

# CONCRETE BRIDGE WITH METALIC ENERGY DISSIPATION DEVICE

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**Abstract**—Most reinforced concrete road bridges built in Argentina have their foundations or substructure constructed at the job site. On the other hand, the superstructure typically used consists of precast I-beams with an in situ slab that gives a monolithic connection.

These beams are placed on top of elastomeric bearings, so relative movements between the substructure and the superstructure of the bridge may occur at the event of an earthquake. In order to limit these seismic displacements, buffers are constructed. They are reinforced concrete blocks fixed to the substructure. Their design is usually done following approximate hypothesis which, in highly seismic areas, may be very insecure.

The aim of this work is to show the improvement made in the dynamic response of the structure of the bridge built in the province of San Juan, Argentina, due to the addition of energy-dissipating devices.

In order to predict the seismic response of the structure, mathematical models have been developed. The energy-dissipating devices have been tested in the Lab to analyze their mechanical behavior. Results show that the damage over seismic buffers is significantly reduced, and therefore structural security is raised.

**Keywords**- Energy. Dissipation. Devices. Bridges.

## I. INTRODUCTION

There have been built numerous road bridges in Argentina in high-risk seismic areas, following the layouts and structural diagram shown in Fig. 1, 2, 3 and 4. The superstructure can be appreciated and it consists of: guardrails, deck asphalt, panel

slab, precast beams and cross ties. The substructure consists of the following elements: cross girder and concrete pile.

The cross girder (of the pile or the abutment) holds the support devices, constructed of rubber and steel. On top of these are placed the prestressed precast beams, which are then joined to each other and to the bridge deck by cast in situ concrete cross ties. On both sides of the precast beams are located the "seismic blocks", whose purpose is to avoid excessive displacement in the event of a seismic movement, disarming the original arrangement of the bridge elements and, for severe cases, reducing the possibility of the deck to fall. Figures 5 and 6.

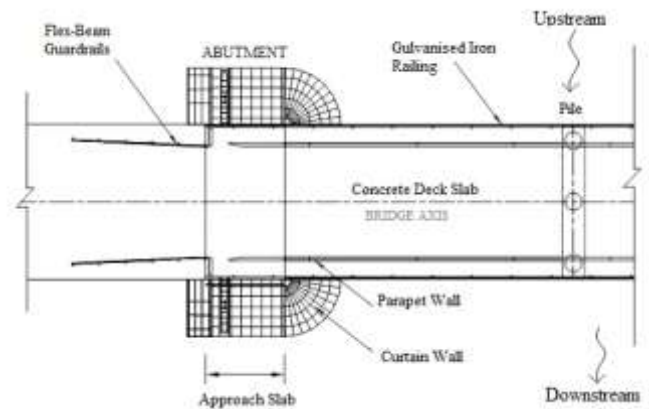


Figure 1. Plant of a section of Bridge that includes one abutment.

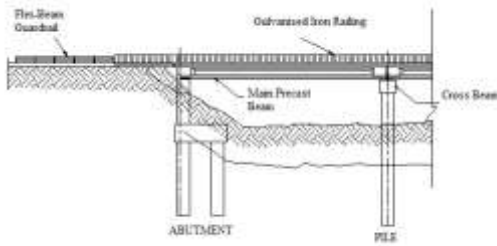


Figure 2. Longitudinal view

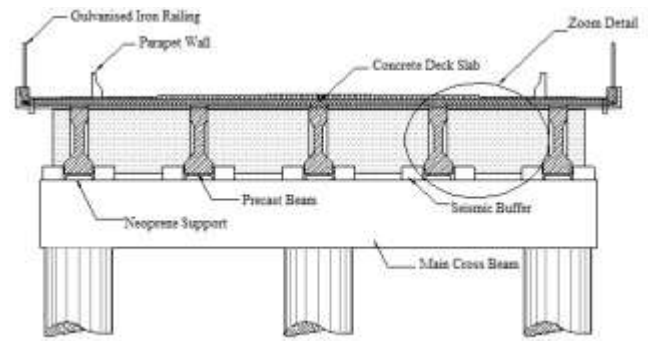


Figure 5. Cross Section of the Bridge

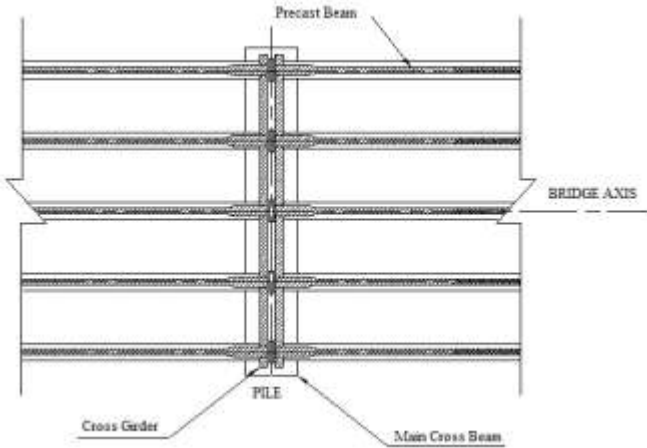


Figure 3. Plant showing the precast beams supported on the cross beam

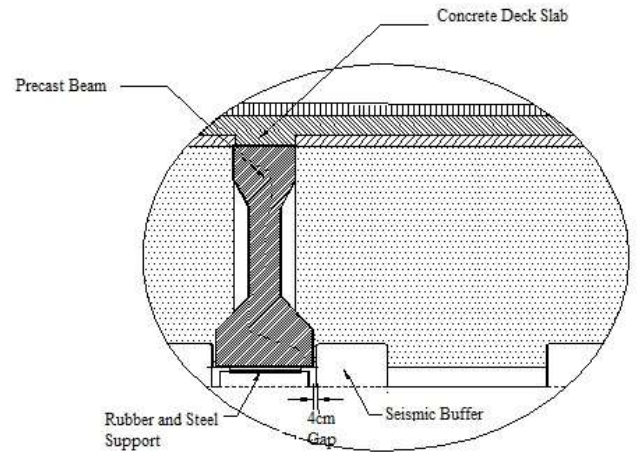


Figure 6. Detail of the support area of precast beam. The separation between the edge of the beam and the seismic buffer is normally about 4cm

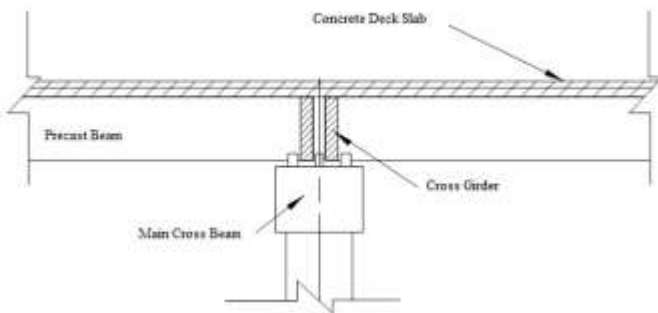


Figure 4. Longitudinal section showing cross tie

## II. AIM OF WORK

This work aims to demonstrate that the current design of seismic buffer for bridges is, in our opinion, incorrect and that it is possible to increase the safety of the structure incorporating energy dissipation devices that reduce the possibilities of impact and minimize the forces of collision between the structural elements of the bridge.

## III. CONVENTIONAL DESIGN OF SEISMIC BUFFERS

Seismic buffers are generally designed static, considering a force that results from multiplying a seismic coefficient by the reaction of the precast beam. This coefficient is the result of the corresponding seismic response spectrum, reduced by a factor that considers the ductility of the structure.

### Example of Design of Seismic Buffers

The built bridge has 12 sections of 25 meters length each. Five precast beams have been used per section. If the reaction ( $R_v$ ) of each precast beam on the support device for a bridge

category A30 is calculated, following the designation of the National Roads Directorate, the obtained effort will be:

The design force "Fd", usually used for the design of each seismic buffer, is calculated as:

$$F_d = C_s \times R_v = 0.35 \times 540.000 \text{ N} = 189.000 \text{ N}$$

with:

$$C_s = S_a/R = 1.05/3 = 0.35,$$

(Regulation INPRES CIRSOC 103)

S<sub>a</sub>: seismic pseudo acceleration.

R = coefficient of reduction

If having a seismic buffer, with a cross section of 0.20m x 0.40m, at every beam, the shear stress will be:

$$? (\text{N/m}^2) = 189.000 \text{ kg} / (0.20 \times 0.40 \text{ m}) = 2362.5 \text{ kN} / \text{m}^2.$$

#### IV. FORCES THAT CAN OCCUR DUE TO THE IMPACT OF THE MAIN BEAM HEEL WITH THE SEISMIC BUFFER AT A SEVERE SEISMIC MOVEMENT.

The bridge located Sorocayense, province of San Juan-Argentina, was modeled using the software SAP 2000, version 7.4. The foundation soil consists of gravels with a medium to dense compaction degree (GP and GW). Spring elements were used to model the contact between the piles and the soil. At the board level the masses corresponding to the middle section of the bridge were assigned, considering only dead weights. The following seismic records were used in the analysis:

- Argentina: Caucete, November 23, 1977
- Chile: March 3, 1985, Lolleo N10E, Melipilla N20E and Viña N70W,
- USA: El Centro (Imperial Valley 1940), Corralitos NS (Loma Prieta 1989), Arleta EW and Sylmar NS (Northridge 1994)
- Mexico SCT (1985)
- Japan: Port Island (instrument 1) (Kobe 1995)

Using gap elements, the contact between the heel of the precast beam and the position of the seismic buffer was modeled, defining an opening of 4 cm.

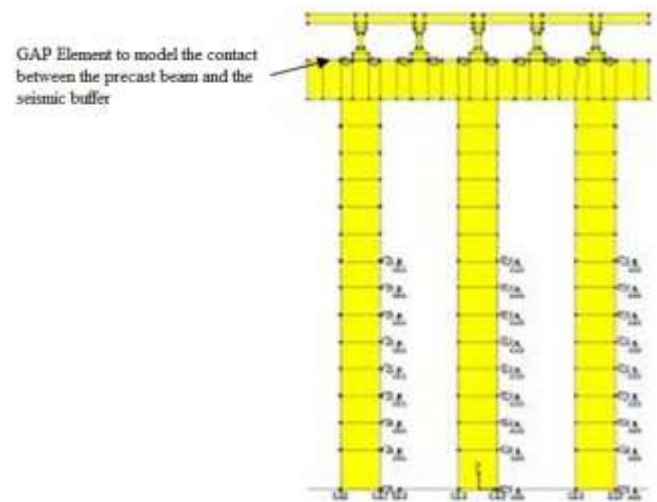


Figure 7. Model for Finite Element of the Bridge. Pile, Cross Beam, Precast beams and the Deck observed.

The following results presented in Table 1 are the outcome of the aforementioned analysis. It shows that the impact forces are far superior to those of a simplified static analysis, such as that described in section "Conventional Design of seismic buffers". This impact forces can surely cause significant damage to the structure. Figure 8 shows the beam at the time of contact with the buffer.

TABLE I. SUMMARY WORKSHEET OF EFFORTS ON SEISMIC BUFFERS

REGISTER	PLACE OF REGISTER	MAXIMUM ACCELERATION (%g)	IMPACT FORCE (Kn)	STRESS AT BUFFER (Kn/m2)	COMMENTS
Caucete	San Juan - RA	0,173 g	1472	9200,0	An important structural damage is estimated, due to the exceeded shear resistance.
Melipilla	Chile	0,686 g	4416	27600,0	
Viña	Chile	0,237 g	2576	16100,0	
El Centro	E.E. U.U.	0,358 g	3680	23000,0	
Sylmar	E.E. U.U.	0,843 g	5299,2	33120,0	
Arleta	E.E. U.U.	0,344 g	4416	27600,0	
Corralito	E.E. U.U.	0,629	2944	18400,0	
México	México	0,171 g	5152	32200,0	
Kobe	Japón	0,310 g	4416	27600,0	

g: acceleration of gravity

Buffer: Seismic resistant buffer

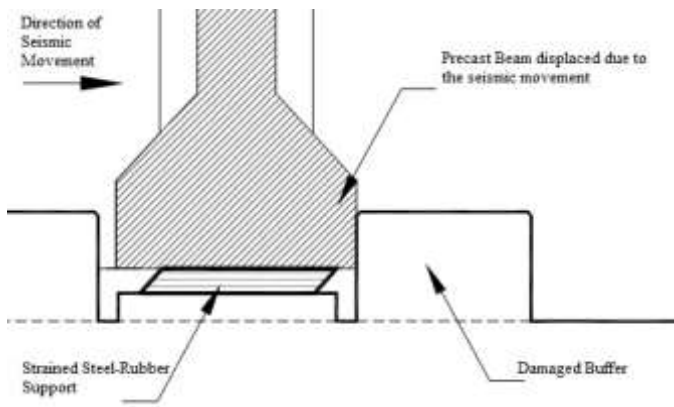


Figure 8. Displacement of the precast beam during the earthquake that can cause damage to the structure

## V. ENERGY-DISSIPATION DEVICES. BRIEF REVIEW.

All vibrating structures dissipate energy due to internal frictions, plastic deformations or a combinations of both. It is a fact that the greater is the dissipation of energy, the smaller is the amplitude of the vibrations. Some structures have a very low damping, about 1% of the critical, and consequently experience great amplitudes of vibration for severe and moderate earthquakes, that is why the techniques that improve dissipation energy are very effective in reducing the amplitudes of vibration. Many systems have been proposed and used to increase the damping of structures at the present, constructed of different materials and devices. These systems can be used in new structures such as in those that need to be repaired.

In last years, important advances have been made for the developing of the concept of passive dissipation and many structures in the world have these devices. In general they are characterized by increasing the dissipation capacity of the structures where they are installed on.

Energy dampers work either by converting kinetic energy to heat or by transferring energy between different modes of vibration. The first method includes devices that operate on the principle of friction due to displacement, metal fluency, phase transformation in metals, strain of viscoelastic solid elements, forcing viscous liquids to flow through holes. The second method is based on adding supplementary oscillators that work as dynamic vibration absorbers.

Below are some of the best known, along with its main characteristics.

- **Metallic Energy-Dampers:** One of the effective mechanisms for dissipation of energy is through the inelastic deformation of metals. The idea of using metal dampers in structures to absorb the energy that earthquakes introduce into them, began with the conceptual and experimental work of Robert Kelly and Skinner.

- **Frictional Dampers:** Friction is an excellent mechanism for energy dissipation that has been used in the automotive industry in automobile brakes, transforming the kinetic energy into heat.

A wide variety of devices have been proposed and developed in Structural Engineering, that differ from each other in the mechanical complexity and the materials in which they slide on. It is important to minimize the stick-slip phenomenon in order to avoid high frequency excitation. It should be ensured that the selected slip material does not significantly alter the coefficient of friction after time. The design idea for these dampers is that they do not slide for moderate earthquakes or wind induced loads.

Usually these devices have an adequate performance and are not affected by the amplitude of the loads, the frequency, or the number of cycles. The design of structures with these devices requires a nonlinear analysis in the time domain.

- **Viscoelastic Dampers:** Metallic and frictional dampers are primarily used to reduce the effects of earthquakes on structures, whereas dampers made of viscoelastic materials can be used to reduce vibrations caused by wind and / or earthquakes.

The behavior of viscoelastic materials under dynamic loads depends on the frequency of the excitation, the strain and the ambient temperature. Recent experiments and analytical studies have demonstrated the effectiveness of viscoelastic dampers used in steel and reinforced concrete structures for a wide range of earthquakes.

- **Viscous Fluids Dampers:** Fluids can be used to dissipate energy and therefore have been applied in numerous designs. One type of these energy dissipation devices consists of a cylindrical piston submerged in a viscoelastic fluid. Viscous fluids dampers have been employed in military and aerospace constructions. Their characteristic is that they have viscous linear response for a wide range of frequencies.
- **Tuned Mass Dampers (TMD):** The concept of Tuned Mass Dampers (TMD) dates from the 40s. It consists of a secondary mass with an element that links it to the primary structure and gives it certain rigidity. The hysteresis cycles that occur increase the damping in the primary structure.

## VI. ENERGY DISSIPATION DEVICE PROPOSED FOR THE BRIDGE

In the Project of the bridge in Sorocayense it was decided to adapt a Metallic Damper. The reason for this selection is its economy, since no special materials or techniques are required

for its manufacture, and can be built at any workshop equipped with a lathe. The material used in this case is Steel SAE 1010. Fig. 9, 10 and 11 show the chosen location of the damper in order to capture the relative displacement between the superstructure and substructure. Pictures 1, 2 and 3 show the device used on the Sorocayense bridge.

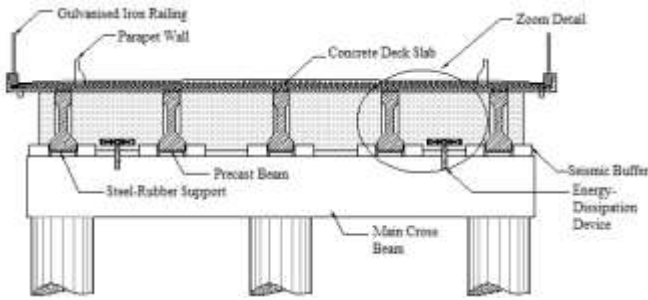


Figure 9. Cross Section of the bridge- Position of the Metallic Damper

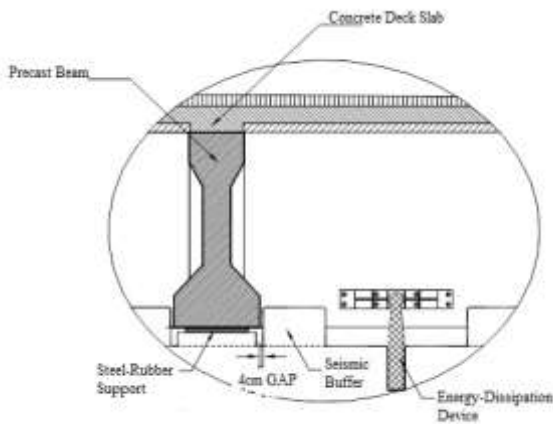


Figure 10. Detail of the support area of precast beam. See 4cm Gap

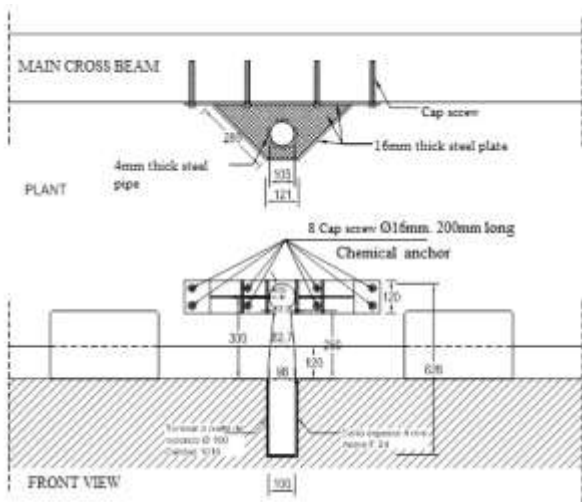


Figure 11. Outline of the proposed damper



Figure 12. View of the damper. Bridge in Sorocayense, San Juan-Argentina



Figure 13. Damper used in the bridge in Sorocayense

## VII. TESTS TO OBTAIN PROPERTIES

A geometric design of the dissipation device was modeled and then it was tested to obtain its constitutive law. The results of these tests were used in the mathematical modeling that was performed to obtain the bridge behavior with the incorporation of these devices. The pictures No. 3 and No. 4 show a prototype damper after being tested.

### VIII. RESULT OF INCORPORATING THE HEATSINKS TO THE BRIDGE

TABLE II. SUMMARY OF THE RELATIVE DISPLACEMENTS BETWEEN THE SUPERSTRUCTURE AND INFRASTRUCTURE BY INCORPORATING THE HEATSINKS

REGISTER	PLACE OF REGISTER	MAXIMUM RELATIVE DISPLACEMENTE (cm)	OBSERVATIONS
Caucete	San Juan - RA	2,4	No impact at the buffer. The displacement is smaller than the 4cm gap.
Melipilla	Chile	3,9	
Viña	Chile	3,0	
El Centro	E.E. U.U.	3,6	Impact at the buffer registered
Sylmar	E.E. U.U.	4,0	
Arlita	E.E. U.U.	3,7	No impact at the buffer. The displacement is smaller than the 4cm gap.
Corralito	E.E. U.U.	3,0	
México	México	3,9	
Kobe	Japón	3,6	

### IX. FINAL COMMENTS

Table 1 and Table 2 summarize the results of this work. In the case of incorporating energy dumpers, impact at the buffer is observed only for the Sylmar register, but with a smaller force. If the bridge were truly exposed to an earthquake like Sylmar's, the alternative is to place a more robust damper.

Construction work has been completed at the Sorocayense bridge. The work was carried out within 18 months.

The cost of incorporating energy dissipation devices is less than 0.8% of the value of the complete structure. It is considered that this amount is insignificant in the face of the good behavior shown in the computer analyzes performed and the laboratory tests of the same.

The design allows replacement of the metallic dampers when they are seriously damaged as they act as fuse elements.

### X. SERVICE LIFE ESTIMATION

TABLE III. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 1									
Número de Ciclos para el 50 % de la Vida Útil									
Deformación específica ε2 (%)									
	1%	2%	3%	4%	5%	6%	7%		
Deform. Espec. ε1 (%)	1%	337	101	49	46	25	20		19
	2%	304	112	51	41	22	18		18
	3%	398	120	69	30	34	28		15
	4%	218	124	54	41	31	18		13
	5%	225	104	58	30	28	16		15
	6%	345	92	58	34	29	13		14
	7%	308	104	59	30	26	19		16

TABLE IV. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME

AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 2									
Número de Ciclos para el 50 % de la Vida Útil									
Deformación específica ε2 (%)									
	1%	2%	3%	4%	5%	6%	7%		
Deform. Espec. ε1 (%)	1%	334	106	57	48	20	21		19
	2%	292	120	53	43	23	18		17
	3%	411	113	67	27	33	25		17
	4%	247	107	60	45	27	19		12
	5%	221	110	58	31	31	16		13
	6%	318	92	62	35	30	13		16
	7%	278	91	56	31	24	19		18

TABLE V. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 3									
Número de Ciclos para el 50 % de la Vida Útil									
Deformación específica ε2 (%)									
	1%	2%	3%	4%	5%	6%	7%		
Deform. Espec. ε1 (%)	1%	359	100	52	49	24	19		20
	2%	296	110	52	49	23	18		17
	3%	368	114	65	30	26	25		15
	4%	241	118	54	42	31	20		14
	5%	224	96	57	27	27	14		13
	6%	364	102	70	34	29	12		15
	7%	311	86	54	30	29	19		17

TABLE VI. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 4									
Número de Ciclos para el 50 % de la Vida Útil									
Deformación específica ε2 (%)									
	1%	2%	3%	4%	5%	6%	7%		
Deform. Espec. ε1 (%)	1%	270	99	49	42	25	20		19
	2%	312	112	54	44	22	18		19
	3%	407	125	59	28	27	24		15
	4%	229	113	60	42	31	19		14
	5%	182	103	53	34	24	15		15
	6%	340	97	59	37	30	13		14
	7%	247	94	49	35	28	18		18

TABLE VII. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 5									
Número de Ciclos para el 50 % de la Vida Útil									
Deformación específica ε2 (%)									
	1%	2%	3%	4%	5%	6%	7%		
Deform. Espec. ε1 (%)	1%	386	112	61	48	22	21		18
	2%	313	122	56	45	22	20		18
	3%	408	113	62	31	32	25		15
	4%	242	128	56	48	27	16		14
	5%	249	105	61	28	26	15		15
	6%	382	102	59	37	29	13		16
	7%	269	101	56	32	26	17		17

TABLE VIII. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE

APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 6								
Número de Ciclos para el 50% de la Vida Útil								
Deformación específica ε2 (%)								
		1%	2%	3%	4%	5%	6%	7%
Deform. Espec. ε1 (%)	1%	305	103	52	45	21	21	20
	2%	291	113	48	36	23	18	17
	3%	375	96	68	32	30	27	16
	4%	254	116	63	39	29	17	13
	5%	211	105	54	34	30	14	13
	6%	320	105	62	38	29	11	15
	7%	271	98	54	29	25	19	15

TABLE IX. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 7								
Número de Ciclos para el 50% de la Vida Útil								
Deformación específica ε2 (%)								
		1%	2%	3%	4%	5%	6%	7%
Deform. Espec. ε1 (%)	1%	357	104	53	41	23	21	19
	2%	321	118	49	46	24	19	17
	3%	360	113	58	32	29	27	18
	4%	240	113	58	42	26	20	11
	5%	194	104	51	35	24	16	15
	6%	354	93	66	35	27	11	16
	7%	288	99	53	31	28	18	17

TABLE X. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 1 a Nº 7								
PROMEDIO del Número de Ciclos para el 50% de la Vida Útil								
Deformación específica ε2 (%)								
		1%	2%	3%	4%	5%	6%	7%
Deform. Espec. ε1 (%)	1%	335	104	53	46	23	20	19
	2%	304	115	52	43	23	18	18
	3%	390	113	64	30	30	26	16
	4%	239	117	58	43	29	18	13
	5%	215	104	56	31	27	15	14
	6%	346	98	62	36	29	12	15
	7%	282	96	54	31	27	18	17

TABLE XI. STRAIN E1 IS APPLIED UNTIL 50% OF SERVICE LIFE IS OVERCOME AND THEN E2 IS APPLIED COUNTING THE NUMBER OF CYCLES. RESULTS CAN BE APPRECIATED IN THE TABLE.

SERIE DE ENSAYOS Nº 1 a Nº 7								
VIDA ÚTIL								
Deformación específica ε2 (%)								
		1%	2%	3%	4%	5%	6%	7%
Deform. Espec. ε1 (%)	1%	0.995	0.967	0.963	1.139	0.952	1.068	1.225
	2%	0.920	1.030	0.962	1.105	0.970	1.032	1.161
	3%	1.069	0.998	1.022	0.026	1.079	1.262	1.076
	4%	0.834	0.987	1.001	1.097	1.084	1.024	1.002
	5%	0.808	0.957	0.964	0.924	1.072	0.927	1.030
	6%	0.994	0.924	1.055	0.976	1.079	0.841	1.099
	7%	0.907	0.926	0.986	0.935	1.039	1.024	1.113

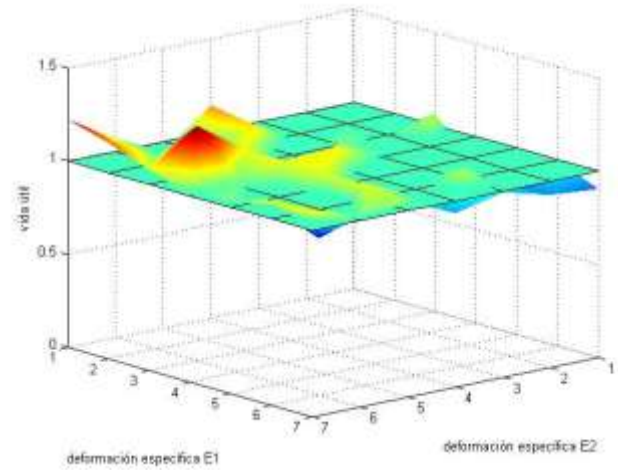


Figure 14. Service Life

PROPOSED EXPRESION TO CALCULATE FATIGUE DAMAGE

After processing test results with an optimization function of Matlab, which minimizes the quadratic error between the proposed expression and the test results. The function that best represents the estimation of the service life is the following:

$$N = 574 \varepsilon^{-\left(1,58 + \frac{\varepsilon}{2,5\varepsilon_r}\right)}$$

$\varepsilon_r$  : Rupture strain obtained from an axial traction test.

$\varepsilon$  : Specific strain for a cycle

N: Number of cycles until rupture

The expression contemplates the fact of having cycles of different amplitude for the same external excitation. This function with the Miner's Rule together, allows the estimation of damage that a cycle produces to the specific strain "ε".

This expression is obtained from a combination of different specific strain tests. For any excitation, such as an earthquake, complete cycles must be counted using the Miner rule (Palgrem-Miner et al, 1945) for which there is a routine developed in Matlab to perform this calculation.



Figure 15. Traction test of a steel bar



Figure 16. Fatigue damage and rupture due to fatigue

## XI. CONCLUSIONS

- The conventional static design is insufficient to estimate the impact forces between the beam and the seismic buffer.
- The incorporation of Energy Sinks substantially increases the safety of the analyzed bridge at a very reasonable cost.
- The displacement and impact force are controlled in one of the most critical elements as is the lower part of the support of the precast beam.

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