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Fused seismic shock absorbers - an innovative solution for the high-speed rail viaducts of the AVE Granada Line, Spain

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ABSTRACT: The high-speed AVE railway line to Granada is to cross a highly seismic area with an irregular topography. The design of a viaduct for one section requires its deck to be connected to one of its abutments by shock absorbers which generally act as rigid connections but which dissipate energy and protect the structure from overloading during a large earthquake. A solution has been developed, incorporating the modification of a standard shock absorber to feature an innovative fused connection. This connection is designed to resist fatigue from service loading, and to fail in a controlled manner under the action of a high seismic load, freeing the device to act as a damper. It thus provides seismic protection of the viaduct at its fixed point, contributing to an efficient abutment design. The device's design and behaviour are described with reference to its fulfilment of the requirements of EN15129 and the testing that has proven its innovative functionality. The incorporation of this newly developed device in the construction of the viaducts shall result in increased structural efficiency, simplifying construction and reducing costs.

1. Introduction

The area around Granada in southern Spain has been known for its seismicity since Roman times. More recently, earthquakes in nearby Lorca (Murcia) in 2011 highlighted the persistence and dramatic potential of such events in the area. It is also an area with a rugged terrain around the mountains of Tejeda, Almijara and Alhama in the Sierra Nevada range. The new AVE high-speed railway line to Granada will traverse this region, requiring its designers and constructors to ensure its safety and serviceability in spite of seismic threats. In particular, structures such as viaducts must be protected from the type of seismic activity that is relatively common in the area [1], and must remain useable by emergency traffic even following a very large earthquake – conforming to the Spanish railway norm NCSP-07 and its European equivalents. The desire to improve efficiencies and reduce costs while fulfilling all such requirements has motivated the responsible engineers to consider how common seismic protection solutions can be adapted and developed to optimally achieve this for each structure.

This is particularly important where the seismic design load case is decisive for the design of the substructure (piers, abutments and foundations) and the connections to the bridge deck [2]. For continuous bridge deck solutions, in designing for longitudinal resistance, there are three basic options: with a fixed point at one abutment, with a fixed point at the middle pier, or a damping strategy with shock transmission units (STUs) at the abutments [2].

A solution presenting a variation of that third approach is presented here for a viaduct over the Rio Frio on the Loja variant of the AVE line. Instead of STUs, the engineer proposed the use of shock absorbers (SA) with very low damping exponent at an abutment, incorporating a fuse element which provides rigidity during normal operation.

2. Seismic Damping Strategies

The main objective of a seismic damping system is to reduce seismic loads on a structure. Figure 1 shows how the response of a structure (its acceleration during a seismic event) can be reduced by increasing damping.

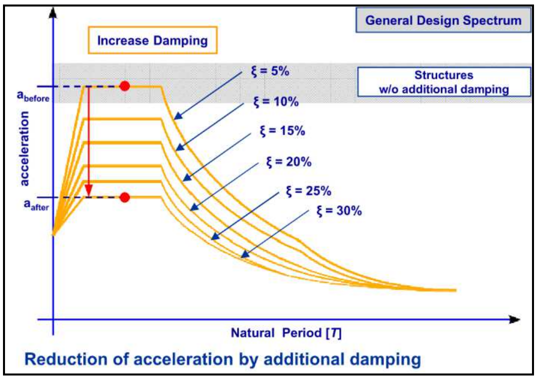


Fig. 1 – Response spectra for a structure with increasing damping

In terms of energy balance, the aim is to dissipate by heat the earthquake-induced energy that could be transmitted into the structure, resulting in damaging hysteretic energy due to plastic deformation of its materials. The energy dissipated in the dampers is of course to be added to the kinetic energy and elastic energy that are natural and reversible seismic responses of the structure.

Among the different seismic damping devices available, fluid viscous dampers have found wide application in bridge structures. This is due to their simplicity and their high performance.

A fluid viscous damper consists primarily of a cylinder with a piston. The cylinder is filled with an viscous elastomeric material, the fluidity of which depends on the damping performance to be achieved. The material circulates in the cylinder through small openings in the piston. The resulting resistance creates friction which dissipates large amounts of energy as heat.

The constitutive law of fluid viscous dampers follows the equation

$$F = C.v^{\alpha} \qquad (1)$$

where F is the damping force, C is the damping constant, v is the velocity and α is the damping coefficient representing the fluid nature and its circulation behaviour through the piston. The exponent α has a value between 0 and 1, with a value of 1 representing linear behaviour

The coefficient α for this project has a value of 0.04, as it is explained in points 3.1 and 3.2. However, it is important to understand at this point that non-linear dampers with values for α in the order of 0.1 or below have lower sensitivity to low velocities. In the context of this project, a fuse element is added to the damper to prevent any movement at such low velocities. But most importantly, they transmit lower forces in cases of extremely high velocities and provide much higher energy dissipation.

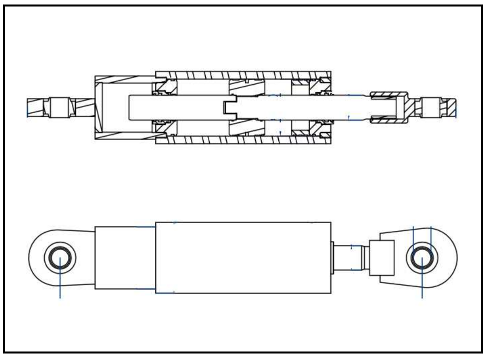


Fig. 2 –Section of a typical shock absorber (top) showing piston, and elevation (bottom)

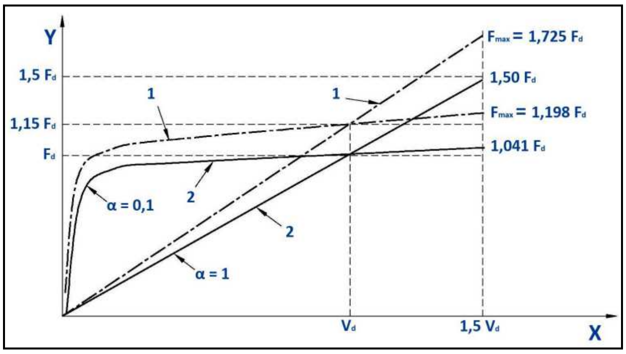


Fig. 3 – Force (Y) versus Velocity (X) curves for a linear damper (α=1) and a non-linear damper (α=0.1) – as per Equation 1

3. The seismic protection of the viaduct over the Rio Frio

3.1. The bridge context

The viaduct has a single continuous deck with 12 spans and a total length of 580m – 10 spans of 50m, one of 35m and one of 45m.

The bridge is designed with a pre-stressed concrete deck, supported by one guided and one free sliding bearing on each pier.

The fixed point of the bridge deck in terms of longitudinal horizontal loads is at one of the abutments. Dampers at this point shall minimise the maximum forces transmitted to the abutment. Each damper shall consist of a shock absorber with an added fuse system.

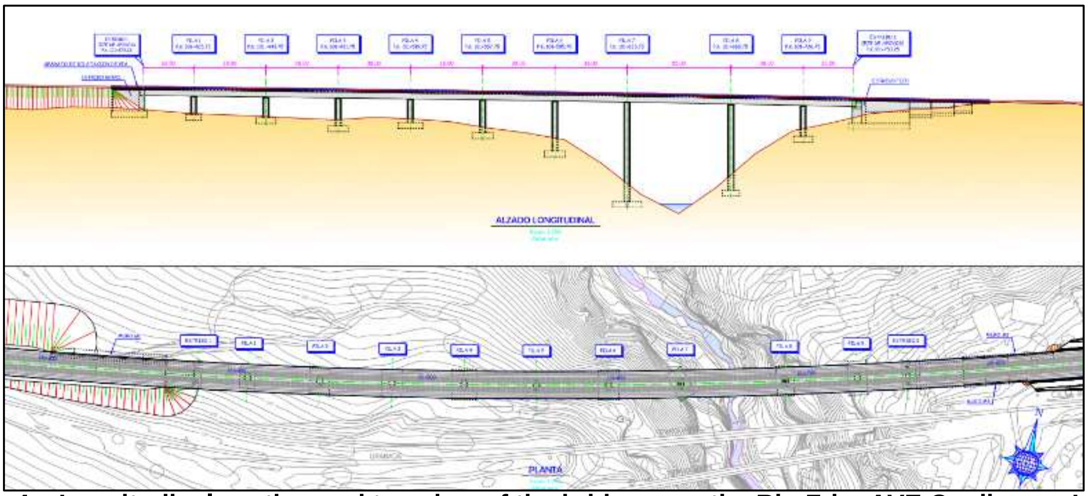


Fig. 4 – Longitudinal section and top view of the bridge over the Rio Frio, AVE Quejigares-Loja

3.2. The design requirements for the shock absorbers

The relevant standard for railway viaducts, NCSP-07 [1], specifies that only limited damage is to be expected from frequent seismic events, with repair costs not being disproportionate to initial construction costs. Section C7.6 of this standard requires that the structure remains in service after Serviceability Limit State (SLS) events which include small frequent earthquakes.

As a consequence, the yield point of the fuse must not exceed the SLS horizontal force (including Frequent Seismic Event, Rail track - Structure Interaction and Shortening of the deck) as calculated in Table 1. It also includes an extra 10% safety margin to enable the shock absorber to start acting. In addition, to limit the loads transmitted to the abutments, the shock absorbers must start acting at their maximum damping force. To ensure this, considering that the shock absorber design includes a safety margin of 1.5 according to EN15129 [3], a very low α exponent is chosen, with a value of just 0.04.

Table 1 – Longitudinal loads on dampers

Load case	**Load (kN)**
Frequent Earthquake	27,370
Rail track - Structure Interaction	1,982
Friction on pot bearings (3%)	3,885
Shortening of the deck	1,216
Safety margin (10%)	3,445
Total	37,898

It is calculated that the loads transmitted to the abutment in the Ultimate Seismic Accidental case, without this damping, would be of 79,304 kN – more than double the value with the damping (refer to Table 1), resulting in a need for major strengthening of the structure and a bearing system able to transfer these longitudinal loads. The value offered by this damping solution is therefore evident.

3.3. The shock absorber with fuse solution as designed

In order to make the viaduct capable of withstanding a seismic event as required by its design, it was determined that eight devices would be required to resist the loads specified by the bridge designer. The design of these devices, based on the shock absorber, is shown in Figures 5 to 7. The behaviour of the dampers is presented in Figures 8 and 9.

The devices fulfil the following requirements, remembering Equation 1 ($F = C.v^{\alpha}$):

- C = 4974 kN.m/s
- A = 0.04
- v_{max} = 0.3 m/s
- F_{max} = 4740kN at maximum velocity (v_{max})
- Maximum stroke = 200mm (+/- 100mm)

The system's fuse is composed of nine elements, arranged in a circle around the shock absorber, in a steel housing. The housing, with diameter 643mm, is circled in Figure 5 and 7, and a section through it is shown in Figure 6 (with same part circled). Each fuse element consists of a steel element which is designed to fail in shear (fuse section area as calibrated by trial and error after break-away testing), ensuring equal performance when the shock absorber is subjected to both the tension and compression forces that can arise during an earthquake.

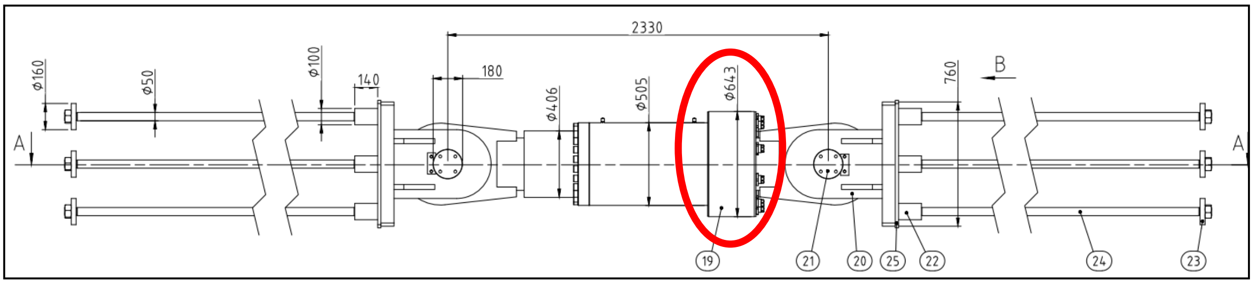


Fig.5 – Elevation of the Reston-SA shock absorber with concrete anchors and fuse

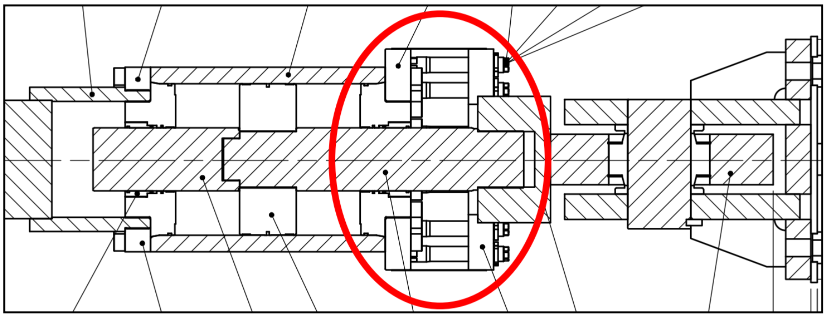


Fig.6 – Detail of the fuse arrangement for the shock absorber

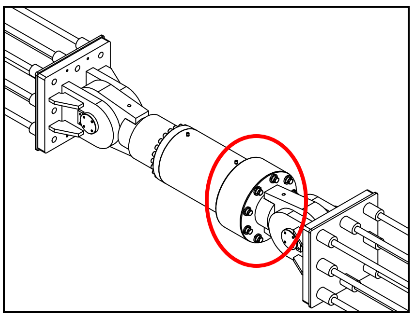
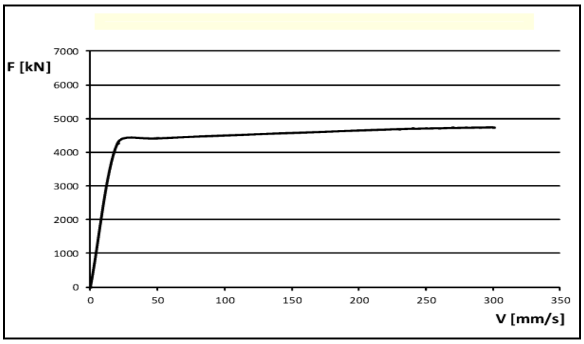


Fig.7 – 3D-view of the device



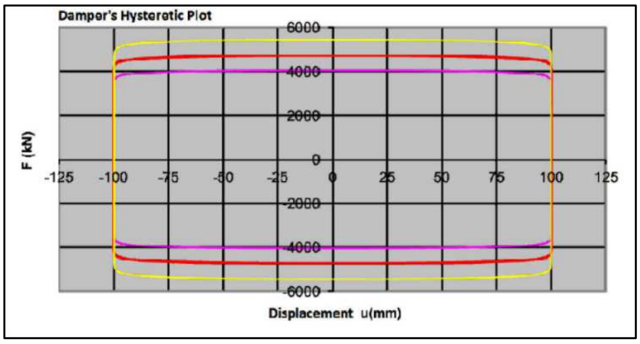


Fig.8 – Damper's constitutive law

Fig.9 – Damper's hysteretic plot

4. Testing and certification in accordance with EN 15129

Testing and certification of the damper according to the European Standard EN 15129 was required by project specifications. Separate testing of the shock absorber on which the damper is based, and of the added fuse feature, was planned.

4.1. Testing of the shock absorber according to EN 15129 (Section 7.4.2) [3]

Testing is planned to take place at the UCSD Caltrans Facility in San Diego, USA in July 2014. This will include Low Velocity Testing, Constitutive Law Testing and Damping Efficiency Testing (see Table 2). In order to expedite the process, some testing is being carried out at the Politecnico di Milano, Italy with the use of a scaled prototype for the low temperature (-25°C) and high temperature (+50°C) testing (Figures 10 and 11).

The characteristics of the prototype damper are as follows, remembering Equation 1 ($F = C.v^{\alpha}$):

- C= 787 kN.m/s, α = 0.04, v_{max} = 0.06 m/s, F_{max} = 750 kN and maximum stroke = +/- 50mm.

Table 2 – Testing procedure according to EN 15129 (Section 7.4.2) [3]

Item	Test	Requirements	Reference [3]
1	Pressure test	No leakage of fluid after internal pressure equivalent to 125% of the maximum damper load. Pressure maintained for 120 (s).	7.4.2.2
2	Low Velocity Test	The reaction force shall be less than 10% of the design force (Fm) after one (1) fully reversed cycle of imposed axial displacement, going from 0 to d_{th} = ±50 mm and back to 0, at constant absolute velocity $v_1 \leq 0.1$ (mm/s). Repeated at +50°C and -25°C, on a smaller damper.	7.4.2.3
3	Constitutive Law Test	At each velocity, impose three (3) fully reversed cycles of axial displacement from 0 to $+d_{bd}$, to $-d_{bd}$ and back to 0, where d_{bd} is the seismic design displacement. Repeated at +50°C and -25°C, on a smaller damper. All the experimental points of the reaction force characteristic curve shall fall within the tolerance envelope (±15%).	7.4.2.6
4	Damping Efficiency Test	*Loading history:* Six (6) harmonic full displacement cycles of the type $d(t) = d_0 \sin(2\pi f_0 t)$ where stroke d_0 and frequency f_0 are defined by the structural engineer. This test shall be repeated at +50°C and -25°C, on a smaller damper.	7.4.2.7

		For each cycle, the damper reaction shall be within the design tolerance and the energy dissipation shall be greater than 85% of the design value.	
5	Wind Load Cyclic Test	Scope: To verify the capacity of the damper to resist wind-induced vibrations. The damper shall be subjected to cycles at a stroke d_0 and frequency f_0 as specified by the structural engineer. The damper shall not bind, seize or break, and after the test the unit shall show no evidence of leakage of fluid.	7.4.2.8
6	Seal Wear Test	No leakage of fluid after testing for 10,000 cycles at an amplitude equal to the maximum thermal displacement d_{th}, with d_{th} ≥10 mm. Afterwards, the damper shall undergo the Damping Efficiency Test to verify that the requirements given are still fulfilled.	7.4.2.9
7	Stroke Verification Test	Scope: to ensure that the damper is able to accommodate the design stroke, within a tolerance of 1 (mm).	7.4.2.10

Fig.10 – Prototype damper during testing at Politecnico di Milano, Italy

Fig.11 – Prototype damper undergoing a low temperature test (-25°C)

4.2. Testing of the fuse according to EN 15129 (Section 5.2.4) [3]

Testing was performed in June and July 2013 by the Materials Testing Laboratory of Politecnico di Milano, in its position of Notified Testing Laboratory for the harmonised technical standard EN 15129:2009, ref. Section 5.2.4 Type Testing (of fuse restraints).

4.2.1. Testing set-up and programme

The test set-up is shown in Figures 12 and 13. Testing included Fatigue, Service Load and Break-Away testing, as described in Table 3. Although nine identical fuse elements are arranged around the Reston-SA shock absorber in the project's application, individual fuse elements are tested separately.

According to EN15129 (Section 5.2.4) [3], as long as the devices have the same internal and external geometry, and the same materials and the same kinds of constraint, only two samples must be tested. One of the two samples must pass the fatigue testing.

Fig.12 – A single fuse element in test rig in Politecnico di Milano

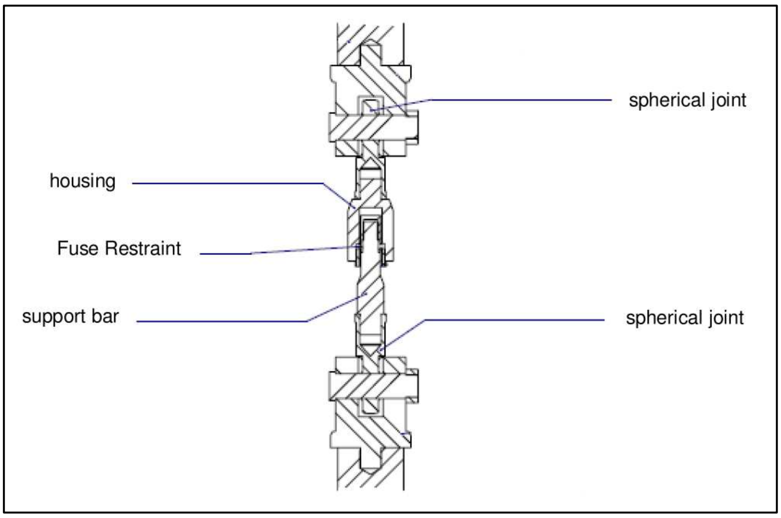


Fig.13 – The test set-up for a single fuse element

Table 3 – Test programme for the fuse elements, according to EN 15129 (Section 5.2.4) [3]

Item	Test	Requirements	Reference [3]
8	Fuse restraint: Service Load Test	Fuse subjected three times to a monotonically imposed load up to the maximum service load of 487 kN without yielding or failure.	5.2.4.2
9	Fuse restraint: Fatigue test	Sample 2 sample is subjected to the application of 2 million cycles cyclic fatigue load of +/-117.5 kN. The load frequency is adjusted depending on the total deflection of the test sample, but in no case shall it exceed 15 Hz.	5.2.4.3
10	Fuse restraint: Break-away test	The fuse element shall be subjected to a monotonically imposed load up to its break-away load of 536 KN.	5.2.4.4

4.2.2. Results

For the Fatigue Test, no signs of yielding or failure were observed in the tested sample. The requirements of EN15129 Section 5.2.4.3 were fulfilled.

For the Service Load Test, the results are shown below in Figure 14. Sample 1 and Sample 2 were tested at a service load of +487 kN, then inverted to -487 kN and back to 0 kN, with three cycles on each sample. The resulting deformation was measured on each cycle. The requirements of EN 15129 Section 5.2.4.2 were also fulfilled.

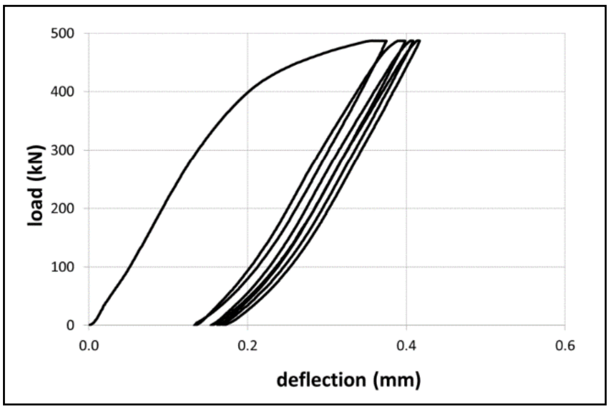


Fig.14 – Service Load Test - Curve Load - Deflection for one the fuse elements (#2)

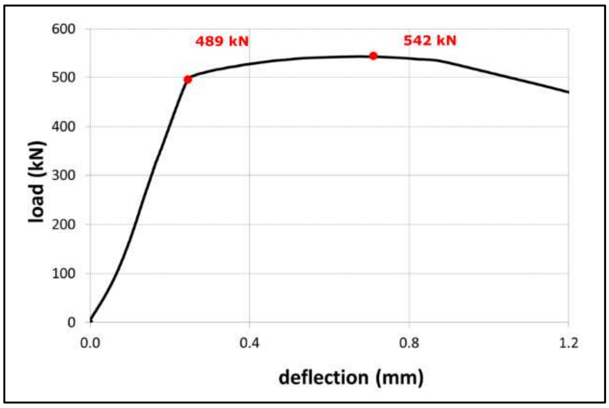


Fig.15 – Break-Away Test – Load/Deflection curve for one of the fuse elements (#2)

For the Break-Away test, the fuse specimen was subjected to increasing loads until it failed at 542 kN. The load/deflection curve shows a marked change in slope, which was likely due to yielding of steel, at 489 kN (see Figure 15). The results are presented in Table 4.
For this test, the tolerances were defined by the project's design engineer at -2% to +10% from the target value of 536 kN, for the break-away load. For the Yield Load, the difference had to be positive with respect to the target value of 478.5 kN, to ensure no yielding before the service load (see Table 4).

4.2.3. Testing of the fuse - Conclusions

The following table extrapolates the results from the type testing on the fuse elements to the actual number of fuse elements that are to be used in the Reston-SA shock absorbers.

Table 4 – Average Results for Break-Away and Yield Load Test for two fuse elements

Test	Fuse Elements	Mean Load per unit	Total Load	Theoretical Load	Difference	
[-]	[no.]	[kN]	[kN]	[kN]	[kN]	[%]
Break-Away Load	9	550.2	4951.8	4740	+211.8	+4.47
Yield Load	9	488.5	4396.5	≥ 4306 (Service Load)	+90.5	+2.10

As shown in Table 4, the total fuse break-away load deviates from the theoretical value by 4.47%, considerably less than the tolerance limits [-2%; +10%] specified by the engineer and the tolerance of ± 15% allowed by EN 15129 for break-away load. For the total yield load – the load at which the fuse restraint starts to yield and requires the fuse restraint to be exchanged – the difference is only +2.1% in relation to the service load.

This was achieved by material and shape research of the fuse elements that had been tested internally prior to finalization of the design.

The tested fuse restraint design has passed the type testing according to EN15129 Section 5.2.4.

5. Conclusions

This seismic protection device, combining a shock absorber and a specially developed seismic fuse, has successfully passed the prescribed stringent testing with tolerances that were even lower than specified by EN 15129. The incorporation of the device in the construction of the viaduct of the AVE Granada Line shall result in increased structural efficiency, simplifying construction and reducing costs. By providing an alternative to conventional earthquake resistance design measures, it saves the major strengthening works which would otherwise be required, if the benefits of energy dissipation and damping were not incorporated in the design. It thus demonstrates the potential benefits of tailoring existing technology to suit particular circumstances – combining the benefits of existing widespread technology and the innovativeness of suitably qualified engineers.

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