Standardized Determination of Dynamic Loads Transmitted to Structures – Exploration of Alternative Approaches

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1 Introduction

In civil engineering, structural design has traditionally been based on static load assumptions. However, the increasing use of numerical simulation in adjacent fields—such as vehicle restraint systems (VRS) on bridges or tornado protection structures—raises new challenges. These domains generate highly dynamic loads, which are often reduced to a peak value and then directly applied as static loads to civil engineering components. While simple, this conservative practice tends to produce significant overdesigns, conflicting with today's goals of structural optimization and energy/material efficiency.

This paper explores strategies to bridge the gap between dynamic simulations and static design in civil engineering. It draws on two practical cases: (1) the development of the FD P98-435 methodology, a simulation-based approach to quantify loads transmitted by bridge-mounted safety barriers, and (2) EDF's use of LS-DYNA to assess the anchorage performance of protective structures.

Beyond full dynamic modeling—accurate but resource-intensive—alternative strategies are considered: an equivalent static force approach, energy-based impulse methods, and validation-based extrapolation techniques. These aim to retain the richness of dynamic simulations while enabling realistic and efficient static design in engineering practice.

2 Vehicle Restraint Systems – Development of the FD P98-435

2.1 Introduction

The forces transmitted to bridges by road restraint systems must be considered during the design or rehabilitation phase. However, current standards (NF EN 1991-2) provide only generic load classes that are not easily applicable to real cases, and no harmonized method exists for determining these forces. Existing approaches vary widely, leading to significant differences in the estimated force levels. In response, dynamic numerical simulation has been adopted as the reference method for VRS correlation. With increasing traffic density and heavier vehicles, accurately assessing these forces has become crucial—especially for existing or specific structures. The French Normalization Committee dealing about Vehicle Restraint System (VRS) has developed a harmonized method for evaluating impact forces.

This method is described on a road restrain system below.

2.2 Model presentation and correlation

XENON from ROUSSEAU is a L2 Vehicle Restraint System according to EN 1317 definition.

It means that this device, designed for bridges, can restrain a 13t bus running at 70 km/h under at 20° impact angle (TB51), a 1500 kg vehicle running at 110 km/h at 20° (TB32) and as well as 900kg light car running at 100 km/h under the same 20° impact angle (TB11).
The correlation has been made numerically with LS-DYNA for the three configurations mentioned. Correlations follow the protocol mentioned in EN 16303 validation a numerical simulation in vehicle restraint systems.

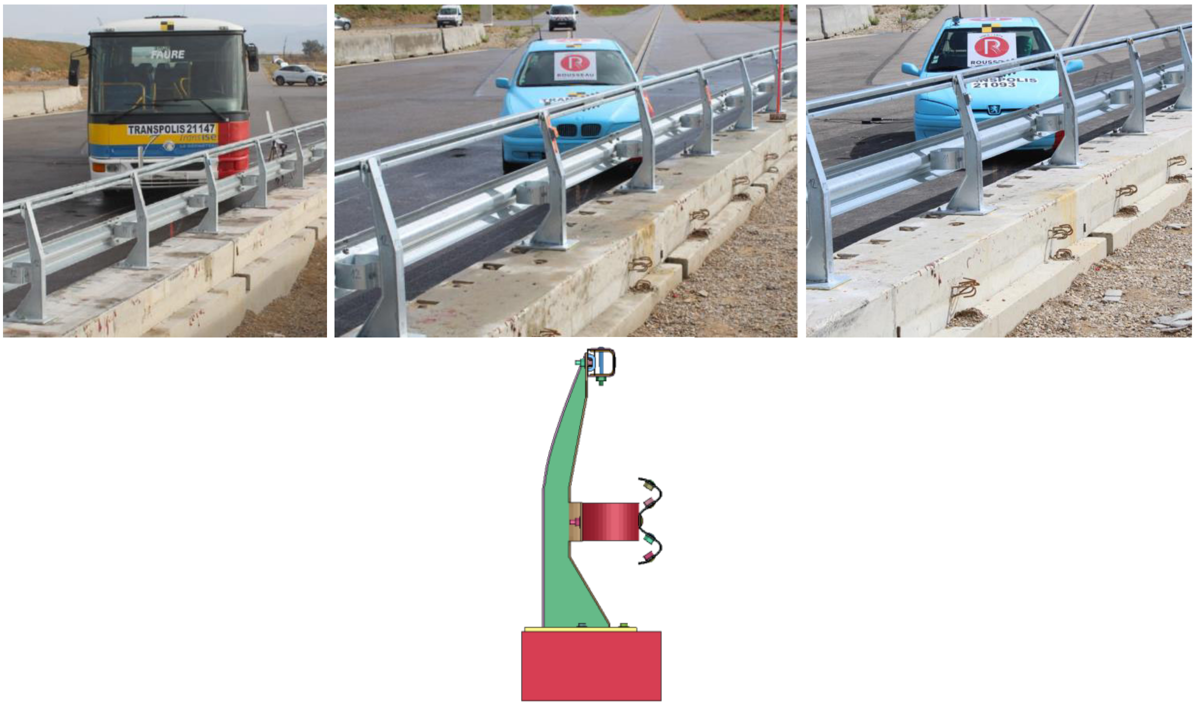


Fig.1: XENON L2 (TB51 – TB32 – TB11 – Numerical model)

The development of this device was made during 2018-2020 to obtain a CE marked product to replace the OVALIE device, made by ROUSSEAU. The OVALIE barrier was made to replace the French Generic device (BN4) for new bridges construction.
The device anchorage on the bridge structure has been kept as very specific and common to the French bridges.
The complexity of the structure optimization is due to the duality of the crash configurations. On one hand, the structure must be stiff to redirect a heavy vehicle and, on the other hand, must be not too aggressive with for light vehicle passenger.
For this purpose, the OVALIE device has been imagined with two main stages: the lower one with an energy absorber designed for light vehicles and an upper one to restrain heavy vehicles.
The optimization process for this barrier has been made coupling LS-DYNA / MESHWORKS / LS-OPT [4].

Fig.2: Comparison of structures after impact (Experimental and numerical)

Moreover, a dynamic test with an impactor has been made to improve the correlation between the experimental and the numerical parts.

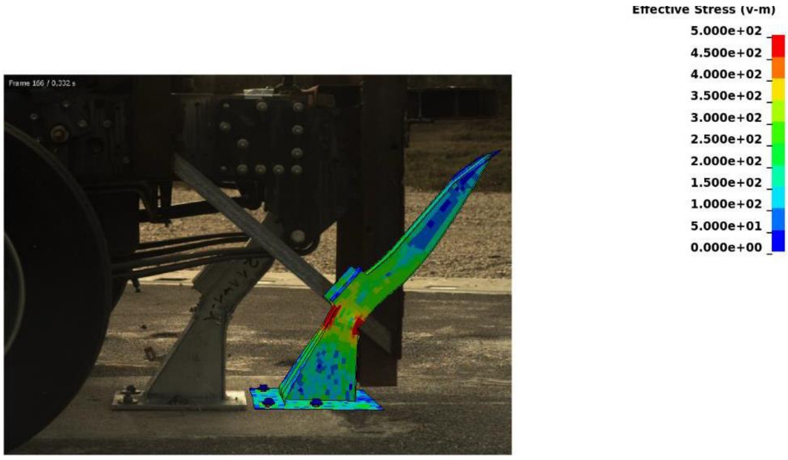


Fig.3: Dynamic impact and validation

2.3 Harmonized method for evaluation impact forces

The dynamic numerical simulation method was chosen because numerical simulation tools have become standard in certification processes based on the European standard EN 16303, and all manufacturers use numerical models to develop their products.
In this way, to have a harmonized method, the choice has been made to use the correlated numerical simulation, on the maximum impact test of the containment level defined in NF EN 1317-2:2010 to output extra values (for example a TB32 for a N2 containment level).

A cross-section is created at the base of the support to output the forces and momentum passing through this section. A maximum of supports are instrumented, as shown.

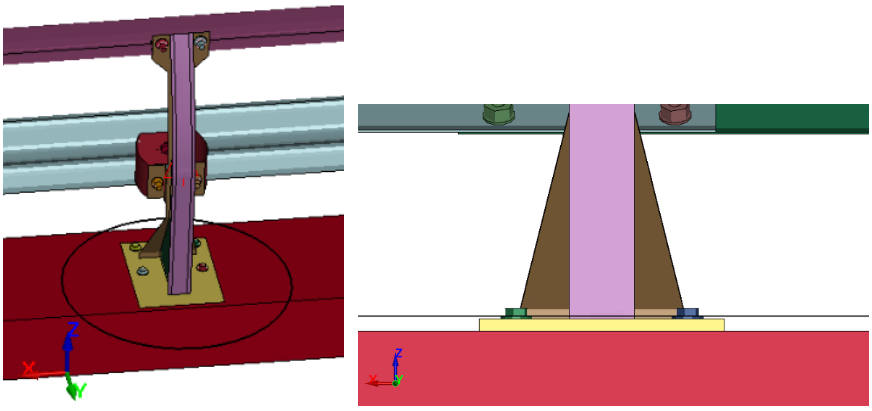


Fig.4: Cross section created at the base of the support

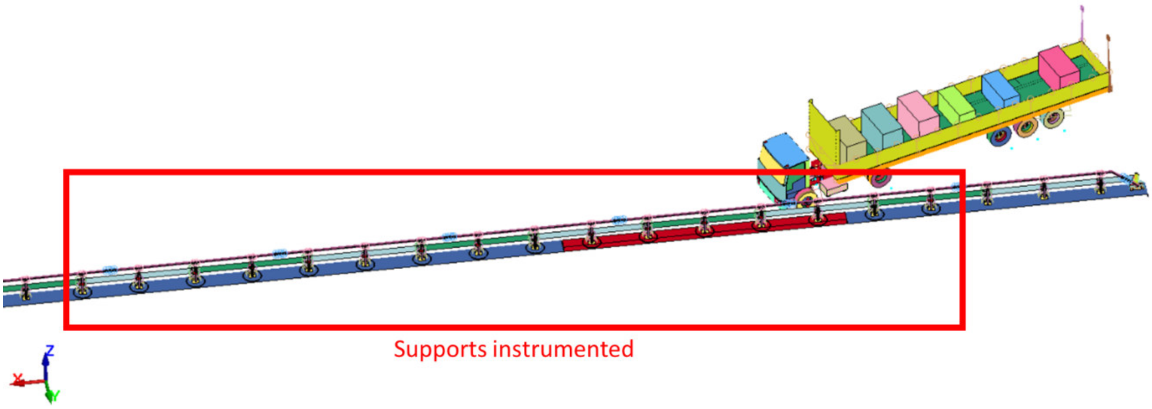


Fig.5: Cross section created at the base of the support

For optimal results, the section plane should pass through the middle of the finite elements, distributing them equally on both sides. The force and moment pairs are measured, and all output data must be filtered using a CFC 60 filter.

2.4 Results with different load cases

In Europe, the EN1317 ([1]; [2]) is the standard which defines how experimental tests must be performed to assess the road safety structure before use.
First, the restraint level is defined by the maximum restraint capability of the structure. Therefore, different tests are specified with different vehicles as described below:

Test	Impact speed (km/h)	Impact Angle (°)	Total mass (kg)	Type of vehicle
TB 11	100	20	900	Tourism vehicle
TB 21	80	8	1 300	Tourism vehicle
TB 22	80	15	1 300	Tourism vehicle
TB 31	80	20	1 500	Tourism vehicle
TB 32	110	20	1 500	Tourism vehicle
TB 41	70	8	10 000	Non articulated truck
TB 42	70	15	10 000	Non articulated truck
TB 51	70	20	13 000	Bus
TB 61	80	20	16 000	Non articulated truck
TB 71	65	20	30 000	Non articulated truck
TB 81	65	20	38 000	Articulated truck

Table 1: Description of the vehicle test shock

The XENON road restrain system has been validated according to EN 1317 to L2 containment level which corresponds to TB 51, TB 32 and TB 11.
Numerical simulations have been made for heavier containment level to measure the force transferring to the bridge.

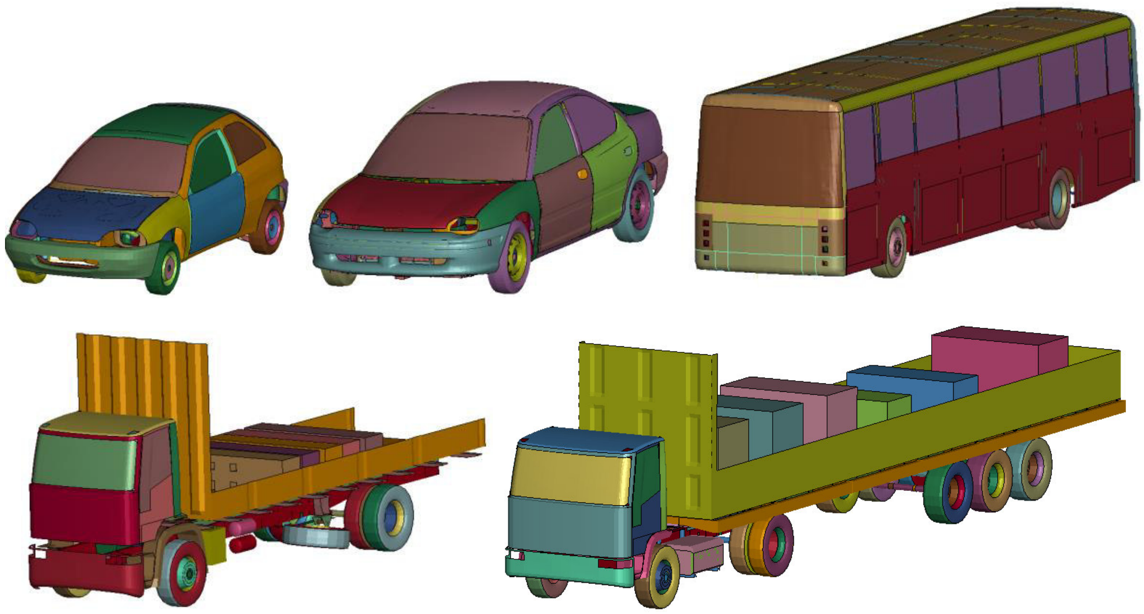
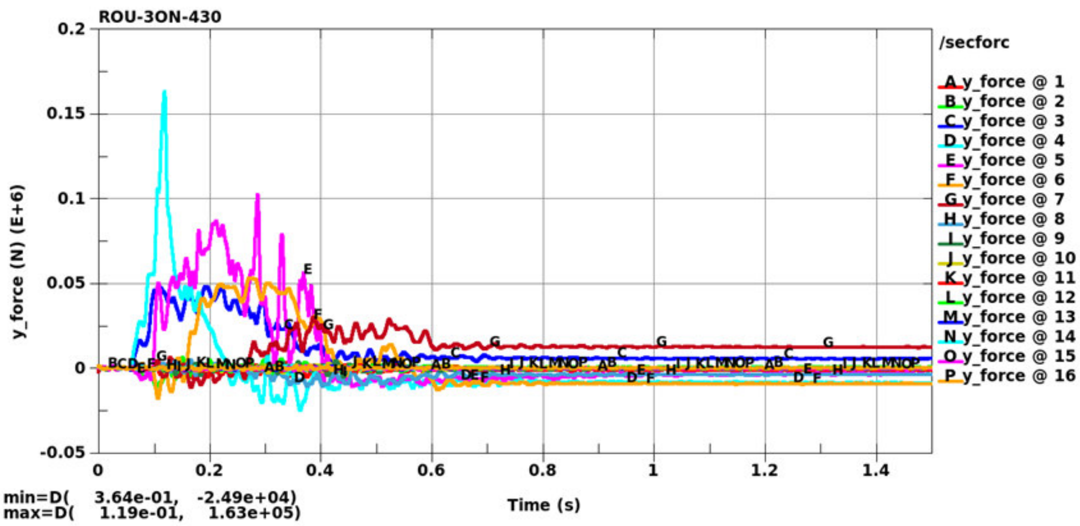


Fig.6: Vehicle for crash testing according to EN 1317 (TB11 – TB 32 – TB 51 – TB 61 – TB81)

Two pairs of force and moment values are studied:

- FY_max (outward direction) with total concomitant MX (around the longitudinal axis of the structure); Total concomitant MX = measured concomitant MX + (FY_max × h)
- Total MX_max (tending to stress the upper fiber) with concomitant FY; Total MX_max = measured MX_max + (concomitant FY × h)

"X" represents the longitudinal axis of the restraint system, and "Y" the transverse axis.
Concomitance is recorded at the same location and at the same time.



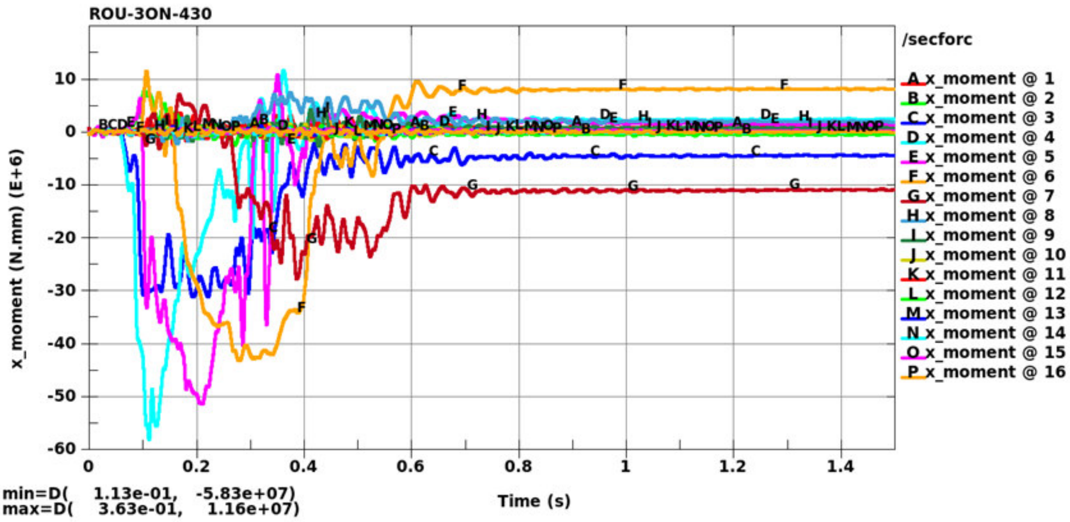


Fig.7: Forces and moments for each support (TB 51 impact)

Forces and moments are filtered to remove the noise in the results. Only the maximum peak force and moment are extracted.

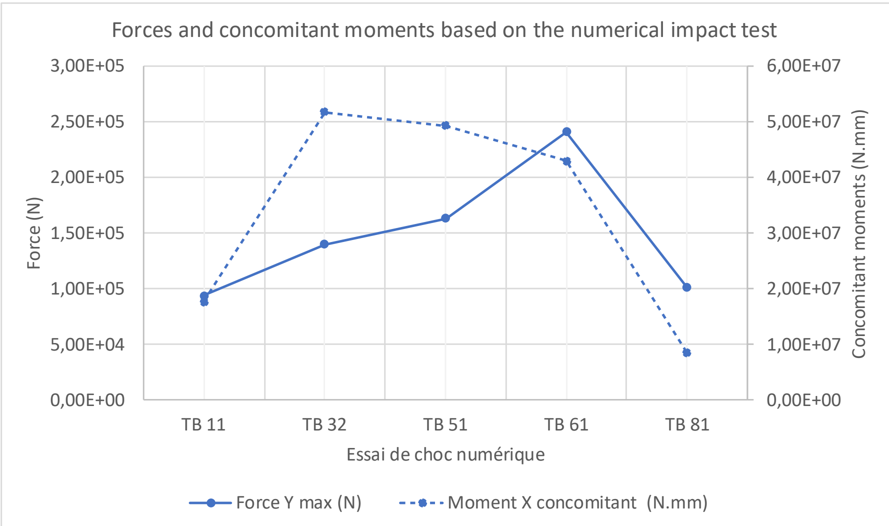


Fig.8: Forces and concomitant moments based on the numerical impact test

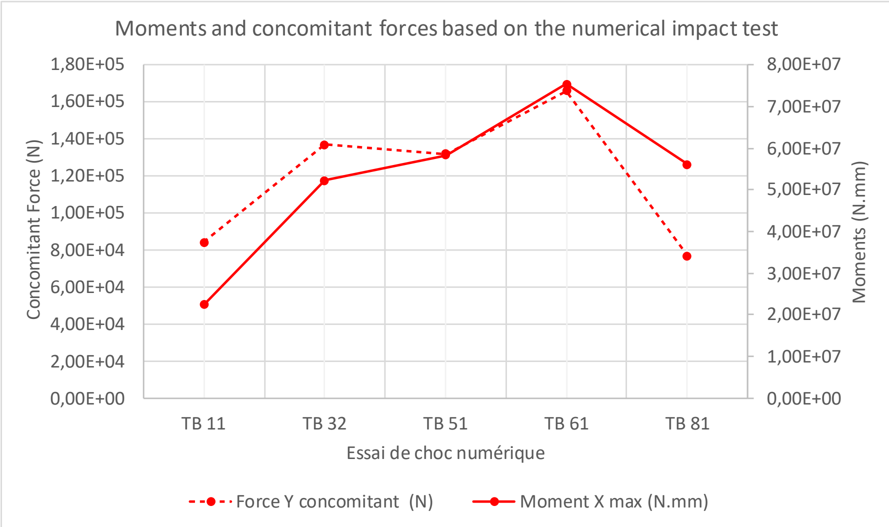


Fig.9: Moments and concomitant forces based on the numerical impact test

The results obtained from the numerical impact tests for various containment levels (TB11 to TB81) highlight the complex relationship between the force transmitted to the supporting structure and the corresponding bending moment. Even though the numerical simulations for TB61 and TB81 have not been correlated with real crash tests, they provide a good indication of the expected results.

These results demonstrate that designing for the highest containment level does not automatically equate to the highest transmitted loads. The structural response depends on multiple factors including the geometry and energy absorption characteristics of the restraint system, as well as the impact configuration. Therefore, the combined evaluation of both force and moment—particularly their concomitance at a given time and location—proves essential in identifying the most critical load cases for the design of bridge decks and supporting civil structures.

The load vector determined by the method presented reflects the behavior of the restraint system corresponding to its certified performance level. However, the forces to be considered in the design of the structure must represent an ultimate load case for vehicle restraint and are generally higher than those observed during the impact (see NF EN 1317-1:2010, paragraph 5.1).
As a result, the forces and moments are scaled by a factor of 1.2 to be used.

2.5 Conclusion for VRS

This analysis validates the use of numerical simulations to assess dynamic load cases in a harmonized way, offering a reliable method to support civil engineering design beyond traditional static assumptions.

The simulation shows that a higher impact on the road restraint system does not necessarily result in higher forces being transmitted to the bridge or the supporting structure.
The main objective of this new French standard is to establish a harmonized and consistent method for evaluating different systems.
To integrate these values into bridge design, as performed by civil engineers, the dynamic forces and moments extracted from the simulation will be used. Traditionally, civil engineers rely on static loads for this type of structural design. However, dynamic loads are significantly higher in magnitude than static ones.

This approach represents the first standardized method explored in this study for determining the dynamic loads transmitted to structures.

3 Anchorages of nuclear installation protective structures

3.1 Introduction

In the last decade, new scenarios related to climate change have appeared for the verification and dimensioning of nuclear power plants including those related to tornadoes aggression risk.
A tornado is a vortex (whirlpool) of extremely violent winds, originating at the base of a thunderstorm cloud when wind shear conditions are favorable in the lower atmosphere.
All regions of metropolitan France are potentially subject to tornadoes, but the north, the northwest, and the Mediterranean coasts are the most exposed areas. Land-based tornadoes are mainly observed in the summer, between May and September, while those affecting coastal areas tend to occur during the cold season.
The scale used to classify tornadoes is the one developed by Tetsuva Theodore Fujita of the University of Chicago. Tornadoes, whether weak or strong, have their own characteristics and are judged by their intensity (Enhanced Fujita Scale), not by their size. The Fujita Scale therefore measures the power of tornadoes when the damage is truly related to this phenomenon. This scale ranges from EF0 (minor damage) to EF5 (incredible damage), considering the type of construction and its strength.
This meteorological phenomenon is of limited duration and extent: it affects a path a few hundred meters wide and a few kilometers long and does not last more than a few hours. The damage caused by tornadoes is due to the following effects:

- Dynamic wind pressure
- Projectiles generated by the tornado, propelled into the air
- A drop in atmospheric pressure

3.2 Impacts definitions

EDF has defined load cases to assess the robustness of its structures. Among them, EDF consider the impact of a 130kg steel tube whose impact speed depends on tornado level and impact direction.

Tornado	EF3	EF4
Maximal tornado wind speed	68 m/s	81.5 m/s
Horizontal impact speed	22.7 m/s	27.2 m/s
Vertical impact speed	15.1 m/s	18.1 m/s

Table 2: Steel tube impacts definitions

The horizontal and vertical speeds are respectively 1/3 and 2/9 of the maximal tornado wind speed.
In order to avoid the systematic use of complex numerical models EDF wanted to use equivalent static loads which is far from being accepted by safety agency. The work presented hereafter has been produced in order to demonstrate the robustness of the approach.

3.3 Model calibration

To bring guaranty to the study outputs, several impacts tests have been reproduced most of all to calibrate the model and reproduce the failure modes.

3.3.1 Steel tube drop tests on HEB300

Two tests were selected because they allow to identify the threshold of anchorages failure:

Test 115 : Impact of a 130kg steel tube at a theoretical impact speed of 27.2 m/s on a HEB300 linked to a steel structure with 6 M22 bolts. The tube impacted the profile with a deviation of about about 8cm. All the bolts resisted to the impact. It is worth noticing that a previous test was conducted on the same HEB (test 114) which impact point was deviated of about 20 cm.

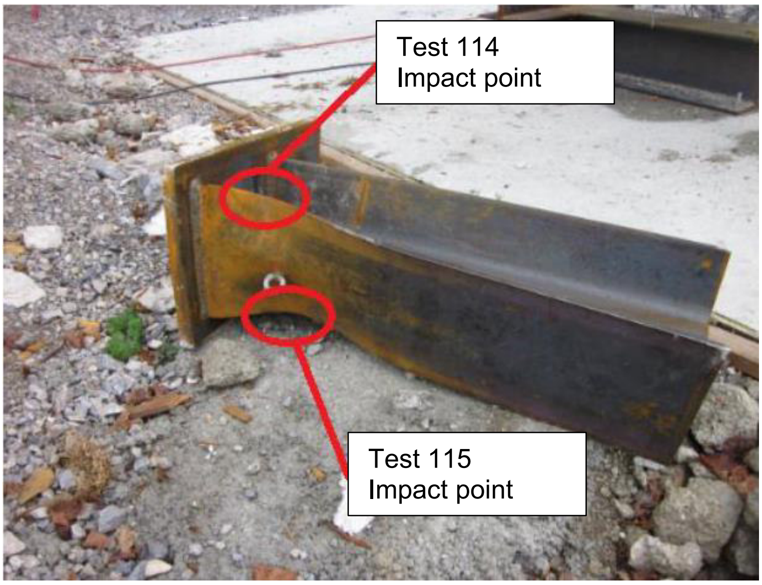


Fig.10: Test 114 & 115 results

Test 126 : Impact of a 130 kg steel tube at 22.7 m/s on a reinforced HEB300 (see Fig.11:) in order to free oneself from the need for precision of the impact point.
Although the test was carried out at low impact speed, all 6 bolts broke.

Fig.11: Drop test 126 set-up

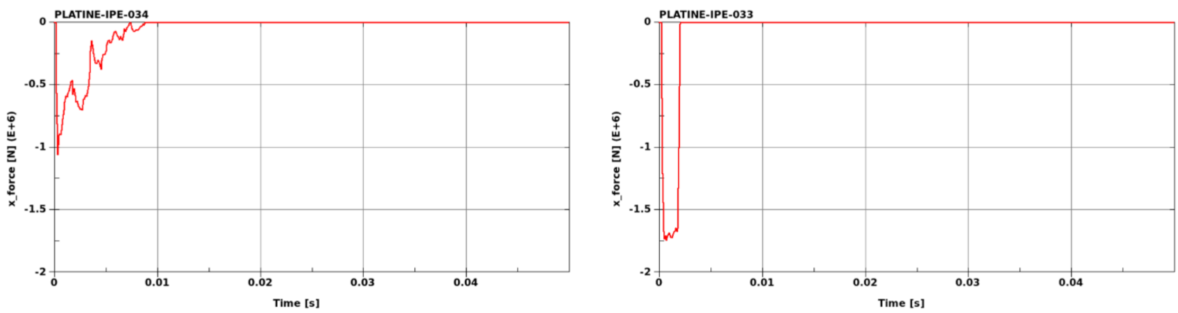


Fig.12: Numerical contact forces for correlation on test 115 (left) and 126 (right)

The contact forces observed during the numerical simulations of those impacts performed with LS-DYNA show high values (>1000 kN) during a relative short time (2.5 - 10ms).

3.4 Impact on tornado curved protection

Test 92 was selected because the test conditions are the same as test 114 et 115 but on a lighter profile (HEA120) and a different anchorage (2xM24 8.8) which were broken during the impact.

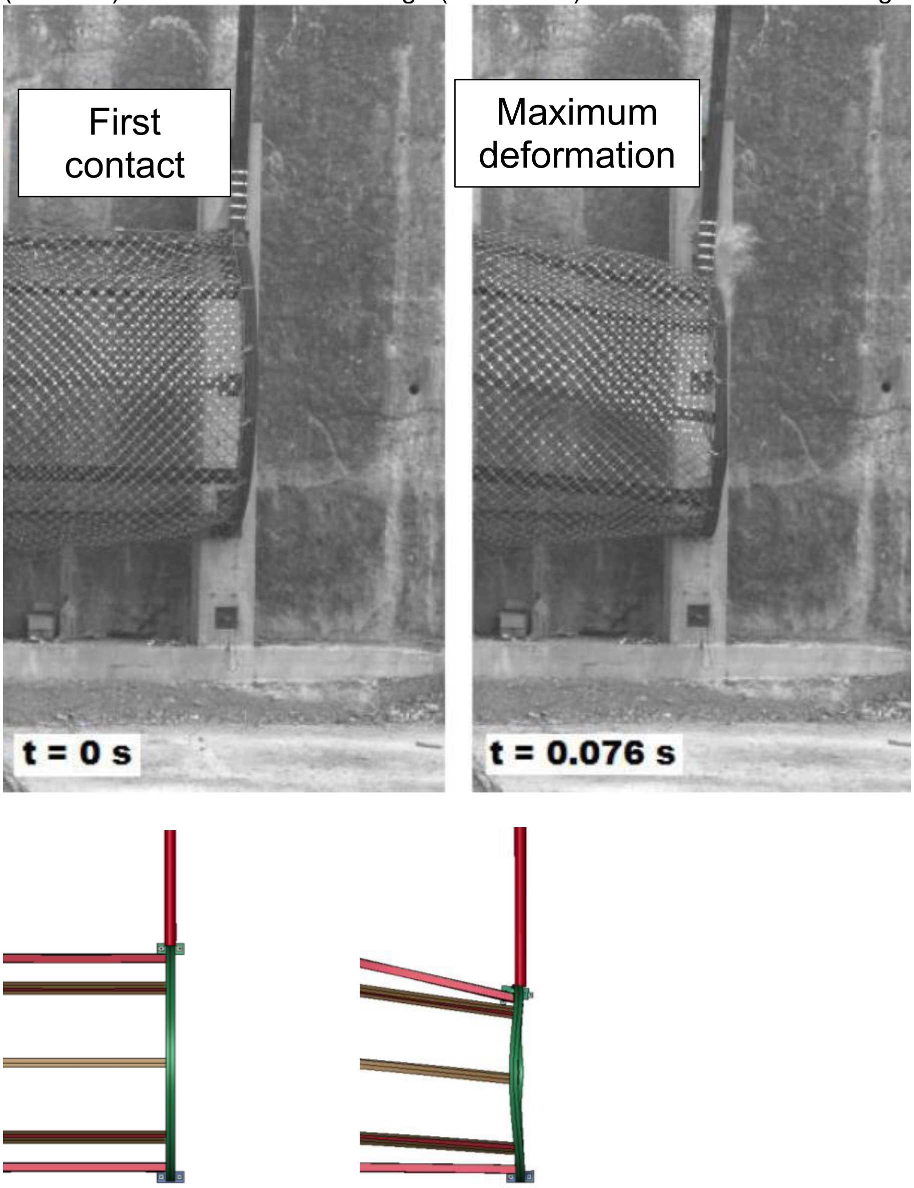


Fig.13: Test-Simulation comparison for test 92

The three test configurations (92, 114 and 126) were conducted with the same philosophy to assess the mechanical characteristics of the anchorages (resp. bolts): If one uses the minimum characteristics of the related quality class, there is no way to reproduce what happened during the test. The choice made for this work was to select the minimum characteristics of the class above (e.g. minimum of 9.8 class to represent an 8.8 quality class). This allows us to have a 100% match of the failure modes of the bolts (resp. anchorages)

3.5 Assessment of existing protection

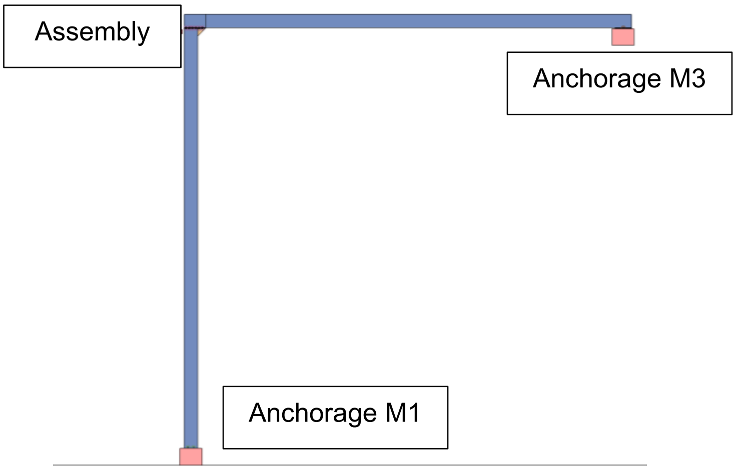


Fig.14: Model of an existing tornado protection

This tornado protection presents 2 anchorages and one post/beam assembly. These three points will be impacted by the steel tube in EF3 tornado conditions.

3.5.1 Anchorage M1

The anchorage M1 is made of 4 M33 8.8 and a HEB300 shear lug casted in the concrete.

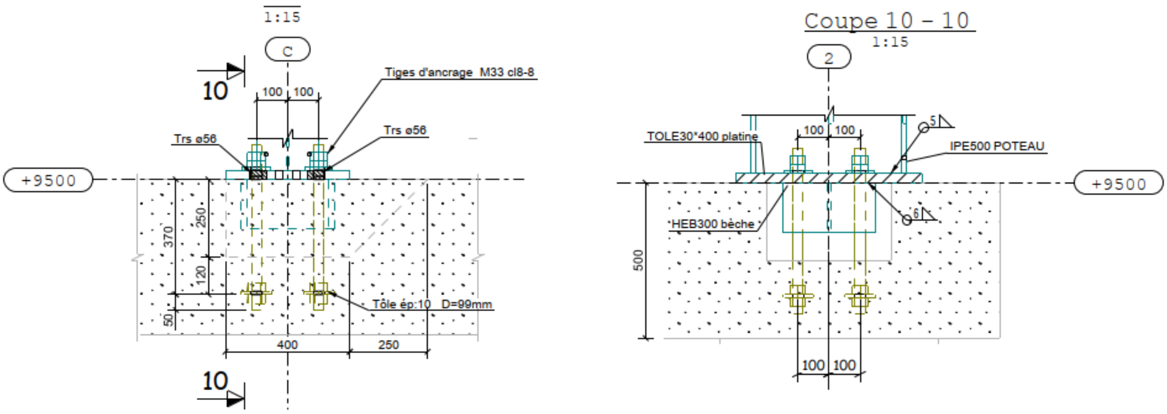


Fig.15: Anchorage M1 details

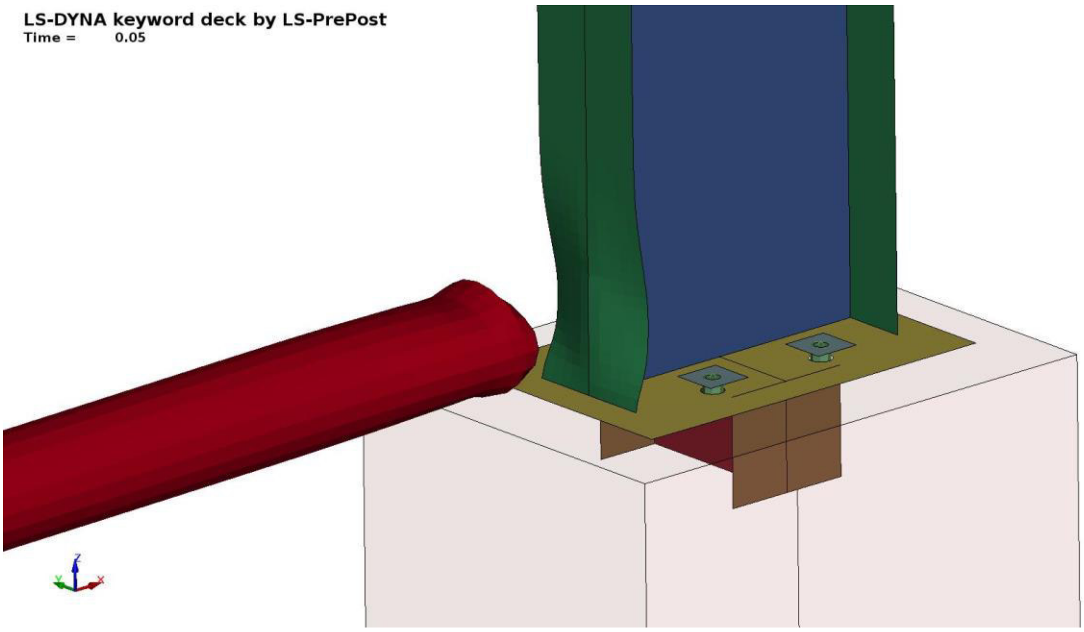


Fig.16: Anchorage M1 impact simulation : final state

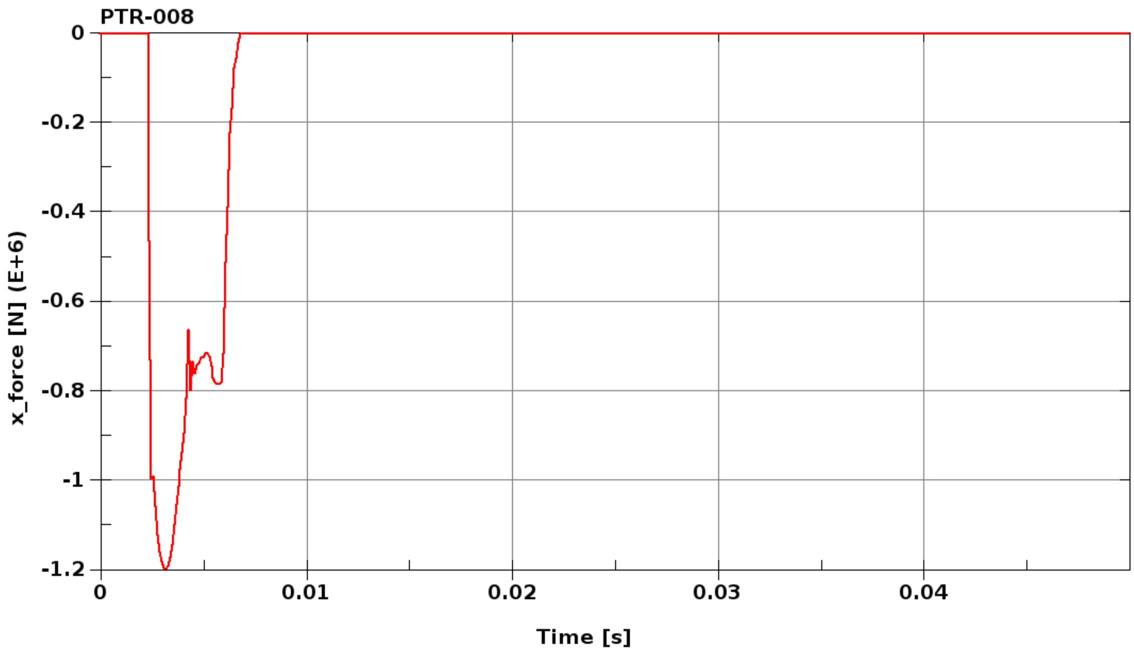


Fig.17: Anchorage M1 impact simulation : Contact force

3.5.2 Anchorage M3

The anchorage M3 is made of 2 M20 8.8 and a HEB300 shear lug casted in the concrete.

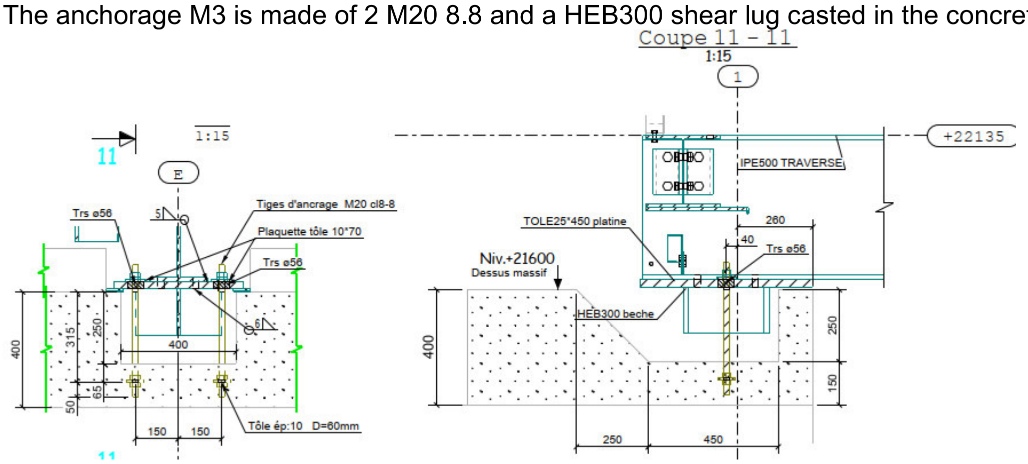


Fig.18: Anchorage M3 details

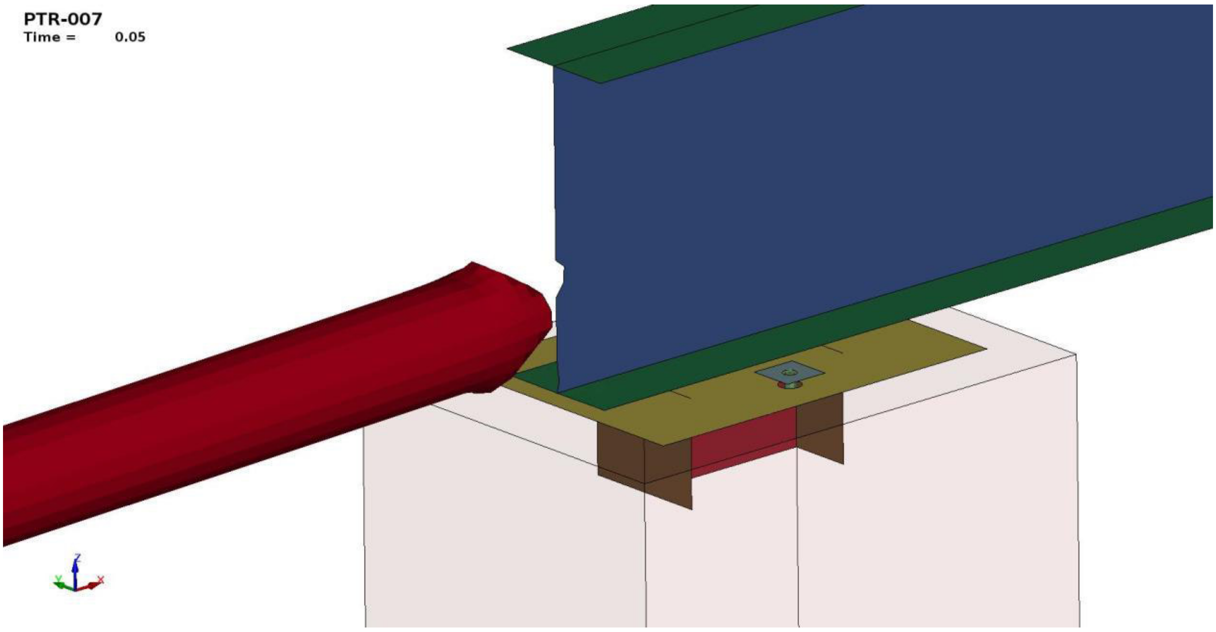


Fig.19: Anchorage M3 impact simulation : final state

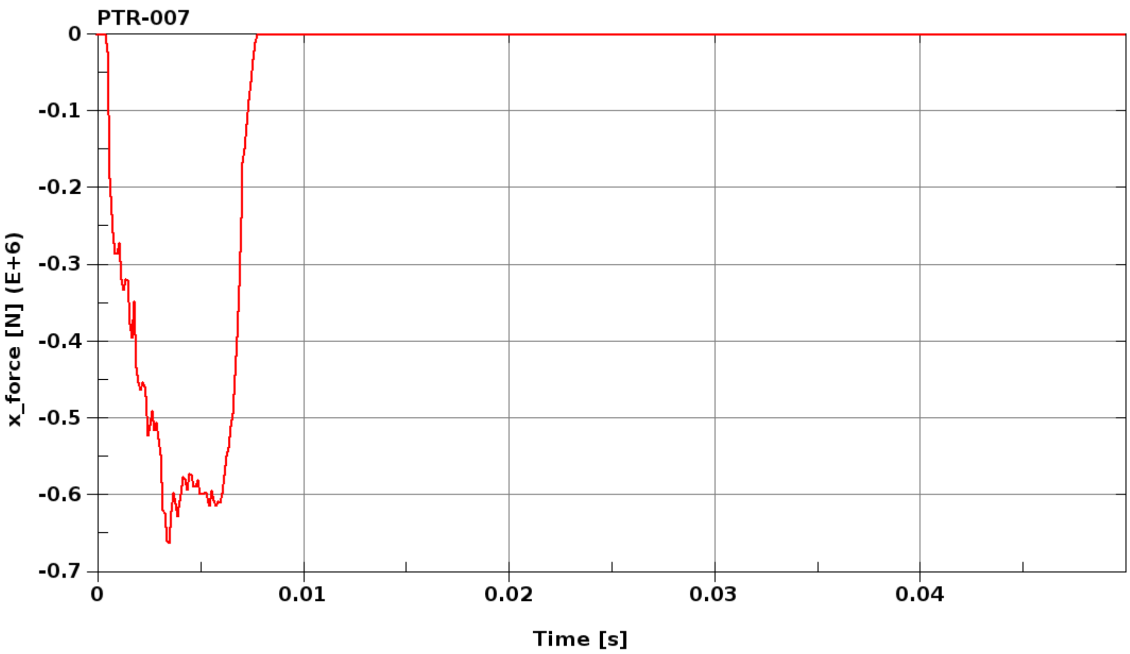


Fig.20: Anchorage M3 impact simulation : Contact force

3.5.3 Assembly

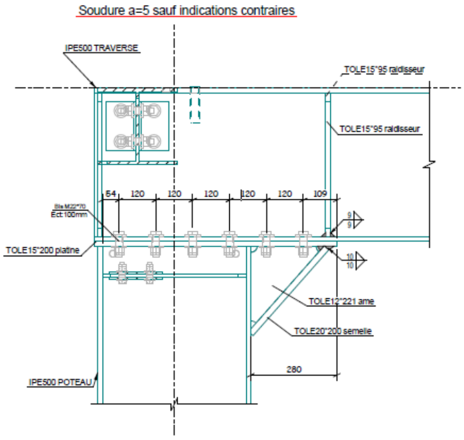


Fig.21: Assembly details

The assembly is made of 12 M22 8.8 bolts

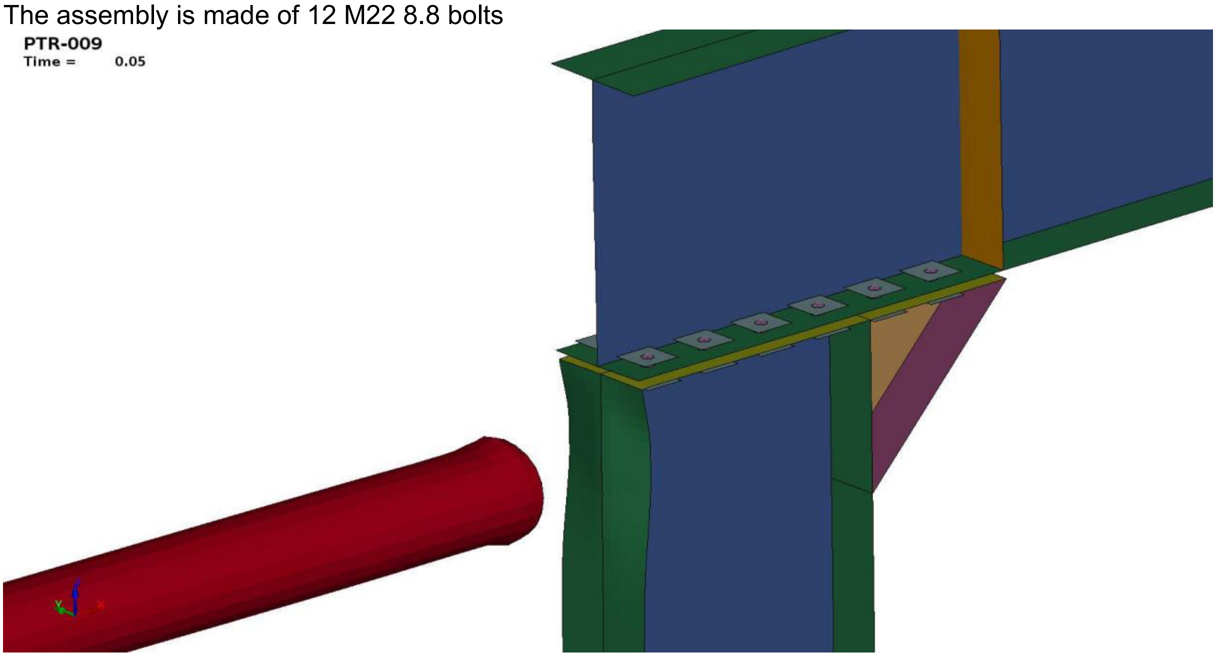


Fig.22: Assembly impact simulation: final state

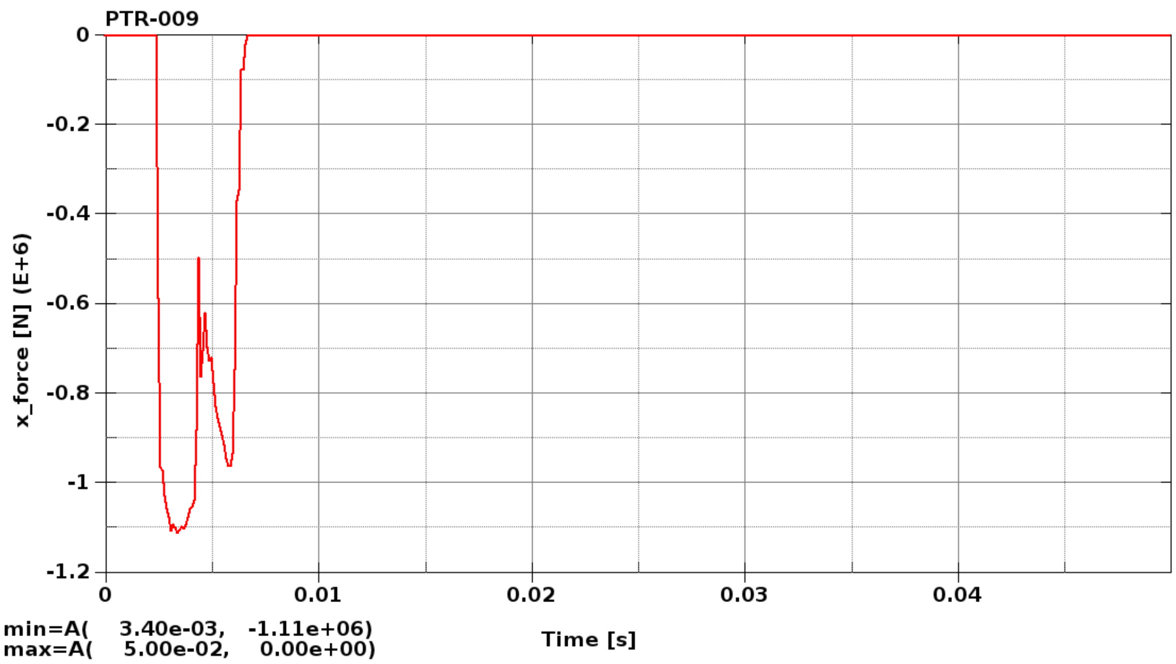


Fig.23: Assembly impact simulation: contact force

The three impacts reported hereabove are performed in the same conditions but present discrepancies in terms of impact forces due to the differences of stiffness of the different impact zones.

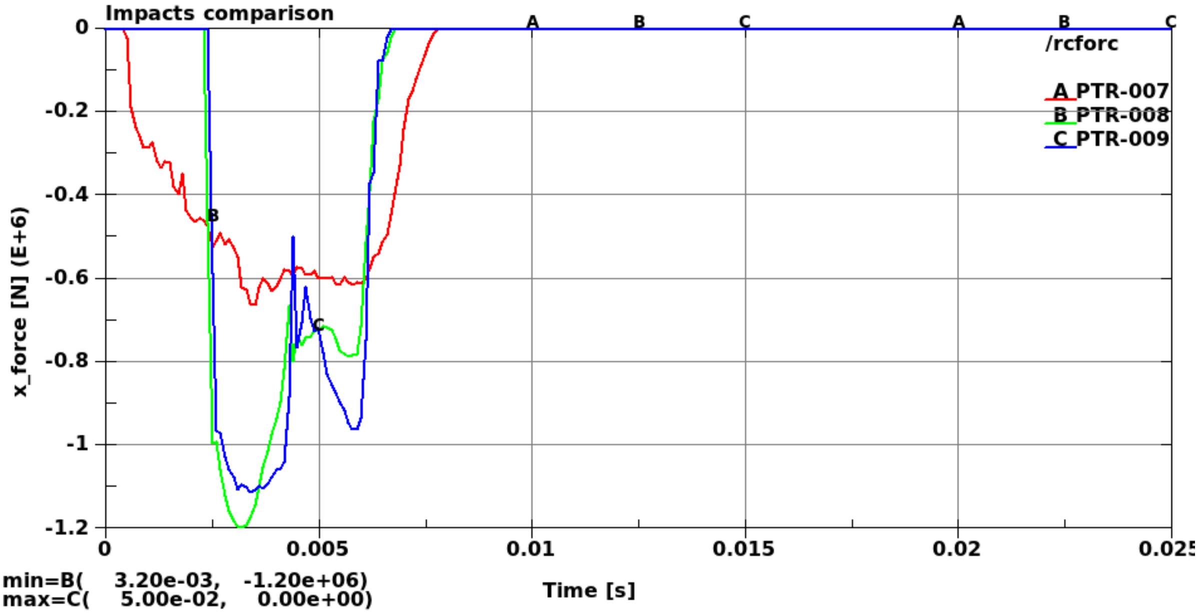


Fig.24: Steel tube impacts comparison: contact forces

The communication of the maximal impact force (pic value) to a design office who will use it as a static force is unfortunately very common but may lead to oversizing of the anchorages.

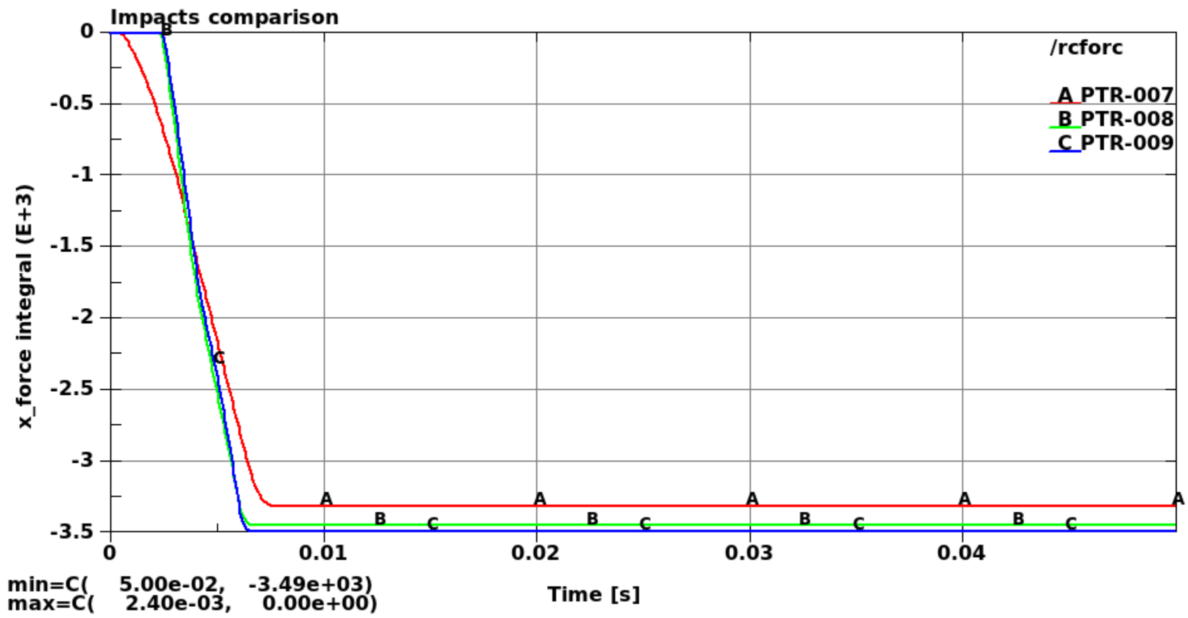


Fig.25: Steel tube impacts comparison: impact forces integration

The integration in time of the impact forces, shown in Figure 25, allows the computation of an average force in computing the slope of the curves during the impact phase.

Load case	Impact force pic value (N)	Average force (N)	Reduction factor (-)
PTR-007	-662 000	447 000	0.68
PTR-008	-1 200 000	767 000	0.64
PTR-009	-1 110 000	812 000	0.73

Table 3: Average forces

4 Comparison of the different methods

The first method mentioned for VRS uses cross section to have the load transmitted to bridges. The second method for nuclear installation uses the contact forces between the impactor and the system.

The following paragraph presents the contact force method with the integration in time applied to VRS for the TB51.

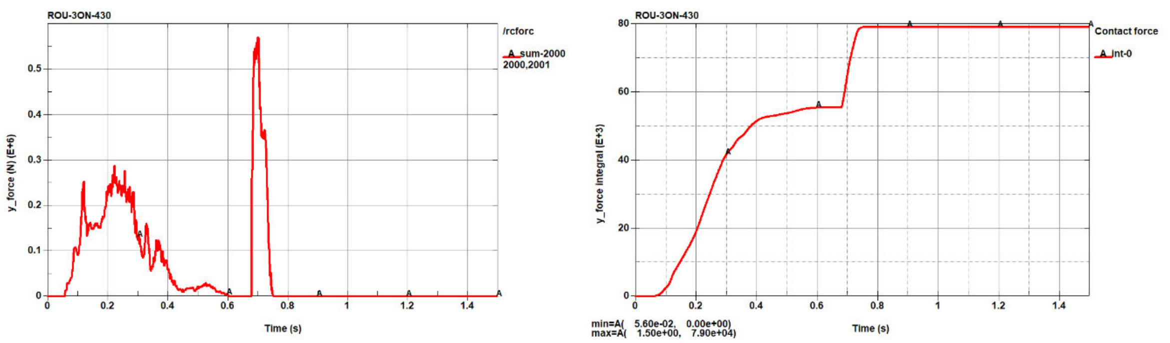


Fig.26: VRS: contact forces and contact forces integrated for TB51

The integration in time of the impact forces allows the computation of an average force in computing the slope of the curve during the impact phase.

Load case	Impact force pic value (N)	Average force (N)	Reduction factor (-)
TB 51	570 320	332 400	0.58
TB 61	430 700	234 200	0.54

Table 4: Average forces for different load cases for VRS

As shown, the reduction factor gives a similar result for both applications.

Regarding those results, the following method mentioned can be used:

- Use a cross section to measure the force,
- EDF proposal is to use an integration over time to find an “average force”.

Other method can be considered:

- Use the force versus displacement curve and take only 80% of the displacement. This curve can be integrated to find an equivalent energy. The equivalent static force would be measured as follow: $F_{moy} = \frac{E}{80\%\ of\ the\ displacement}$

5 Summary

The integration of dynamic simulation into civil engineering practice represents both a challenge and an opportunity. The examples discussed - bridge-mounted safety barriers and protective anchorage structures - illustrate how conventional static approaches can be complemented by advanced numerical tools. Numerical simulation, and in particular LS-DYNA, enables a more realistic assessment of structural response, highlighting critical load cases.

However, even with dynamic simulation, forces can be measured in different ways. These ways lead to different forces to be considered by civil engineers.

Ultimately, the development of harmonized standards, such as FD P98-435, demonstrates that simulation can be systematically embedded into civil engineering codes and practices. This evolution opens the way toward more optimized, resource-efficient, and safer structures, aligning engineering design with the dual goals of structural performance and sustainability.

6 Literature

[1] NF EN1317 Road restraint systems - Part 1: Terminology and general criteria for test methods – AFNOR, September 2010

[2] NF EN1317 Road restraint systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets – AFNOR, September 2010

[3] NF EN16303:2020: “Road restraint systems – Guidelines for computational mechanics of crash testing against vehicle restraint system” – AFNOR, Août 2020

[4] GOUBEL C., "Vehicle Restraint System optimization and robustness assessment using the coupling between LS-DYNA, LS-OPT and DEP MeshWorks software", 12th European LS-DYNA Conference 2019, Koblenz, Germany, 2019