Evaluation of the Statical Decay of Masonry Structures: Methodology and Practice

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Abstract - A procedure of experimental and numerical analysis is described for the determination of the load carrying capacity of masonry walls in existing buildings. The following phases of the procedure are considered:

1) Historical investigation
2) Determination of geometrical characteristics
3) Geotechnical investigation
4) In-situ measurements of characteristics of material and structure
5) Sampling and laboratory testing
6) Preliminary elastic analysis of the structure

1. INTRODUCTION

A comprehensive program of intervention for restoration and recovery of old buildings and monuments of historical centers is being developed in Italy in the last years. Social, cultural, economic and technological problems arise and have to be solved in dealing with the complex, multi-phaceted subject of restoration. We deliberately focus attention on the structural aspects of the problem. The choice of proper technological solutions for restoration of buildings is substantially influenced by the statical behaviour of the construction and by the characteristics of materials.

Load bearing stone and brickwork formed the structure of all buildings and monuments up to the beginning of the XIX century. For the restoration of a building the determination of deformability characteristics and strength limit is needed. Knowledge of the former parameters enables the designer to appraise the structure response to loads. Information on the strength limits of materials makes it possible to evaluate the safety margine of the structure.

In the present paper a procedure of experimental and numerical analysis is outlined for the determination of the load carrying capacity of a masonry structure. We describe an application of the procedure with reference to the viaduct of Porta S.Giacomo (St.James Gate) in Bergamo (1).

This construction was chosen by the "Comune of Bergamo" as a sample structure for the acquisition of data and for testing suitable techniques

(1) The team-work carried out on this occasion has been presented in full detail by the authors at a course on restoration of buildings and monuments held at ISMES in October 1980.

for maintenance and restoration of the town's historical buildings. Particular emphasis is given in the paper to the application of non-destructive tests as sonic and flat jack tests.

Fig. 1 - The Porta S. Giacomo Viaduct in Bergamo

2. HISTORICAL INVESTIGATION

A knowledge of past history of the construction may provide an insight into possible causes of self stresses such as settlements and into the origin of stress state changes such as modification of geometry and dead loads.

The Porta S. Giacomo Viaduct, built around 1592, had originally sand and limestone piers (9 to 11 m high, with a cross section of 2.00 - 3.00 m x 2.50 - 3.00 m), while the deck was a timber-work. In 1780 the deck was replaced with the existing stone arches (Fig. 1). Piers were consequently subjected to a new stress distribution because of the increase in structural dead loads. No documents or drawings of the original construction have been found, but only some old prints (Fig. 2).

In general the historical information is scarce and hence hardly meaningful, particularly for old structures.

3. DETERMINATION OF GEOMETRICAL CHARACTERISTICS

This is an essential step of the procedure, intended to supply a knowledge of the structural behaviour of a construction.

Horizontal and vertical section have to be drawn through the use of traditional survey and measurement methods (Fig. 3).

Fig. 2 - A 1617 print showing the original construction

Inspections have to be made if the geometry of the foundation is unknown. In the case of the Porta S. Giacomo Viaduct they, like the piers, are made of sandstone and reach a depth variable from 1.55 m to 2.50 m. Inspections have also been performed inside the vaults which resulted to have an effective thickness of 35 cm; the remainder being a filling material with a unit weight of 17.0 kN/m^3.

A photographic campaign can be useful, particularly when important cracks or relative displacements take place, possibly together with alterations of structural elements and materials. In this case also a number of meaningful measurements is needed concerning the deformed configuration of walls and other load bearing elements, and distances and relative displacements with time between crack edges. When movements are expected to take place in the future, the setting-up of a long-term monitoring system is advisable using inductive transducers and strain gauges [1]. Recording of all measurements on tape or paper is possible in view of subsequent processing such as plotting of meaningful quantities as functions of time. In the case of the Viaduct in point only slight cracks at the intrados of the first and last arches have been noticed; however no measurements of displacements were carried out.

A photogrammetric survey has been performed (Fig. 4); this will be also useful to assess possible absolute and relative displacements which may occur in the future. The use of photogrammetry has become more and more

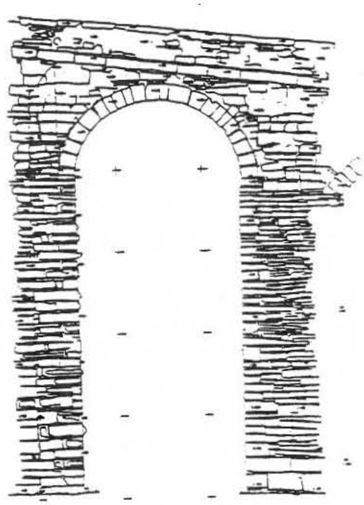

Fig. 3 - Photogrammetry of an archade of the Viaduct

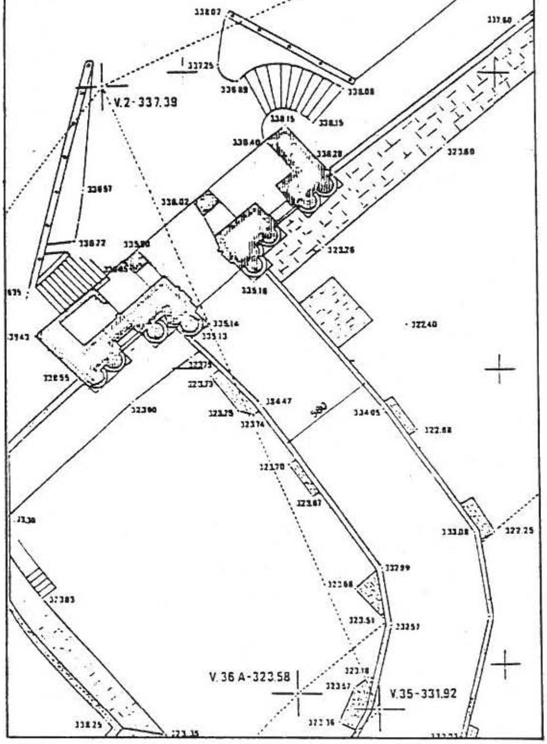

Fig. 4 - Geometrical survey of the Viaduct

frequent for architectural survey in the last decades [2].

3.1 GEOPHYSICAL METHODS

Non-destructive tests able to determine the physical properties of materials can be based on geophysical measurement techniques. These rest on the correlation between the propagation velocity of acoustic waves within a material and its mechanical properties (Young's modulus, Poisson's ratio). Geophysical methods can be classified as active and passive. The former involve an acoustic excitation of the structure to be investigated. The latter are based on the principle that cracks developing in the structure are always associated with the emission of elastic waves, which can be picked up at the surface: having at disposal a sufficient number of picking devices the emission point can be identified [3].

Stone and brick masonry are non-homogeneous, anysotropic materials. Geophysical methods are better used in this case with the aim of characterizing materials in terms of signal propagation velocity and modes, rather than in terms of dynamic modulus of elasticity [4] [5] [6]. Direct velocity measurement tests of active type were performed on two piers of the Viaduct, on two sections for each pier, at 0.4 and 1.3 m from the base. Tests were carried out in two orthogonal directions parallel to the pillar section and in diagonal direction. The components of max amplitude of the signals received had frequency about 5.000 Hz. These tests showed that the piers contained in their outside parts sandstone blocks (2.500 - 3.000 m/s) and coesionless materials ($\leq$ 2.000 m/s) inside. In particular sonic velocity diagrams revealed a discontinuity in one of the piers, due to the presence of an additional structural part built up subsequently against one side of the pier (Fig. 5).

Sonic logging survey can be carried by exploiting holes made for the samples. If these tests are performed on a right measurement base (say less than or equal to 0.50 m), it is possible to obtain sonic velocity diagrams by a plotter. This display system makes it possible to directly correlate velocity, damping and frequency of sonic signals with the characteristics of the material crossed by the borehole.

Results of sonic logging tests made on the piers of the viaduct are represented in Fig. 5.

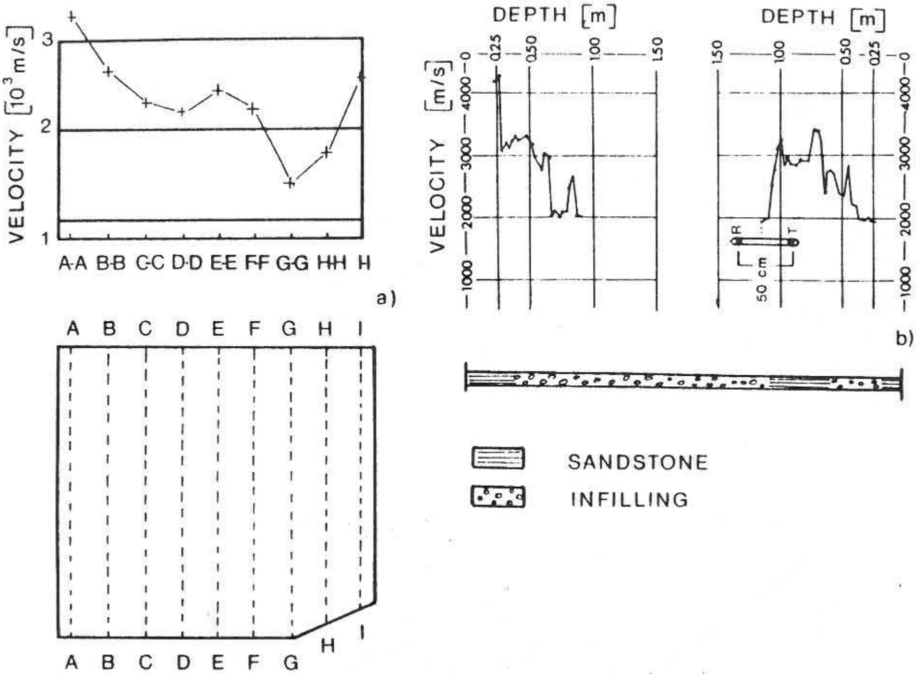

Fig. 5 - Geophysical non-destructive tests. (a) direct measurements of longitudinal acoustic wave propagation velocity according to directrices shown in the drawing. (b) results of sonic logging survey.

4. GEOTECHNICAL INVESTIGATION

Purpose of the geotechnical investigations is to provide the engineer with a knowledge of the subsurface nature and condition at the site of the structure. On the basis of the qualitative and quantitative information obtained the performance of the foundation can be assessed and, if necessary, suitable actions can be decided.

The investigation for the Porta S. Giacomo Viaduct were planned by boring, in situ testing and laboratory analysis. Two holes were drilled near the foundations using the rotary drilling method with continuous coring. Particular attention was devoted to the determination of water levels in the holes. Given the nature of the materials the Standard Penetration Testing (SPT) was chosen as the most appropriate sounding. Laboratory test were conducted on representative samples taken from the drilled holes. As the soils include much gravel and boulders, only classification testing was used and mechanical parameters were derived from correlation with in situ testing and material characteristics.

According to the information obtained, the final log presented in Fig. 6 has been prepared.

In the first two layers water content and Atterberg limits on the fine fraction were very similar. Water content was around 16%, liquid limit w_l ranged between 30 and 45% and plasticity index IP is 10 - 25 %.

Grain size distribution of specimens from the first two layers is given in Fig. 7. Assuming conservatively that the soil behaviour is control-

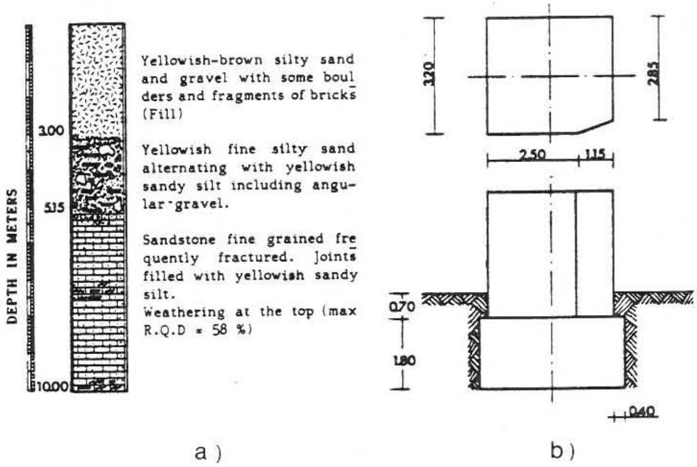

Fig. 6 - a) Profile of the subsoil - b) Elevation and plan of typical pier (dimensions in meters)

led by the fine fraction, an effective angle of internal friction of 32° can be evaluated for soils underlying the structure. Coesion c has been prudentially put to zero.

Considering the low plasticity of soil, the constancy of acting load, the absence of relevant water level oscillations interesting the foundations, it can be concluded that no consolidation problems exist for the Viaduct.

As regards bearing capacity of the subsurface materials, an overall safety factor of about 6 is obtained by evaluating long-term ultimate bearing capacity on the basis of Brinch Hansen approach.

The general conclusion is that the foundations on the Porta S. Giacomo Viaduct are adequate.

5. IN SITU MEASUREMENTS OF CHARACTERISTICS OF MATERIALS AND STRUCTURE

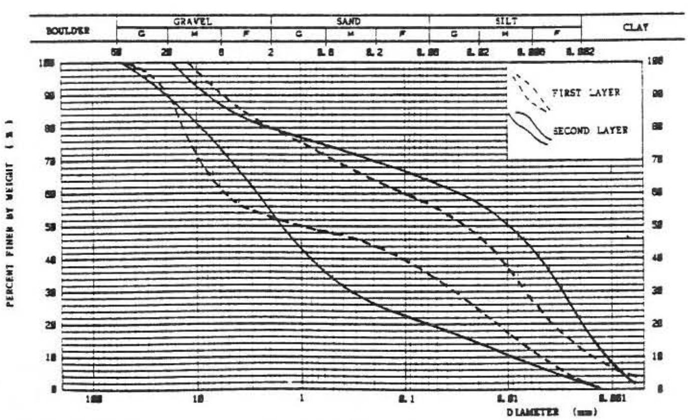

Fig. 7 - Grain size distribution

Laboratory tests applied to brick- or stonework are made difficult by the fact that samples taken from a structure are requested to have dimensions representative of the masonry behaviour. For new masonry codes, different countries require samples of quite large dimensions (at least two and three units large and four courses high). Due to alteration of the mortar in several occasions it is not even possible to take undisturbed samples from the walls of existing buildings.

A testing procedure by flat jacks, similar to those used in rock mechanics, has been set up by P.P. Rossi in connection with the restoration of the Palazzo della Ragione in Milan in 1979-80 [7].

The main advantage of this test consists on the possibility of determining in-situ deformability characteristics without extracting samples and assessing the local stress state within the structure.

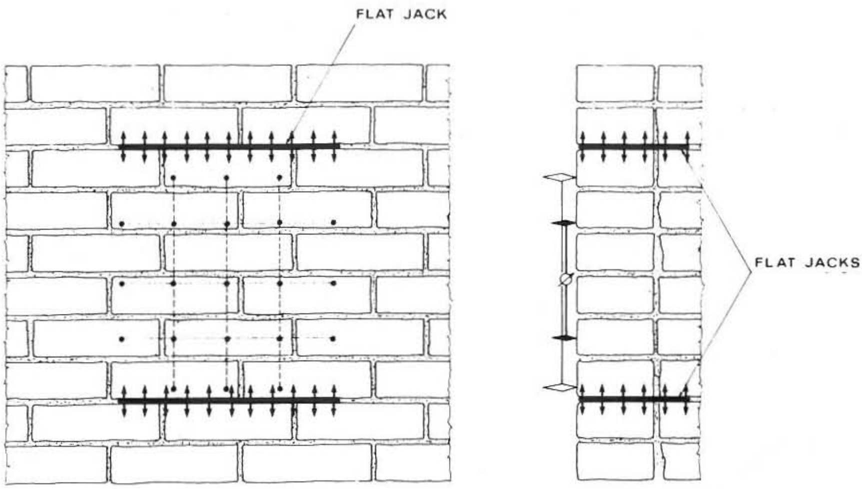

Fig. 8 - Scheme of the flat jack test on masonry walls.

The test consists of two phases. During the first one a plane cutting is made at a mortar layer. The closing of the cut determined by stress release is measured by using movable mechanical strain gauges between points located on both sides of the cut. A special flat jack (less than 10 mm thick) is set inside the cutting; the inner pressure is gradually increased in the jack up to the full elimination of the previous convergency. In this condition the pressure exerted by the flat jack is equal to the preexisting stress in the masonry, taking into account a corrective constant factor depending on the ratio between jack and cuttings surfaces (Fig. 8). This second phase aims at determining the masonry deformability characteristics. For this purpose a second cutting is made parallel to the first one and this will house a second flat jack. The two cuts delimit usually a masonry sample of acceptable size (40 x 40 x 20 cm). A stress state is applied in the direction normal to the lying plane of blocks (Fig. 8). Repeated loading and unloading cycles are performed. In the case of the Palazzo della Ragione a series of tests have been carried out in different parts of the building permitting the comparison of local states of stress. A mathematical model has been developed based on finite element technique, and deformability data from flat jack tests have been used with good results [8].

Flat jack tests have been recently carried out in the bearing brick-masonry walls of a 20000 mq surface building, six floors high, built in 1905 in Milan. They allowed to assess the values of stresses at points of expected stress concentration.

6. SAMPLING AND LABORATORY TESTING

Mechanical tests on specimens represent the simplest and the most

immediate means to determine deformability and strength of materials. Particularly important is the stress-strain plot in compression tests in order to study the brittle or ductile behaviour of the materials, its dilatancy at failure, etc. Also important is to assess the tensile strength of bricks and stones. An interpretation of the failure mechanism of masonry in monoaxial compression tends to demonstrate that the high deformability of the mortar may give rise to tension states in bricks (or stones) [9].

Specimens taken from the masonry walls should be representative of the actual mean behaviour of the masonry as a whole; when samples cannot be removed, even tests on single components (bricks, stones, mortars) may be useful.

Chemical-physical tests may be conducted in addition as qualification tests. It is well known that physical properties as density, porosity, rate of absorption, etc. are related to the mechanical properties (strength in compression, elastic modulus, Poisson's ratio). Particularly important can be the chemical analysis of mortar samples taken from the structure, in order to check their origin (common lime, hydraulic lime or cement).

In the case of Porta S. Giacomo Viaduct some rock blocks were taken in situ in order to determine properties of the lithotypes forming the masonry. From the blocks, 56 mm diam x 122 mm height, cylindrical samples were obtained at laboratory, their axes being normal or parallel to the rock bedding plane. In addition, two corings of 80 mm diam for sampling were made in a pier of the Viaduct. The results of sonic tests were so confirmed as it can be seen from the cross section shown in Fig. 9.

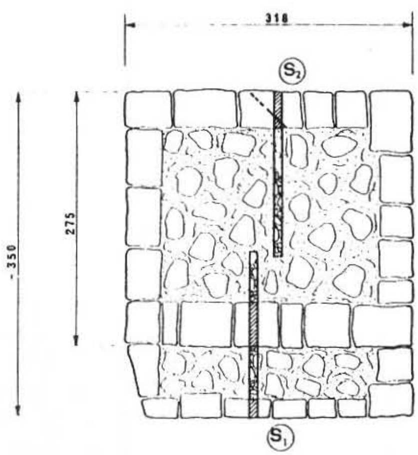

Fig. 9 - Schematic section of a pier of the Porta S. Giacomo Viaduct. S_1 and S_2 indicate the two corings for sampling.

Before the mechanical tests, samples were subjected to a set of qualification tests. Unit weights, propagation velocities of longitudinal elastic waves, etc. were obtained. A specimen of mortar taken from the inside of the pier and examined by the chemical test was characterized as hydraulic lime mortar.

During compression tests, both axial and diametral deformations could be determined on samples. Before failure was attained each sample was subjected to loading cycles (at least three), then brought to failure at controlled deformation velocity. Results characterized three foundamental lithotypes: weak sandstone (E = 10000 MPa, γ = 24.5 kN/m^3, σ_R = 53.5 MPa), hard sandstone (E = 40000 MPa, γ = 26.4 kN/m^3, σ_R = 123 MPa parallel to rock bedding plane); limestone (E = 70000 MPa, γ = 26.7 kN/m^3, σ_R = 133 MPa normal and σ_R = 71 MPa parallel to rock bedding plane).

Compression tests on mortar samples indicated a compressive strength equal to 12 MPa and a Young modulus of 5000 MPa [7].

7. PRELIMINARY ELASTIC ANALYSIS OF THE STRUCTURE

In the study of the bearing capacity of a structure in existence, the determination of mechanical properties of materials and soil is normally followed by a preliminary elastic analysis. This analysis though unrealistic and inaccurate makes it possible to achieve an overall insight into the nature of the structural behaviour and provides results which may be also used for subsequent developements: non-linear elastic analysis allowing for cracking, ultimate state analysis. The flow-chart of Fig. 10 tries to represent concisely the phases and alternatives of numerical analysis of an existing masonry structure [10] .

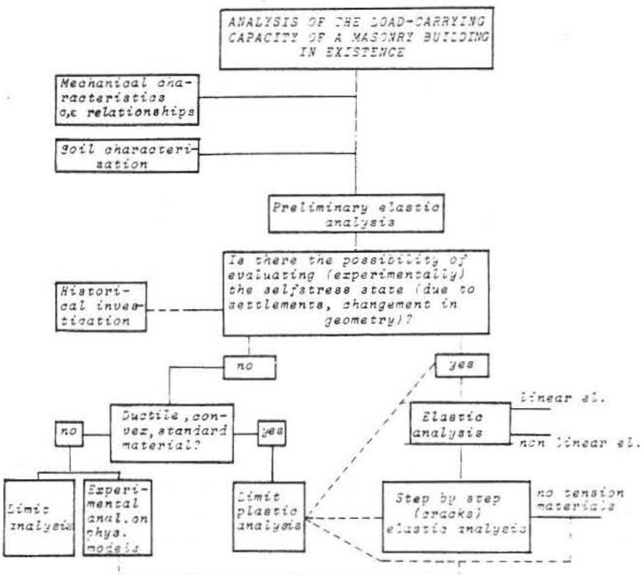

Fig. 10 - Phases and alternatives of numerical analysis of an existing masonry structure.

In the case of Bergamo Viaduct, the largest arch has been analyzed, utilizing a finite element computer program. The study was carried out in two stages, a plane analysis and a tridimentional one. Material has been considered as isotropic. Plane analysis has determined the elastic deformed configuration and principal stresses (their directions and equal level contours). It has been assumed that dead loads were due to arch weight ($\gamma = 25.0$ kN/m^3) and earth filling of the vault ($\gamma = 17.0$ kN/m^3) and live load by a concentrated force, generated by an heavy truck. The first step of elastic analysis has indicated that the resultants of sectional stresses approach the intrados or the extrados depending on the position along the arch, thus revealing the presence of significant bending; in four sections slight tensile stresses have been found (0.18 - 0.30 MPa). The principal direction of max compression stress along the centroidal axis of the arch is almost parallel to this axis, so that the shear force turns out to be modest.

As for the tridimensional analysis, COMET 3D computer code set up by ISMES, has been utilized. Fig. 11 shows the mesh used to this purpose. Again the load consisted of dead-weight, earth filling, a fictitious load (this time disturbed) and the heavy parapet. The tridimensional investigation was carried out in order to study the contribution given by the parapet to the stress distribution in the cylindrical vault. It resulted that max tensile stress at the parapet attains values of 0.1 -

0.2 MPa; which can certainly be carried by the stone wall. Thus, the lack of cracks in the structure appears to be justified.

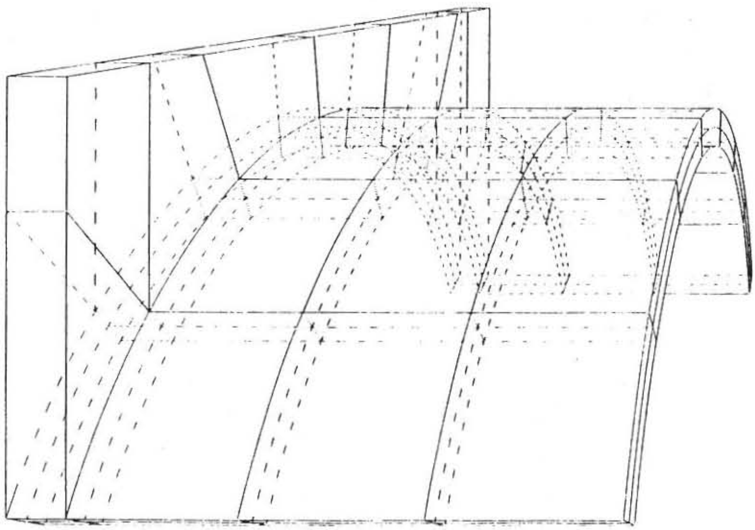

Fig. 11 - The mesh used for the tridimentional analysis of an archade of the Viaduct.

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