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Base Isolation of the Puente Industrial de Biobio: the Control of Performance of Lead Rubber Bearings through an Advanced Quality System

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ABSTRACT

The 6 km toll road "Via Puente Industrial" represents one of the major public infrastruc-ture under development in Chile, linking the Municipality of Hualpén to San Pedro de la Paz. The total investment of the project, about 160 mil-lion dollars, includes the construc-tion of the main section "Puente Industrial", that is the fourth viaduct over the Biobio Riv-er in the Conception region, which also incorporates various complementary works at in-tersections at different levels and railway overpass. The bridge will have a total length of 2.5 km, 2 abutments and 55 piers. Due to the high seismicity of the site, the structure will be seismically isolated with Lead Rubber Bearings (LRB). For this project Freyssinet de-signed, produced and finally tested a total of 784 ISOSISM® LRB. The high number of devices to produce, together with the very demanding performance and testing require-ments, asking to test full scale all the 784 isolators with a maximum variation of 10% on the average performance, represented a real challenge. Freyssinet successfully achieved it, going even beyond the requirement providing an overall variation close to half of the re-quired value, thanks to strict quality and production processes, allowing to control all the steps from characterization of incoming materials, up to vulcanization and test of the iso-lators. This paper aims at analyzing the performance characteristics of the lead rubber bearings provided for this important project with special focus on the quality control pro-cesses that Freyssinet carries on during the full production cycle. This was a mandatory gate to guarantee the performances beyond the requirements of the applicable standard..

Keywords: Seismic Isolation, Lead Rubber Bearings, Full-Scale Testing, Quality Process.

INTRODUCTION

General overview of the project

The toll road "Via Puente Industrial" represents one of the key infrastructure pro-jects un-der development in Chile. The conception of the project dates back to the 70s, being considered since then as a public infrastructure work necessary for the regional urban development.

In the recent years, the province of Concepción has increased its levels of vehicular congestion due to the flow increase of trucks and private cars traveling between the municipality of Talcahuano, Hualpén, Concepción and San Pedro de la Paz and to the neigh-boring ports. Given this, the local and government authorities made the decision to im-prove the road infrastructure to mitigate traffic, improve circulation to industrial areas, de-congest Route 160 and Av. Pedro Aguirre Cerda, ensure logistic routes in the region and reduce the risk of accidents.

The total investment of the project is about 160 million dollars and includes the construction of "Puente Industrial", the fourth viaduct over the Biobio River in the Concepción region of the country, and it incorporates various complementary works at different levels and railway overpass.

Figure 1 shows the geographical area interested by the economic investment, with indication of the new Puente Industrial, under construction at the time of writing this paper.

Figure 1. Map view of Chile's region interested by the infrastructure investment.

Figure 2. Rendering of Puente Industrial.

Characteristics of Puente Industrial

Puente Industrial is a very long infrastructure that connects both banks of the Biobio River and crosses the Los Batros estuary too. It has a total length of 2.520 m, of which 2.094 m straight and 427 m curved, joining the municipalities of San Pedro de la Paz and Hualpén. A rendering of the bridge is shown in Figure 2.

The superstructure is made up of 56 simply supported decks with a span of 45 m each. The infrastructure consists of 2 abutments and 55 piers, each one composed of deep foundations, specifically 4 pier-piles with 2.5 m diameter.

The bridge is located in a high seismic area, therefore it will be protected from earthquake thanks to the seismic isolation approach. Seismic isolation is in fact a response modification technique that reduces the effects of earthquakes on bridges and other structures.

The bridge will be protected against earthquake thanks to Freyssinet's ISOSISM® anti-seismic devices. The following sections will provide an overview of the technical performances of the isolators, the production/quality process and the prototype and quality control tests performed at ISOLAB®, the advanced dynamic testing facility of Freyssinet Group

THE ISOLATION SYSTEM

For the isolation system of Puente Industrial, the use of anti-seismic devices type Lead Rubber Bearings (LRB) was envisaged, in order to combine horizontal flexibility, to re-duces seismic forces in the substructures, and energy dissipation capacity, to limit relative displacements between the superstructure above the isolators and the substructure below.

For this project, Freyssinet designed, produced and tested 784 ISOSISM® LRB, of which 14 (type LRB-N 800x246.5) for the abutments and 770 (type LRB-N 650x204) for the piers, due to different performance requests.

The devices are able to guarantee high level of dissipation (up to 25% equivalent vis-cous damping) for the expected total design earthquake and displacement capacity up to more than 55 cm.

Table 1 gives a summary of the main characteristics of the isolators.

Table 1. Characteristics and performances of ISOSISM® LRB.

Parameter		**ISOSISM® LRB-N 800x246.5**	**ISOSISM® LRB-N 650x204**
Location		Abutment	Piers
Quantity		14	770
Rubber diameter	D_r [mm]	800	650
Total rubber height	T_r [mm]	246.5	204
Total height	T [mm]	460	370
External plate width/length	B [mm]	850	700
Weight	W [kg]	1152	609
Dead Load	D [kN]	1007	1007
Live Load	L [kN]	695	695
Service Load	N_{SLS} [kN]	1701	1701
Max Seismic Load	P_{max} [kN]	550	550
Total Design Displacement	TDD [mm]	+/-286	+/-229
Maximum displacement	d_{max} [mm]	+/-555	+/-400
Effective stiffness at TDD	K_{eff}(TDD) [kN/mm]	2.24	1.97
Effective damping at TDD	ξ_{eff}(TDD) [-]	23%	25%
Energy dissipated at TDD	EDC(TDD) [kNm]	265	163

As previously anticipated, the implementation of the seismic isolation system by means of ISOSISM® LRBs has determined an important decoupling of the superstructure motion (i.e. deck) from that of the substructure (i.e. piers and foundations). In particular, the increase in the vibration period of the bridge to about 2 sec was achieved thanks to the lateral flexibility of the elastomeric component, while the dissipative capacity of the lead core was exploited to reduce the relative displacements of the devices but also the stresses transmitted in the substructure. The combined effect of high horizontal flexibility and energy dissipation has made it possible to optimize the design of piers and foundation piles, reducing structural sections as well as longitudinal and transversal steel reinforcement.

Figure3 below shows a 3D view of ISOSISM® LRB isolator.

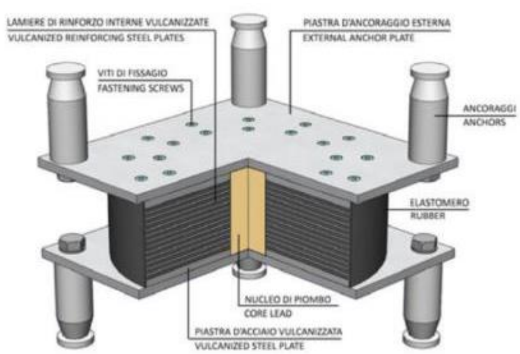

Figure 3. 3D view of ISOSISM® LRB.

QUALITY PROCESS FOR ELASTOMERIC ISOLATORS

The LRBs (Lead Rubber Bearings) supplied for this project are made of alternating layers of a natural rubber compound and steel sheets bonded together by vulcanization. A central lead core completes the device providing the desired amount of energy dissipation.

Achieving a maximum variation of +/-10% on the average effective stiffness rep-resented a real challenge for the production.

The starting point to succeed, is even before the production begins, by checking the incoming raw materials. In other words, only high-quality raw materials, rubber, lead and steel, can provide a high-quality vulcanized device.

On this type of devices, performances are influenced by two main contributions: the cured rubber and the internal lead core. Lead core behavior is straight forward and not examined in this article while the cured rubber behavior is naturally subjected to wider production variability.

The production of such a high number of devices required multiple rubber lots, knowing that a lot is defined as a sequence of continuously manufactured batches while a batch consists in an individual mix or blend of mixes of the same composition. Moreover, to meet the client delivery schedule on site, the production was split in multiple sessions over several months.

To respect the project specifications and ensure a tight tolerance on the full-scale testing, every lot of compound was monitored at the source (milling factory) with different tests such as rheometric curves, physical-mechanical characterization tests, ozone and aging tests etc.

Once each rubber lot was certified to meet the project and Freyssinet internal specifications (which are more demanding to ensure the highest quality standards), the material was sent to Freyssinet production site where a new set of tests were performed on each batch. This allowed the production department to characterize each batch through this double check, in order to guarantee an uniform performance throughout all the mass production.

The manufacturing process of an elastomeric isolator involves the separate treatment of two different materials: rubber and steel. Steel parts quality controls aim to check the correct application of the bonding agent. Although these steps are fundamental to the final outcome and ultimate resistance of the devices, they are not directly responsible for constancy of performance in term of stiffness and energy dissipated.

Finally, rubber and steel parts are bonded together through vulcanization which consists in applying heat and pressure to the assembled elements in a mold for a determined period.

Vulcanization is one of the, if not the, most important steps of the production process, especially when such tight tolerance on production variability is required. Temperature and vulcanization timing are highly dependent on the rubber type and device geometry however this have been mastered by Freyssinet through its experience in thousands of elastomeric devices supplied in hundreds of projects worldwide. The definition of these parameters is hence the key for the success of this last but crucial step of the production. In addition to a good design of this phase, to ensure the same result on each device, vulcanization temperature was monitored on each device by means of a thermocouple inserted in the mold, to immediately detect and manage any unexpected difference in the vulcanization process.

TESTING OF THE ISOLATORS

Following the strict quality control described in the previous section, the isolators have been tested full-scale to check their performances.

Before starting the production, two units of each size have been subjected to a Prototype Test protocol in accordance with AASHTO "Guide Specification for Seismic Isolation Design". This very severe protocol aims at characterizing the tested isolators in order to check the performances in term of effective stiffness Keff and energy dissipation (EDC), comparing them with the design values and to prove a stable behavior of the Lead Rubber isolators, both in term of performances and bonding. The test protocol for the two types of isolators supplied for the new Puente Industrial are shown in Table 2.

The prototype tests were performed in November 2021 at ISOLAB, the Freyssinet dynamic testing facility in Montebello della Battaglia, Pavia, Italy. ISOLAB is a laboratory that Freyssinet developed specifically for dynamic tests of seismic protection devices where the products are tested according to the main international standards and according to the highest calibration requirements like ASTM E4 and ISO 7500 as well as quality system. The laboratory, with its 30 years of experience in the field, in addition to prototype and production quality test, is also dedicated to the R&D that Freyssinet group constantly carries on to be always in first line to provide innovative reliable solutions for the seismic protection of structures and infrastructures.

The prototype tests of the ISOSISM® LRB-N 800x246.5 to be installed on the abutments were performed on the ISOLAB's 70 MN testing machine able to test devices up to 70.000 kN static vertical load and up to 20.000 kN static horizontal load. The testing bench can also develop a vertical dynamic force up to 18.000 kN and a horizontal dynamic force up to 5.000 kN with 1000 mm maximum stroke and 1000 mm/s peak velocity. Figure 4b shows the 70 MN machine.

The prototype tests of the ISOSISM® LRB-N 650x204 to be installed on the piers were tested on the ISOLAB's 50 MN testing machine able to test isolators or bearings up to 50.000 kN of vertical load and up to 20.000 kN of horizontal load. Figure 4b shows the 50 MN machine.

The resulting force-displacement loops from where it is possible to determine the effective stiffness (K_{eff}) and the energy dissipated (EDC) are shown in Figure 5. The difference of the resulting effective stiffness with the corresponding design values is very limited being it less than 2%.

The mass production is still ongoing at the moment of writing of this paper. Anyway, the full quantity for the abutments and more than 50% of the isolators for the piers were produced and successfully tested.

AASHTO Guide specification for seismic isolation design requires for the effective stiffness to not exceed the 20% of variation with respect to the design value for any device tested and that the average of all the devices does not exceed the 10% of the design value. The high level of quality process implemented allowed to achieve an excellent result in term of constancy of performances, with a variation on the single device not greater than 15% and an average value not greater than 6%. Figure 6 shows the results in term of stiffness obtained on the full number of devices tested, highlighting the importance of a strict quality control along the production phases

Figure 4. Test benches at ISOLAB: a) 70 MN; b) 50 MN

Table 2. Prototype test protocol for ISOSISM® LRB 650x204

test #	test name	label	dof	despl. [mm]	forma de carga	max vel [mm/s]	freq [Hz]	carga vert [kN]	ciclos [#]
1	Térmico § GSID 13.2.2.1	TH	long	±40	triangular	-	-	1007	3
2	Viento y frenado: ensayo pre-sísmico § GSID 13.2.2.2	WB1	long	±30	sine	-	-	1007	20
3	Sísmico § GSID 13.2.2.3	S1	long	±222	sine	10	0.007	1007	3
4	Sísmico § GSID 13.2.2.3	S2	long	±56	sine	10	0.029	1007	3
5	Sísmico § GSID 13.2.2.3	S3	long	±111	sine	10	0.014	1007	3
6	Sísmico § GSID 13.2.2.3	S4	long	±167	sine	10	0.010	1007	3
7	Sísmico § GSID 13.2.2.3	S5	long	±222	sine	10	0.007	1007	3
8	Sísmico § GSID 13.2.2.3	S6	long	±278	sine	10	0.006	1007	3
9	Viento y frenado: ensayo post-sísmico § GSID 13.2.2.4	WB2	long	±30	sine	-	-	1007	3
10	Verificación de desempeño sísmico § GSID 13.2.2.5	SP	long	±222	sine	10	0.007	1007	3
11	Estabilidad § GSID 13.2.2.6	ST1	long	±333	triangular	2	0.002	2500	1
12	Estabilidad § GSID 13.2.2.6	ST2	long	±333	triangular	2	0.002	260*	1

CONCLUSION

It is well known that design and erection of big structures requires high level of expertise and competences, as well as manufacturing level from design stage to production and installation.

The paper presented an interesting case study where Freyssinet designed, produced and finally tested of a total of 784 ISOSISM® LRB, of which 14 isolators for the abutments (type ISOSISM® LRB-N 800x246.5) and n° 770 for the piers (type ISOSISM® LRB-N 650x204). The high number of devices to produce, together with the very demanding performance and testing requirements, asking to test full scale all the 784 isolators, represent-ed a real challenge. Freyssinet successfully achieved it, going even beyond the requirements providing an overall variation close to half of the required value. This was possible only because of strict quality and production processes together acting to keep under control all the steps from characterization of incoming material up to the vulcanization of the full isolator and finally to the testing of the full mass production. In the paper, the performance characteristics of the lead rubber bearings have been presented together with the main test results. Special focus to the quality process has been given, that allowed to finally get the exceptional results here presented.

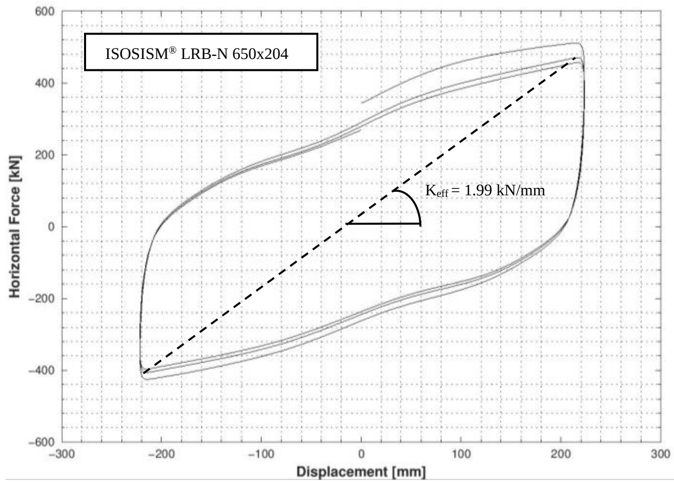

Figure 5. Force-Displacement loop for ISOSISM® LRB-N 650x204

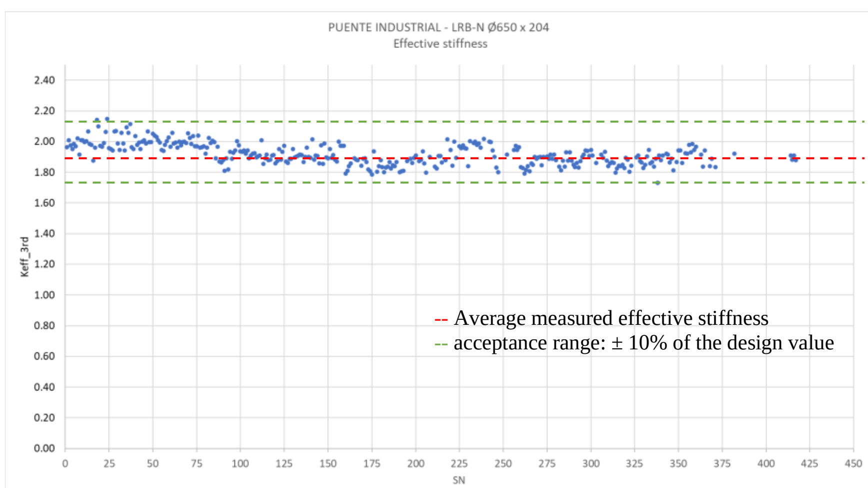

Figure 6. Effective stiffness from Quality Control tests for ISOSISM® LRB-N 650x204

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