper is to precisely simulate the local behaviour of welded and bolted connections of equipment to the concrete structure. Connections have been modelled more precisely, with all gaps, friction between surfaces and bolt prestressing. The concrete structure was simplified or omitted. Therefore, a direct simulation of the impact of missile on the concrete structure was not possible. To achieve the most accurate results, measured vibrations of the concrete structure were used as boundary conditions.

The goal of the simulations was to find material characteristics and contact type and settings to have similar results to those measured in tests. The primary focus was on displacements, then moved to accelerations and frequencies.

STRUCTURE

The mock-up structure was made of reinforced concrete. Material characteristics are listed in Table 1.

Table 1: Material characteristics

	Characteristic	Target value
Concrete	ρ [kg/m^3]	2500
	ν [-]	0.2
	Compressive strength	C40/50
Rebars	ρ [kg/m^3]	7850
	f_{yk} [MPa]	500
	E [MPa]	200 000

The structure is 2,5 m wide and is composed form the following basic elements: impacted wall, rear wall, lower slab, upper slab and cantilever. Shape, dimensions, and supports of the structure are visible in Figure 1.

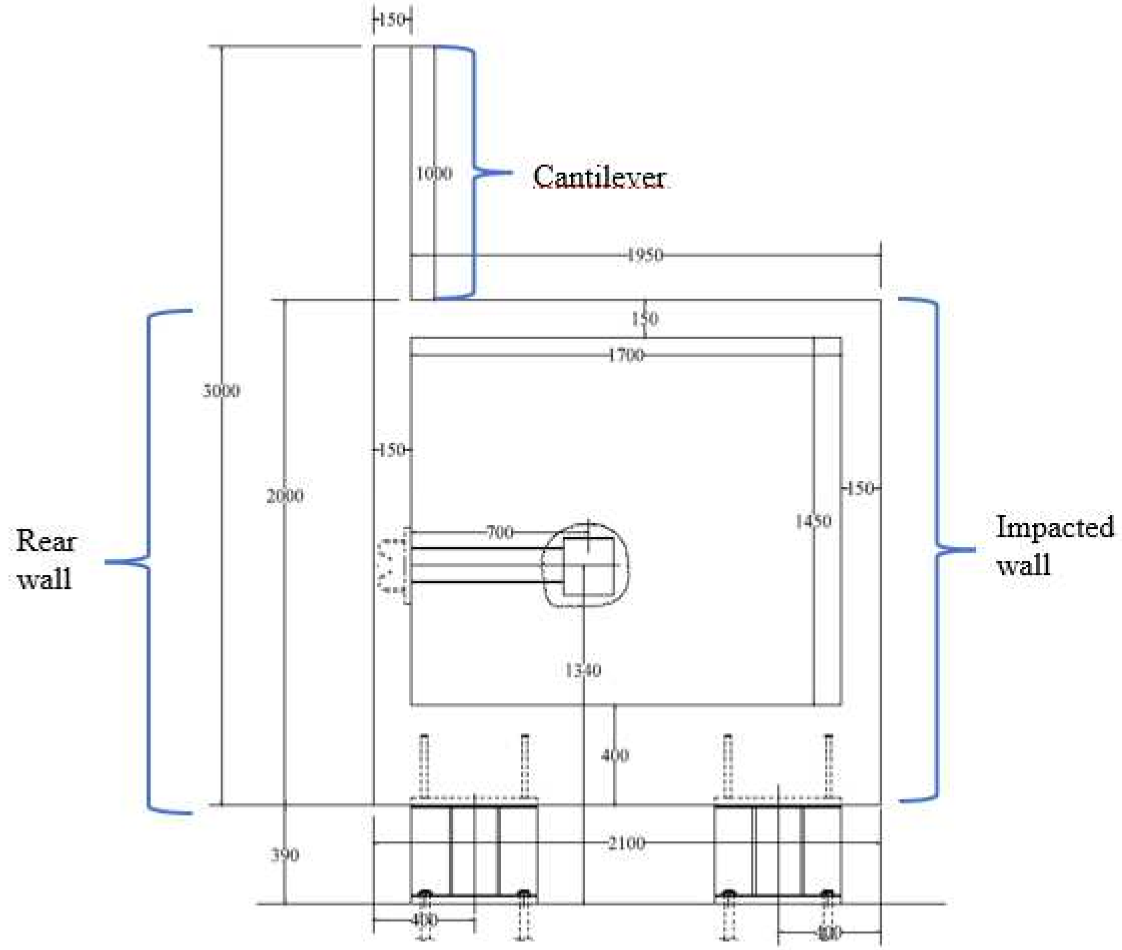

Figure 1. Side view of the structure

Equipment is represented by I beam with a weight at its end. I beam is connected to a metal plate, which is embedded into the concrete wall. Two types of connections are used: bolted and welded. Bolted connection was made of 8 bolts.
Nineteen displacement transducers and nineteen accelerometers were placed on the structure. Positioning of transducers and accelerometers are shown in Figure 2. The measured directions are:

Z – Impact direction:	D01, D02, D03, D1, D3, D4H, D6H, D7, D8HZ, D9b, D9w, A1H, A3H, A4, A6, A7, A8H, A9bH, A9wH, A10bH, A10wH
Y – Vertical direction:	D2, D4V, D5, D6V, D8V, D10´, A1V, A2, A3V, A5, A8V, A9bV, A9wV, A10V, A10V´.
X – Transverse direction:	D8HX

For this paper, only measurements from transducers D7, D3, D6H, D6V are used as boundary conditions, and measurements at points D10, D10´, A10V, A10V´ were used for the comparison with the results of the numerical model.

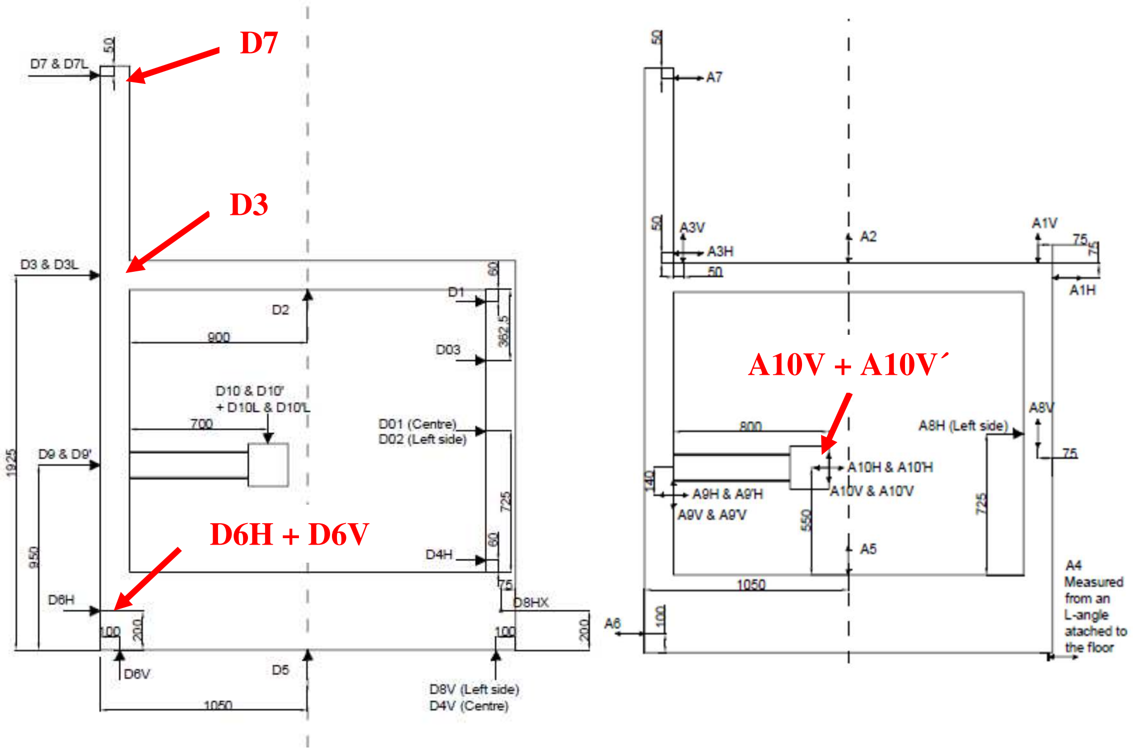

Figure 2. Displacement and acceleration sensors

NUMERICAL MODEL

In this paper we focused on the precise modelling of the connection between the concrete structure and the installed equipment. Other concrete structures need to be simplified or omitted – otherwise the computing time would be time-consuming. Only the rear wall and cantilever were modelled. Upper and lower slab ware replaced by supports: the upper slab by a support with free rotations in all directions, the lower slab by a support with all movements and rotations fixed. The front wall was completely omitted with no further modifications on the model.

The cantilever was modelled as a shell with a maximum element size of 30 mm. The rear wall was divided into two sections. The upper part of the rear wall was also modelled as a shell with a maximum element size of 30 mm. The rest of the rear wall was modelled by solid elements, with decreasing size towards to the connections between the wall and the equipment. The size of the elements at the location of the connections is 5 mm max. The concrete structure was fully modelled with linear materials.

In the model with a welded connection, all contacts were set as bonded. This means that any force, displacement, or move is fully transferred in both directions of the contacts.

In the model with bolted connection, several types of contact were used. Bonded contact was used between concrete wall and metal plate, and between bolts and nuts. All other contacts were set as frictional with a friction coefficient 0.2. The initial bolt prestressing was not specified in the test specifications, therefore a set of different levels of pretension was calculated. Non-linear behaviour was expecting only in bolts and in the vicinity of the bolts. For these locations, non-linear material was used: bilinear dependence with a yield strength of 250MPa.

Full numerical model is shown on Figure 3.

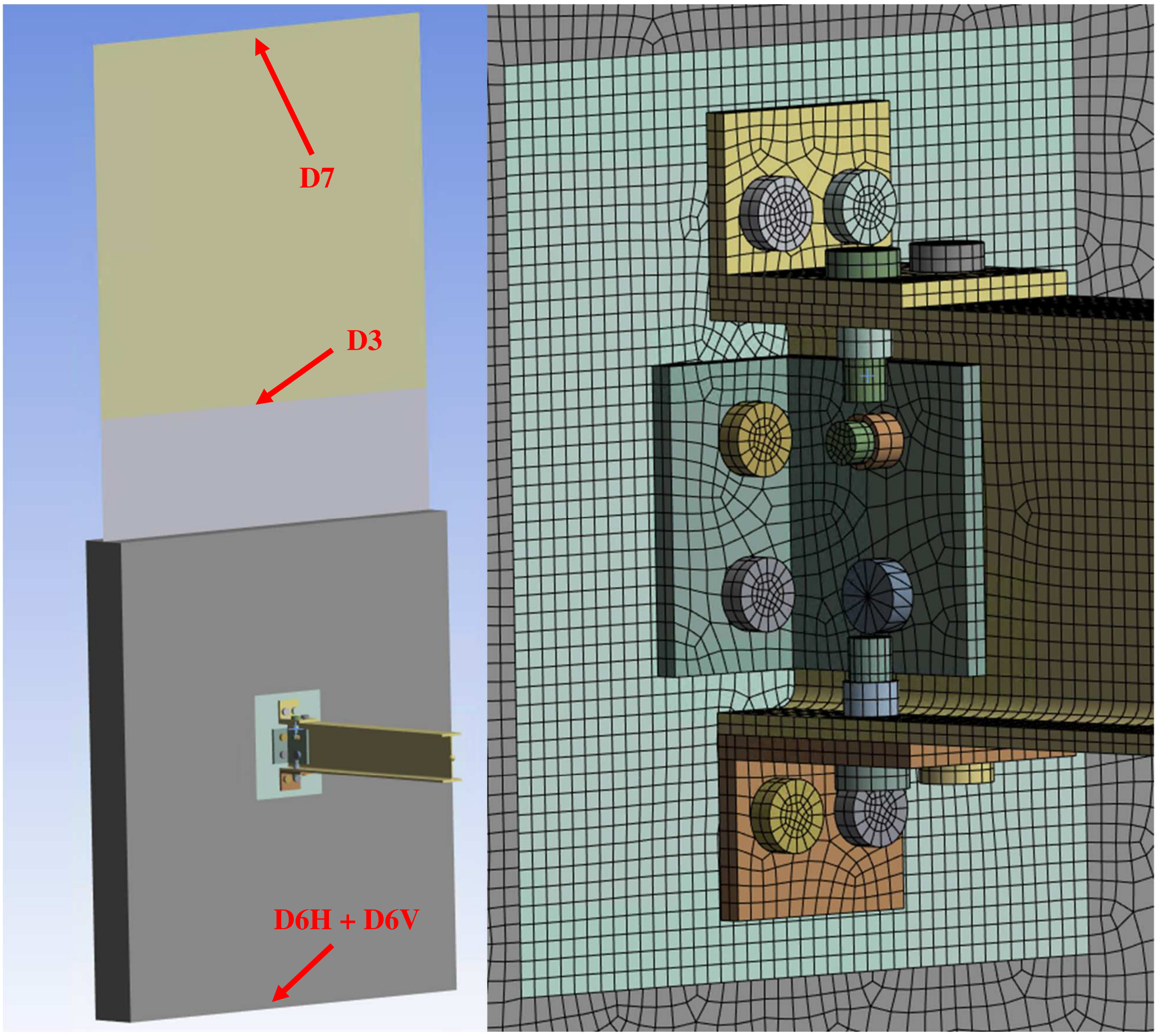

Figure 3. Numerical model and detail of bolted connection and position of loads

SET UP

The same measured displacements were applicated to both connection models. This approach should give nearly identical vibration at the locations of connections as were the vibrations during impact tests. Measurements from D6H and D6V were applicated on the bottom support, measurements from D3 to the upper support and D7 to the top of the cantilever. The applicated displacements are shown in Figure 4. The locations of the applicated displacement can be seen in Figure 3.

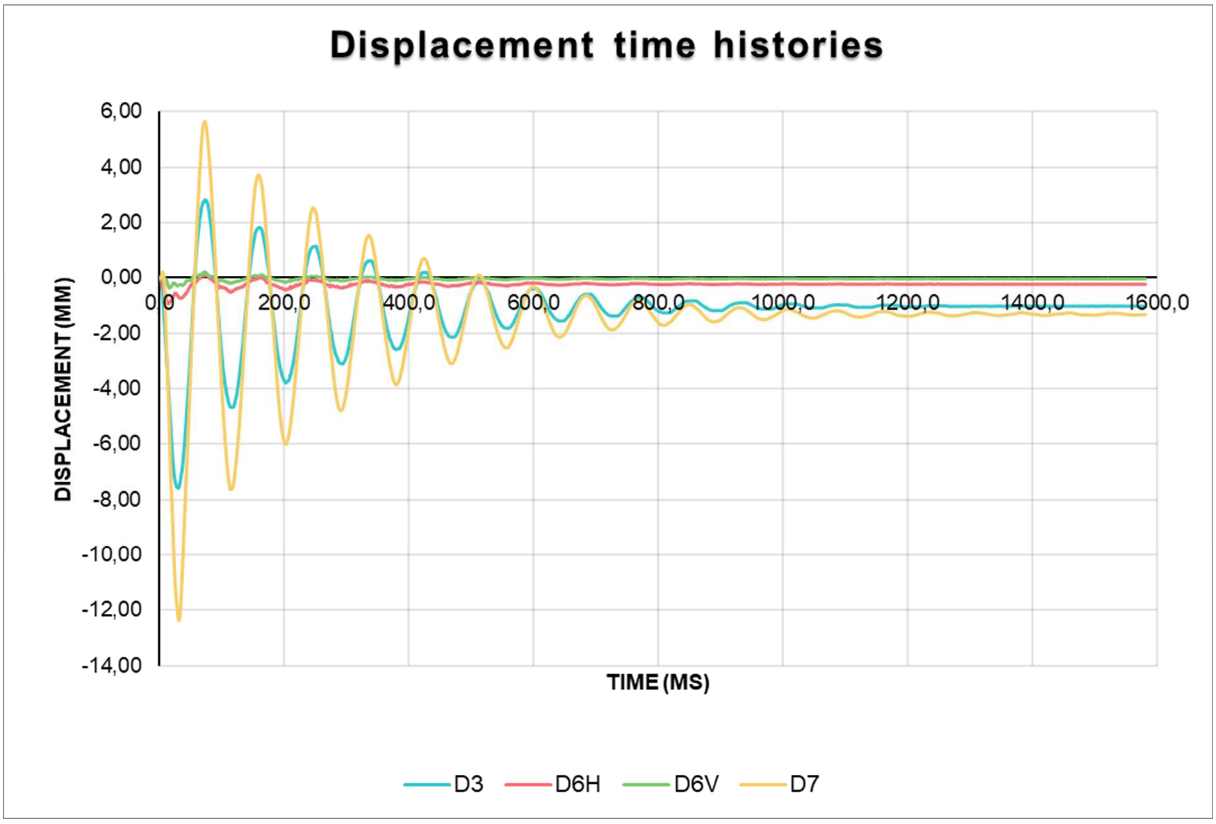

Figure 4. Applicated displacements

Welded Model

On the welded model, our goal was to find accurate setting of the concrete material characteristics to simulate almost the same behaviour of the model as of the real structure. Many simulations were calculated. Between simulations, we changed material characteristics of the concrete to achieve more accurate results. The changed characteristics were Young´s modulus, damping factors alpha and beta.

Bolted Model

We started by applying of final materials characteristic of concrete from welded simulations. This setting should give us the most accurate behaviour of concrete structure. With these settings, our focus in the next step was to set the right amount of pretension of bolts to simulate real behaviour of bolted connection of equipment.

RESULTS

Welded Model

The results from the welded model were compared with measurements from the tested structure. Three types of results were compared – displacements, accelerations, and frequencies. We managed to achieve almost the same displacements as it was measured, but we were slightly off in acceleration and frequency. One of the reasons could be the size of the time steps, we had approximately 10 times larger time step then used in measurement. Also, we did not apply the non-linear characteristic of the concrete. Any cracks or other damage in the concrete wall may lead to different frequencies, but this effect is not applied in our model. For the clarity of this paper, only the deformations and frequency results are shown in Figures 5 and 6.

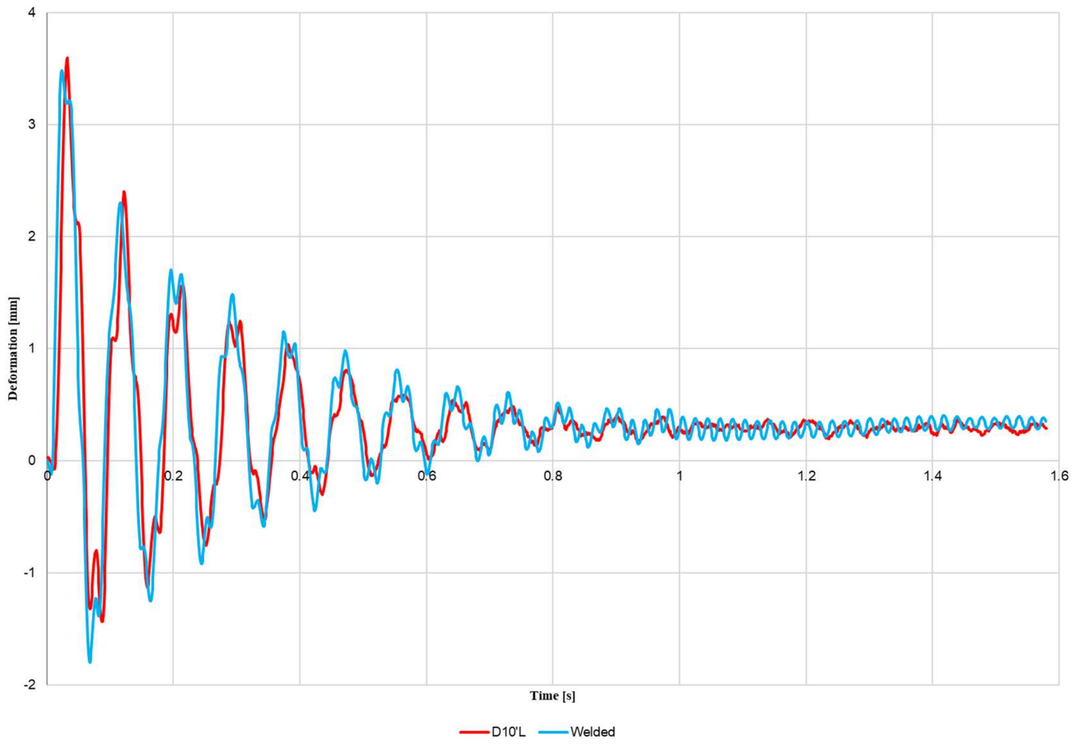

Figure 5. Compared deformations

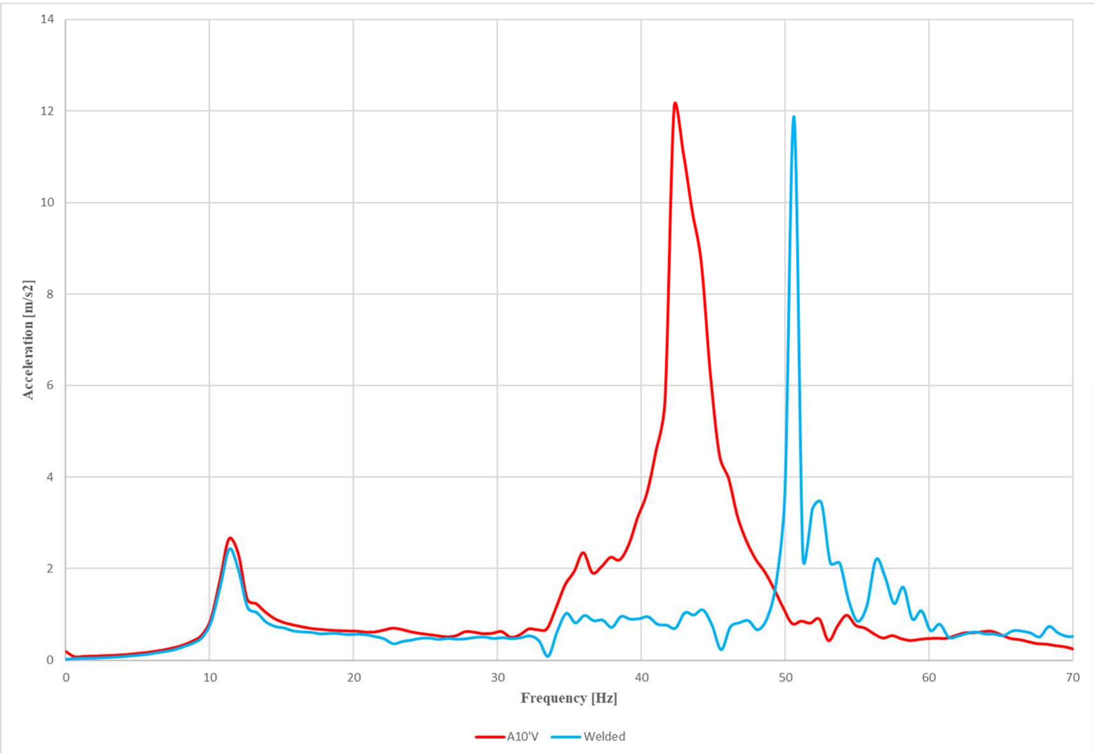

Figure 6. Compared frequencies

Bolted Model

We performed numerous calculations of the bolted model. The differences between the calculations were mainly the level of pretension of the bolts. The results using 3 different pretension levels are shown in Figures 7 and 8.

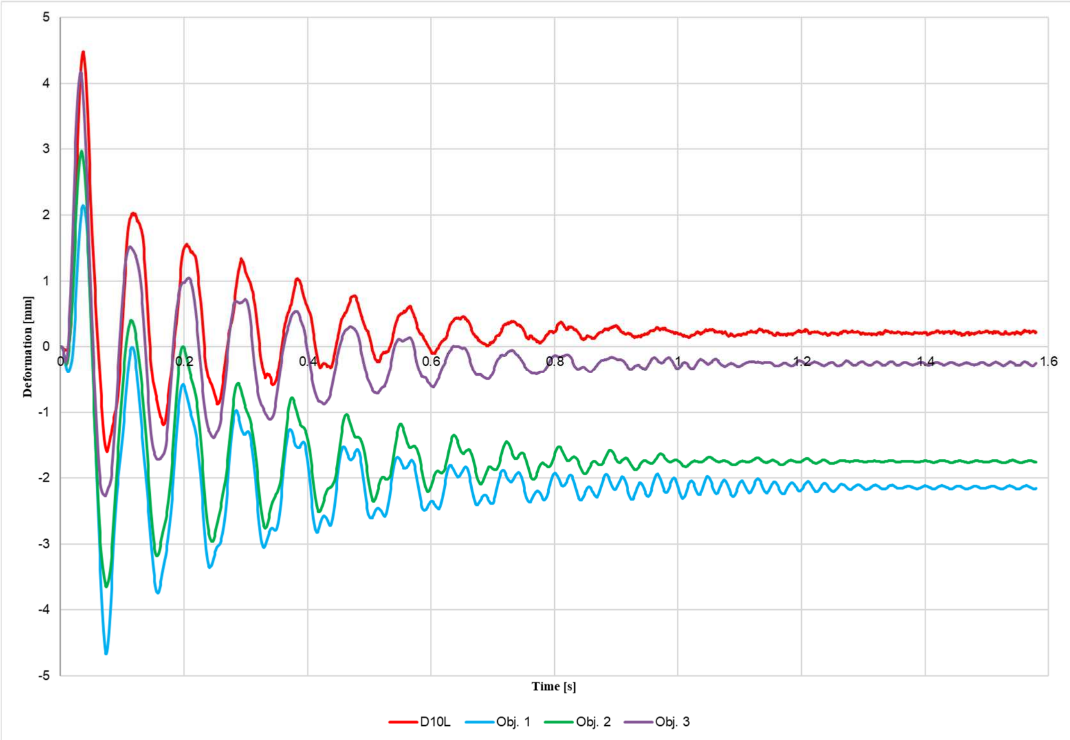

Figure 7. Compared deformation

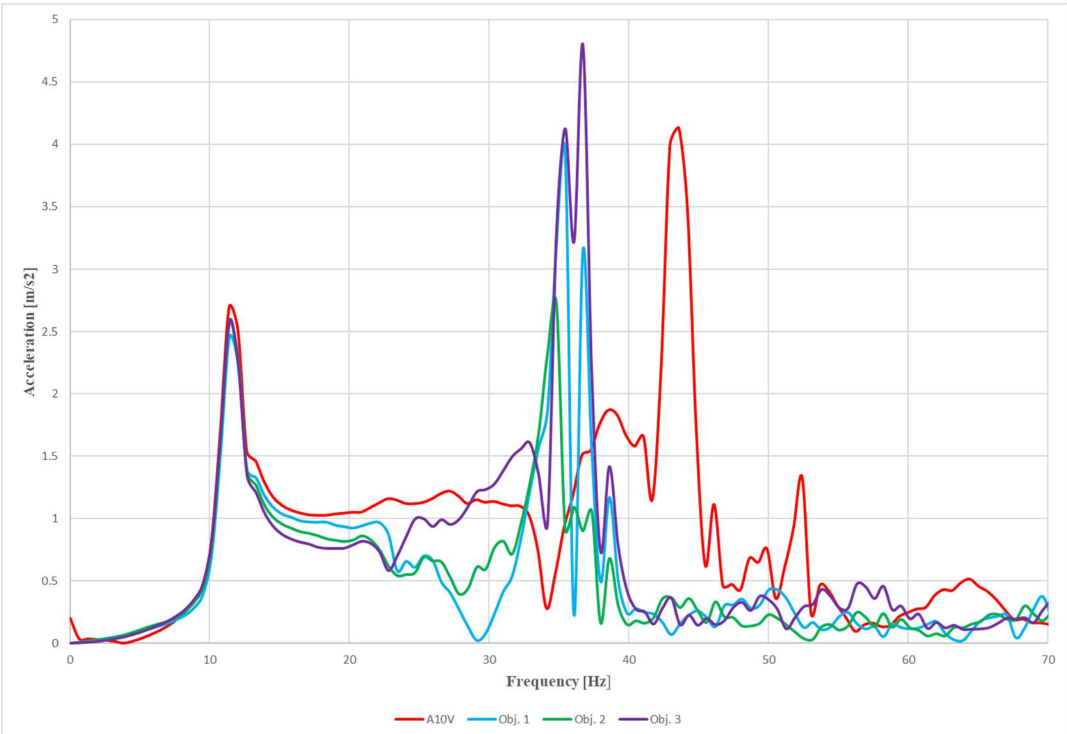

Figure 8. Compared frequencies

Final level of pretension forces, corresponding adjustment, stress and utilization are shown in Table 2.

Table 2: Final pretension forces

	Obj. 1	Obj. 2	Obj. 3
Adjustment	0.03 mm	0.04 mm	0.08 mm
Force	≈ 15.39 kN	≈ 20.01 kN	≈ 27.71 kN
Stress	≈ 100 MPa	≈ 130 MPa	≈ 220 MPa
Utilization	≈ 40 %	≈ 52 %	≈ 88 %

CONCLUSION

Welded Model

As was presented, our goal with the welded model was to find the correct material characteristics of the concrete. The final material characteristics can be seen at Table 3.

Table 3: Final material characteristic of concrete

Material characteristic	Value
Young´s Modulus	26 000 MPa
Poisson´s Ratio	0.18
Damping factor α	3.3
Damping factor β	0.000119

With these characteristics, we achieved a good match in deformations. At the frequencies, there can be seen 2 dominant peaks. The first one, around 12 Hz, shows good agreement with the real structure and corresponds to the global shape of vibration of the concrete structure. The second peak is shifted around 10 Hz to higher frequencies. This can happen from two main reasons – cracks in the concrete and the type of contact between the metal plate and the I beam. For this contact, type bonded was used, which transfer all forces and movements without any deformations or energy losses. It would be more accurate to simulate contact with a special element for welding. This option requires a detailed specification of used welds, but there are any information about the type and size of used welds in the structure specifications. With these limitations, simulation of a bonded contact appears to be the best option available.

Bolted Model

On the Figure 7 there could be seen the effect of the prestressing level of bolts. A higher prestressing force approached a better final deformation. Since we did not know the exact pretension of the bolts applied in case of the real structure, from these results we could tell that the pretension was high, almost at the full potential of the material.

The shape of time history of deformation corresponds to the shape of real structure during the time of impact. For post-impact vibration, the numerical model shows slightly more vibration than was measured on the real structure.

Similar to the welded model, there are two dominant peaks in the frequencies. The first peak, corresponding to the global shape of vibration of the concrete structure, shows an almost perfect match. The second peak is shifted around 10 Hz to lower frequencies. The effect of prestressing level is not clearly visible, the amplitude varies with no dependence on prestressing force. Even the shift in frequency is almost the same for each prestressing force. To find the effect of prestressing on the second frequency peak, there would be required to make a sensitivity analysis with more levels of prestressing forces, for example from 5% to 100% of the steel yield strength. The shift of the second peak could also be caused by other variable parameters, e.g. friction coefficient. We used a uniform coefficient of 0.2 for all contacts, but it would be more accurate to conduct a study and set a different coefficient for each type of contact.

REFERENCES

Hervé, G. (2022). “Gap Effect and Modeling”, *Proc., Workshop on the phase B of IRIS Phase 3 program*, EDF Lab SACLAY.