Load test to collapse on the masonry arch bridge at Urnieta

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ABSTRACT: This paper presents the previous activities, the development, and the full test on a masonry arch bridge located in Urnieta, Basque Country, Spain. The first task was the estimation of the collapse load by means of several tools developed to analyze this type of structures (commercial and educational software), starting off with real initial data like the geometry, and hypothetical data like material properties (crushing strength masonry), height and nature of the backfill, etc.

Afterwards, a more detailed inspection led to a more refined value of the ultimate load in order to define the auxiliary structure and equipment (anchorages, reaction beam, hydraulic jacks, etc.), as well as the instruments and data recording devices.

Finally, this paper describes the load test process and the results. A local failure was achieved at the sandstone voussoirs of the barrel, without a clear pattern of movements.

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1 INTRODUCTION

The design and construction of the new *Urumea Highway* (an alternative access to the city of San Sebastián) forced the inevitable demolition of a masonry arch bridge near Urnieta, Guipúzcoa, Basque Country, Spain. This bridge remained out of use during the last 50 years, but took part of the old Plazaola Railway, completed in 1912. Rails and ballast were not present on the bridge after dismantling the line by the mid 1950's.

The local government (Diputación Foral of Gipuzkoa), proposed a research program associated to the demolition process, thought to learn, to understand such noble structures from the experience of this test. FHECOR Consultant Engineers signed the agreement to carry out such work, preparing firstly a complete protocol of the theoretical and experimental activities related to this case study.

Before the load test, a progressive anamnesis and analysis job was made in order to evaluate, in a "realistic" manner, the geometry, properties of materials, different load-test procedures, ultimate load and previsible failure mode.

After the load test, a remarkable activity —autopsia— was carried out to characterize the real internal geometry and material distribution and arrangement of structural elements. Additionally, some cores and samples were taken in order to afford a deeper material properties of masonry. This would enable the possibility of re-evaluating the structure to understand the gap between theoretical estimations of ultimate load and experimental results.

2 OBJECTIVES OF THE INVESTIGATION PLAN

- To measure the real margin of safety factor of the structure in relation with current load patterns of standards (Spanish code IAPF-06).
- To contrast the real failure mode with the theoretical estimations.

- To describe the evolution of damages of the bridge with incremental loads.
- To know the internal morphology of the structure to compare the results of the initial analysis based on the hypotheses with the analysis with real data.

3 DESCRIPTION OF THE STRUCTURE

3.1 Location

Figure 1 shows the geographical location of the bridge.

Figure 1. Location of the bridge

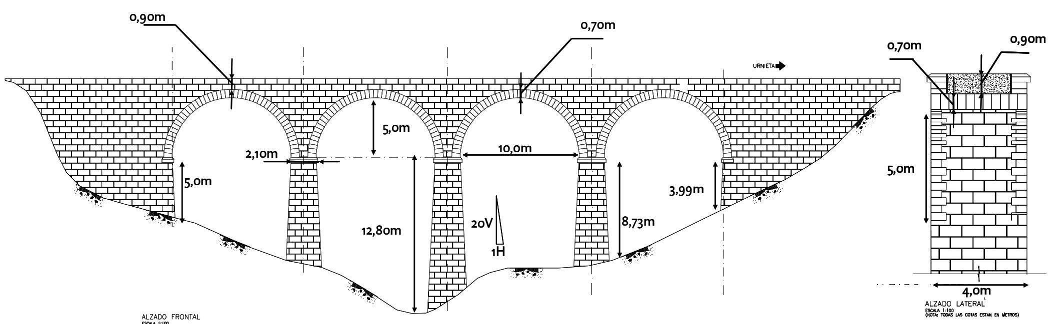

Figure 2: Geometrical configuration of the bridge

3.2 Geometrical data and materials

The bridge had four arches 10 m span made on sandstone of good quality and excellent execution. Piles, spandrel walls and abutments were made on limestone. Figure 2 summarizes the dimensions of these elements, and table 1 shows the typical ratios.

Table 1 : Geometrical data and principal ratios.

		Dimension M	Ratios	
Span	L	10	d/L	≈ 1/14
Rise	r	5	r/L	1/2
Thickness of arch barrel	d	0.70	t_s/L	≈ 1/4
Depth of fill at crown	h	0.90		
Height of pier	h_p	8.75 – 12.60		
Thickness of a top of piers	t_s	2.10		
Bridge widh	B	4.0		

4 METHODOLOGY

The study was divided into several stages: initial estimation of the ultimate load; deeper analysis of the “real” geometry and configuration of the bridge (height of the rigid backfill in particular); re-analysis of the structure to refine the “reasonable likely” load-bearing capacity; and design of the details of the load-applying system, instrumentation, techniques of de-construction and so on.

4.1 Collapse load estimation

The initial structural analysis consisted on a parametric study made with the program RING 1.5. The resulting load-bearing capacity was between 3,500 and 7,500kN, as a function of the backfill’s height. At this moment, the height of the backfill was assumed to be $r/2 + d$, that is, about 3.20m. Figures 3 and 4 summarize the obtained results after a parametric study.

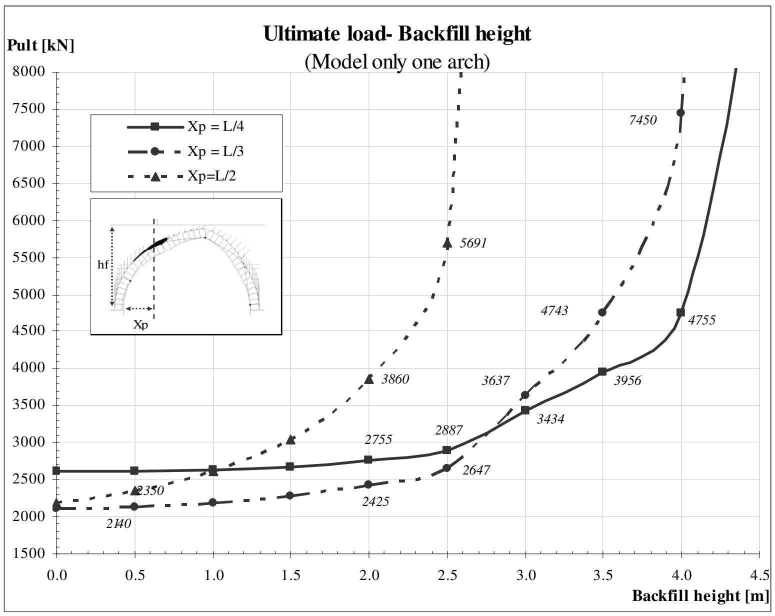

Figure 3: Estimation of ultimate load of a single arch as a function of the backfill’s height

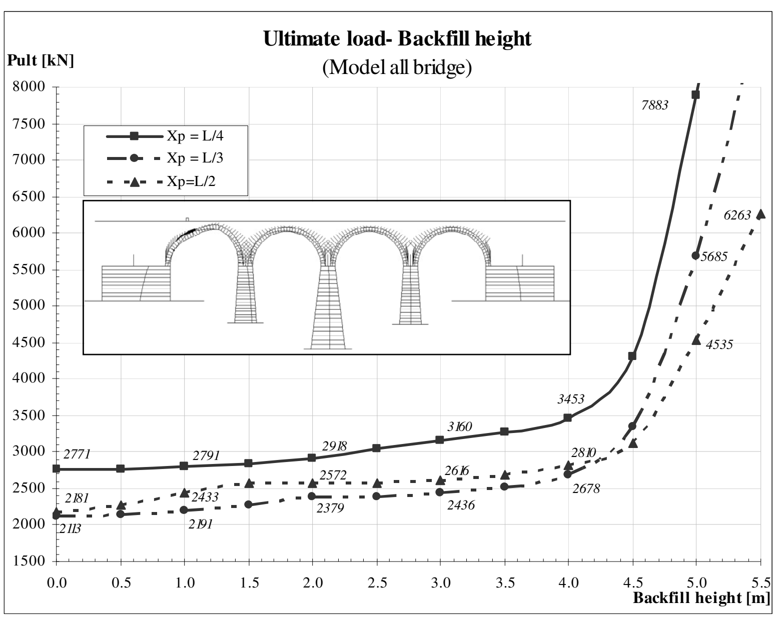

Figure 4: Estimation of the ultimate load considering the whole structure

4.2 Special inspection and refinemet of the load-bearing prediction

Due to operational reasons, and taking into account that a multi-span failure seemed to be unlikely, it was decided to test the arch adjacent to the abutment (the first from the right side in figure 2. Since the load-bearing capacity of such type of structures is strongly dependant on the height and nature of the backfill, a recognition campaign of these materials was developed on the opposite side of the bridge (on the left side, according to figure 2). Additionally, geotechnical tests were made to determine the resistance of the granular fill to the penetration and to establish their different levels of superficial compaction (figure 5).

Figure 5: Removal of fill and geotechnical studies

Beneath a layer of clay and limestone rubber, a sound concrete made up on cement and lime was observed. This inspection detected a higher top level of the backfill (up to 5.70m), slightly over the arches. As mentioned above, the highest load-bearing capacity of the structure, provided that the load were applied exactly at the extrados of the barrel, gave a theoretical value of P_{ult} equivalent to 7,000kN. The foreseen failure mode was a typical four-hinge mono-arch mechanism. The position of the load leading to the minimal collapse energy was $L/3$, as shown in figures 6 and 7.

In order to ensure such a circumstance (load applied at the extrados), a concrete prism was conceived, isolated from spandrel walls and from the rest of the fill material.

4.3 Test arrangement

Several alternative solutions were analyzed and compared. Due to both economical and practical reasons the general arrangement summarized in figures 6 and 7 was designed: a set of longitudinal and transverse powerful steel girders, reacting against the deck through four hydraulic jacks, 10,000 kN capacity each, with the help of deep ground bar anchors. The total weight of materials arranged on the deck was 17 tons.

4.4 Equipment and instrumentation

To register displacements for each load increment, 10 wire LVDTs (5 on one arch face and 5 along the longitudinal axis of the barrel) were installed. Additonally, a topographic control of the displacements was also made on the same points of the boquilla, as shown in figure 8.

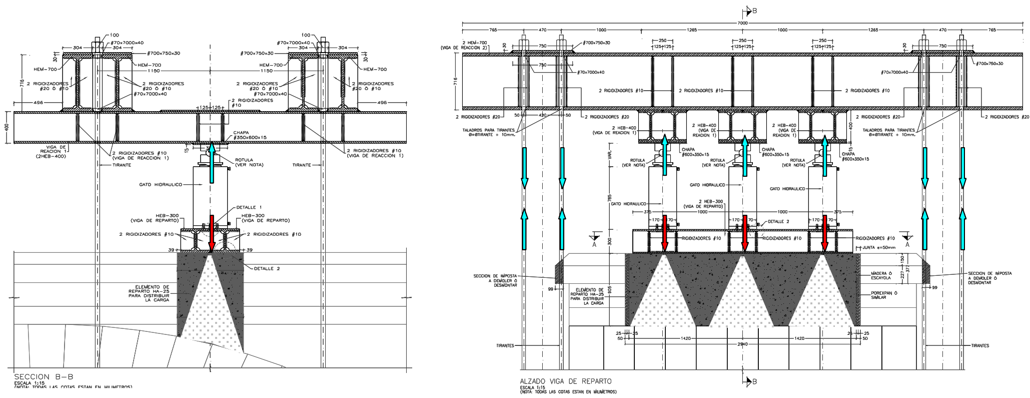

Figure 6: Load system

Figure 7: Location of the points of control of movements

5 LOAD TEST

The *in situ* test took place finally on May 16th, 2007. A first set of zero movements and loads was firstly completed.

The load steps were defined in increments of 500 kN, registering loads, displacements and eventual damages after completion of each step.

The test itself lasted about four hours. The measured maximum load applied by the jacks was 7,467kN. The detected failure mode was the simultaneous crushing of the voussoirs of the barrel and arch face, immediately beneath the applied load. No hinge or relevant movements were detected. Just at the end, during the last load step, a separation of spandrel walls and some cracks at voussoirs or opening of their joints were detected.

6 ANALYSIS OF RESULTS

6.1 Failure mode and movements of the barrel

The highest movement is about 8.5mm (average value at failure beneath the line of load). The observed tendency was a slight downwards movement of crown zones and lateral displacements at springs.

Figure 8: Left: general arrangement during the test. Right: failure mode.

6.2 Description of damages observed during the test

Before the applied load by jacks reached 6,500kN, no relevant damages were detected at piers, abutment, spandrel walls, boquillas and barrel. Only at this load level a crack between arch face and spandrel wall was detected at the position of the applied load (*L*/3).

When the applied load reached 7,500kN, a progressive crushing of the barrel, as well as a separation of the spandrel wall and the barrel was detected. The limestone voussoirs collapsed within an area that extended from the point beneath the load line and its symmetric respect to the center of the arch (see figure 8).

6.3 Ultimate load and "safety coefficient"

It becomes evident that the bridge had a great safety margin. Although the purpose is quite different and the load distribution is not directly comparable, the applied load is, roughly, seven times greater than the Spanish "official" load pattern, that is, four point loads of 250kN, separated 1,6 m, plus a uniformly distributed load of 80kN/m.

6.4 Check on crushing

The previous comment on the "safety coefficient" must also take into account that the foreseen failure mode was not crushing of material, but the formation of a four-hinge mechanism. Some complementary tests are being carried out at the moment of preparing this paper, both on blocks and on wall samples, in order to compare them with the theoretical estimations.

7 RECOGNITION DURING DEMOLITION

Figure 10 shows a "physical" transverse bridge section during the de-construction works of the bridge. The aforementioned sort of concrete found as backfill can be easily detected underneath a layer of clay and gravel. The height of this sound backfill is equivalent to 80% of the arch raise.

Spandrel walls showed a steped section, being its width 0.8m at the top and increasing 1H:5V.

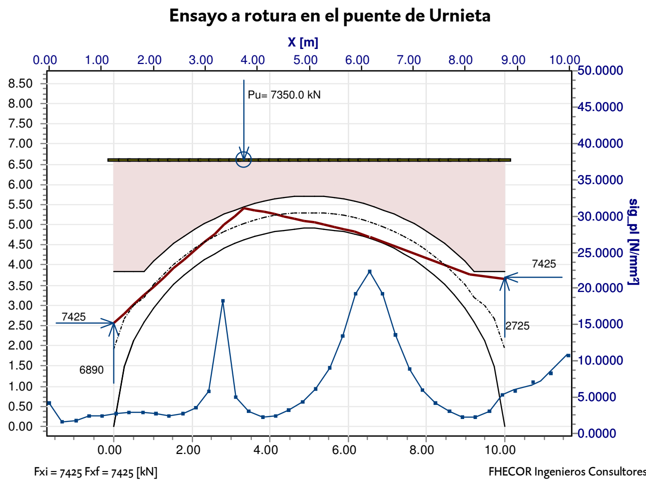

Figure 9: Estimation of the stress level of the barrel (program VLASTA)

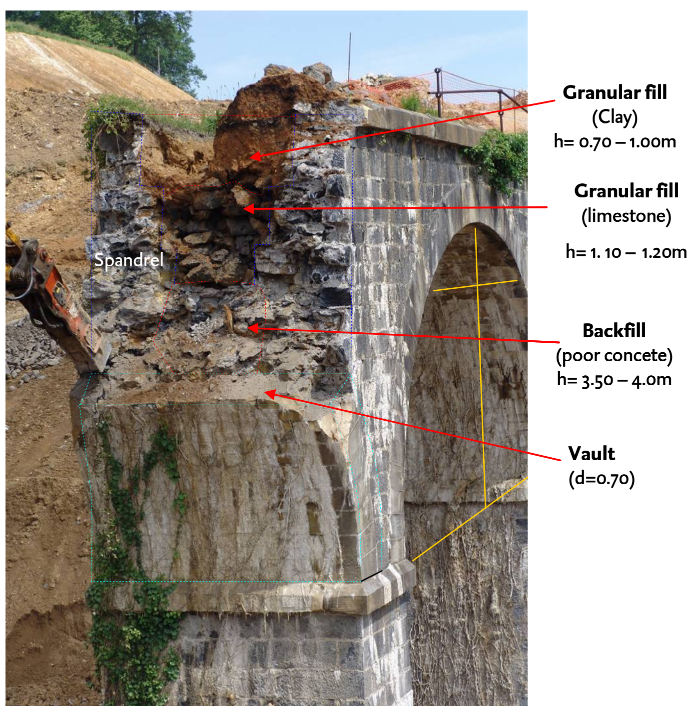

Figure 10: View of the internal parts of the bridge.

8 CONCLUSIONS

Although the estimated load-bearing capacity of the bridge was around the theoretically estimated value, the failure mode was different: four-hinge mechanism instead of crushing of material. This conclusion is strongly influenced by the crucial role played by the backfill. So, while classical methods of analysis trend to disregard the strength of masonry because the formation of mechanisms is proven to take place first, for reduced backfill contribution, this situation may become unrealistic when dealing with sound and high backfill, as it is usually the case of railway masonry bridges and it becomes necessary to assess their bearing capacity in a more precise way.

The movements of arches, piers and spandrel wall were rather negligible, even at very high load ratios. In this regard, the contribution of such stiff and healthy spandrel walls as the Urnieta bridge showed may be determinant, especially in this rather narrow bridge.

The knowledge of the internal geometry and nature of the structure is essential to assess its bearing capacity, and should be thereof a matter or routine praxis.

The authors wish to encourage the realization of such type of tests, whenever possible and within the love and respect to such masterpieces of engineering.

9 ACKNOWLEDGMENTS

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