Damage characterization in stone columns by dynamic test. Application to the Cloister of Girona Cathedral, Spain

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ABSTRACT: This contribution provides an overview of the use of a method based on dynamic identification for the detection and characterization of damage in 24 stone columns located in the XI-century cloister of Girona Cathedral in Spain. An attempt to estimate the work axial load applied on the columns from the measured natural frequencies, is also presented. In order to calibrate the method, a full-scale model of the columns was subjected to increasing load in laboratory to observe the evolution of modal parameters under axial load. The column was dynamically evaluated 14 times for different load levels. 48 dynamic tests (2 per column) were also developed *in-situ* to monitor the columns.

Figure 1. Cathedral of Girona, XI-XII Century.

1. INTRODUCTION

The wish for scientific and respectful strategies for the study and preservation of historical constructions has promoted the development of a wide variety of effective non-destructive or quasi-non destructive tools of inspection (such as endoscopy, electromagnetic tomography or flat jack test) which can be used to obtain information about the internal composition of the structural elements or about the mechanical properties of the existing fabrics. Among these methods, dynamic identification, based on the measurement of the vibration response, constitutes one of the more versatile, fully non-destructive techniques of inspection. Dynamic identification can be used to monitoring the structure both locally (aiming at the identification of a properties of a single element or part) and globally (aiming at the characterization of overall properties). The method is based on the fact that modal parameters (notably frequencies, mode shapes, and modal damping) are functions of the physical properties of the structure (mass, damping, and stiffness). In particular, dynamic identification can be used for health monitoring, since the changes in the physical properties due to damage will cause, at its turn, detectable changes in the modal response.

The development of vibration-based damage detection technology has been closely coupled with the evolution, miniaturization and cost reduction of Fast Fourier Transform (FFT) processes and computing hardware. The reader is referred to the report by Doebling et al. (1996) for a full literature review on historical development and *state of the art* on dynamic health monitoring. Several researchers have developed a variety of methods to correlate variation in dynamic properties with the existence of damage. Cawley and Adams (1979) was among the first to use measured changes in natural frequencies for predicting the location of damage in a two-dimensional structure. More rcently, Vestroni and Capecchi (1996) used dynamic identification to assess damage location and quantification in cracked beams. Detection of the damage in prestressed concrete and RC beams, using dynamic system identification, has been also studied by Maeck and De Roeck (1999). As many inverse problems, damage identification does not allow a straightforward solution but requires sophisticated solution strategies. Many algorithms have been proposed by different authors to approach and solve this problem (Shen and Taylor 1991, Liang et al. 1992, Casas and Aparicio 1994). In the case of historical constructions, dynamic evaluation presents additional advantages besides its fully non-destructiveness. An advantage is found in the possibility to repeat the test many times and thus to extend it to a large number of similar structural elements. This is clearly illustrated by Ellis' (1989) usage of the dynamic test to evaluate the integrity of 534 stone pinnacles of the Palace of Westminster in London based on wind excitation and laser remote measurements.

The wish of preserving the integrity of the columns of the cloister of Girona Cathedral prevented the application of some conventional tests (core extraction or static load testing) that would have caused some deterioration, however limited. Because of that, dynamic test was preferred and executed by attaching dynamic sensors to the columns and exciting them by means of hammer impact. Historical research was conducted to locate the origin of the stone and a few new specimens were extracted from the original quarry in order to develop the parallel laboratory research. The activities carried out in laboratory included static uniaxial compression tests, dynamic modulus measurement and a full-scale load increasing dynamic test). It must be mentioned that the tests were developed in recently extracted stone, with no influence of age.

2. DESCRIPTION OF THE CATHEDRAL AND CLOISTER

The cathedral, originally started to be built during 11th century, is the result of the superposition of different architectural styles since the first known Romanesque building that was consecrated in 1038. It offers four architectural styles: Romanesque, Gothic, Renaissance and Baroque, which is not a very frequent occurrence.

The cloister, built during 11th and 12th centuries, represents fully the spirit of the Romanesque era, conserved entirely, despite the fact that some double columns and capitals display signs of erosion which affects the limestone rock, sculptured to create a series of Biblical representations which form a valuable part of the Catalan Romanesque period. They belong to the previous cathedral, of which only the old bell tower is conserved. The tower ("Tower of Carlemany"), built during 11th century, serves today as the buttress of the Gothic nave.

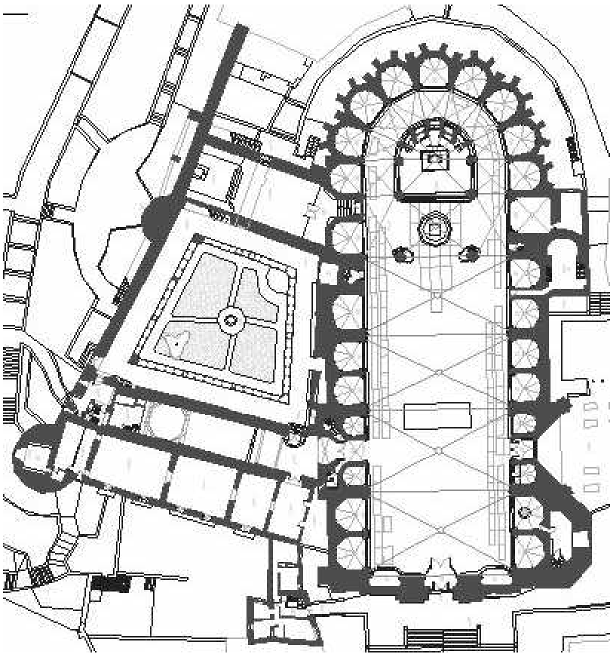


Figure 1 : Overview of the Cathedral and Cloister

The Gothic nave, which is the widest in the world and measures 22.98 meters, is at the same time, the widest of any style, excepting that of St. Peter's in Rome (which measures 25 meters). While the construction of a temple with three naves was initiated, the proposal to continue it with only one nave caused the suspension of the works and motivated an intermittent discussion between those in charge and the technicians, which lasted fifty years. In 1417 the Cathedral Chapter held a meeting with the masters of the works and infamous experts. After hearing their opinion, the Chapter was inclined towards the single-nave plan, which converted the Cathedral into a unique monument in the history of world Gothic architecture.

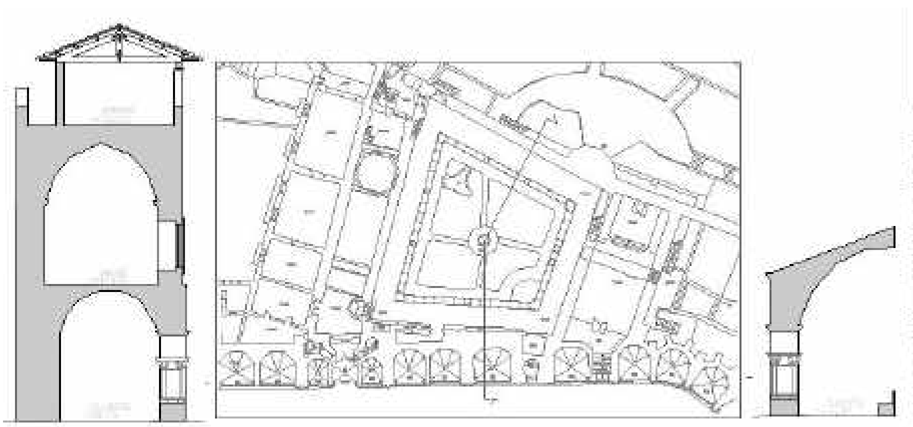


Figure 2 : Detail of Cloister and evaluated columns.

3. EVALUATION OF DYNAMIC PROPERTIES OF 24 LIMESTONE COLUMNS

The cloister of the cathedral is nowadays subject to a sound project of restoration requiring a general study of the structural state of the columns. It was decided to develop only non-destructive evaluation. By this way, dynamic evaluation was an alternative and the first testing campaign is presented in the next paragraphs.

One of the four sides of the cloister vas fully tested, including 24 columns that were tested twice yielding a total of 48 dynamic tests. No significant variation between the result obtained in the two tests carried out each column was observed. Dissipation of the impact energy took place in about 0.3 seconds. Basically, one mode was always clear and in some cases the second mode was also observed.

The generation of impulsive force was caused through a 10- pounds hammer applied at mid-span of every column with a single impact. A dynamic transducer consisting of a ceramic accelerometer was attached in horizontal direction (Figure 3).

Figure 3 : Acquisition system (left) and accelerometer attached on a column (right)

A clear pattern was observed on the time-response diagram of every column. Very *clean* time responses were extracted. A typical example of those plots is presented in figure 4.

After obtaining the first natural frequency for every column, a clear trend can be observed. Columns next to one of the corners of the cloister present higher frequencies and columns close to midway present lower frequencies (figure 5). As can be observed in figure 3, columns are displayed by pairs, and the frequencies of two twin columns were always the same. This proves that variation in frequencies is mostly due to location than material or geometrical parameters. Data acquisition was developed using a routine of Labview code, on an interval of one second, and acquiring at a frequency of 30,000 Hz.

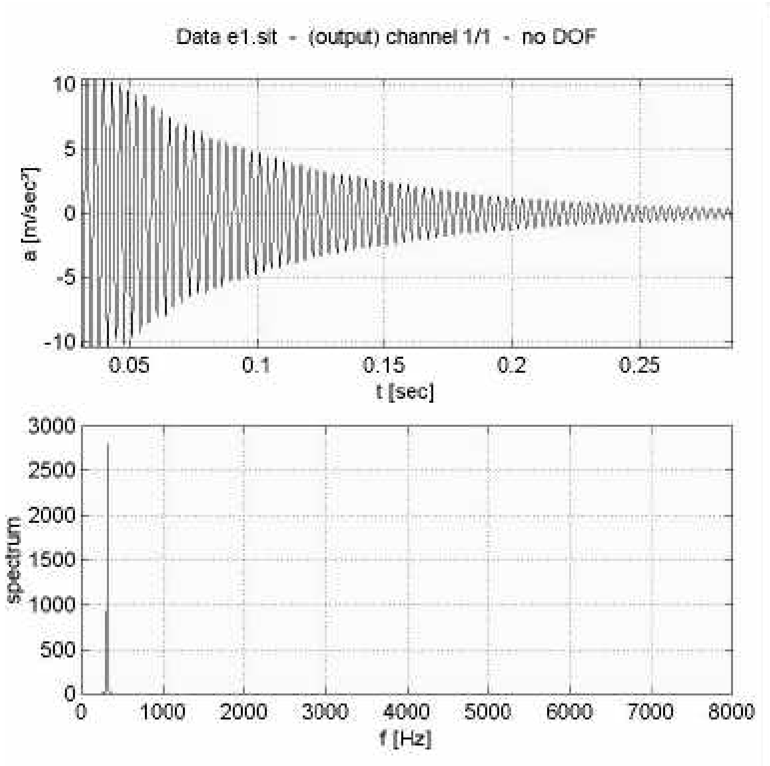


Figure 4 : Typical time-response of a column (above) and FFT diagram (below).

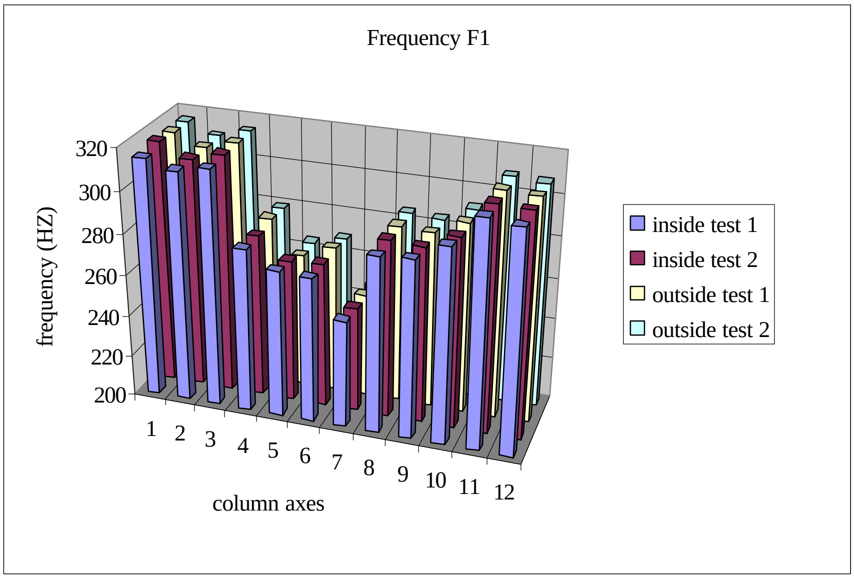


Figure 5 : Distribution of first frequency in the cloister columns (1 to 12).

4. INCREASING AXIAL LOAD LABORATORY DYNAMIC TEST

A full-scale model of the columns was constructed using stone taken form the original quarry. Although the origin is same, it must be noted that the time exposition to atmosphere conditions of the laboratory specimen is obviously very reduced compared to the ancient columns of the cloister. The specimen was installed in a press machine, supported in two steel plates with not restriction to rotation. The section of the column was circular with a diameter of 15 cm and an area of about 177 cm^2

As in the cloister, the technique used to generate the impulsive force consisted of a soft single impact applied at midspan. The column was subjected to an increasing axial load varying from 0 to 260 kN. Stresses due to axial load varied from 0 to 14.7 Mpa. The application of the load was divided into steps of 20 kN. (14 steps) and evaluation of dynamic properties was done at the end of every step, under static load.

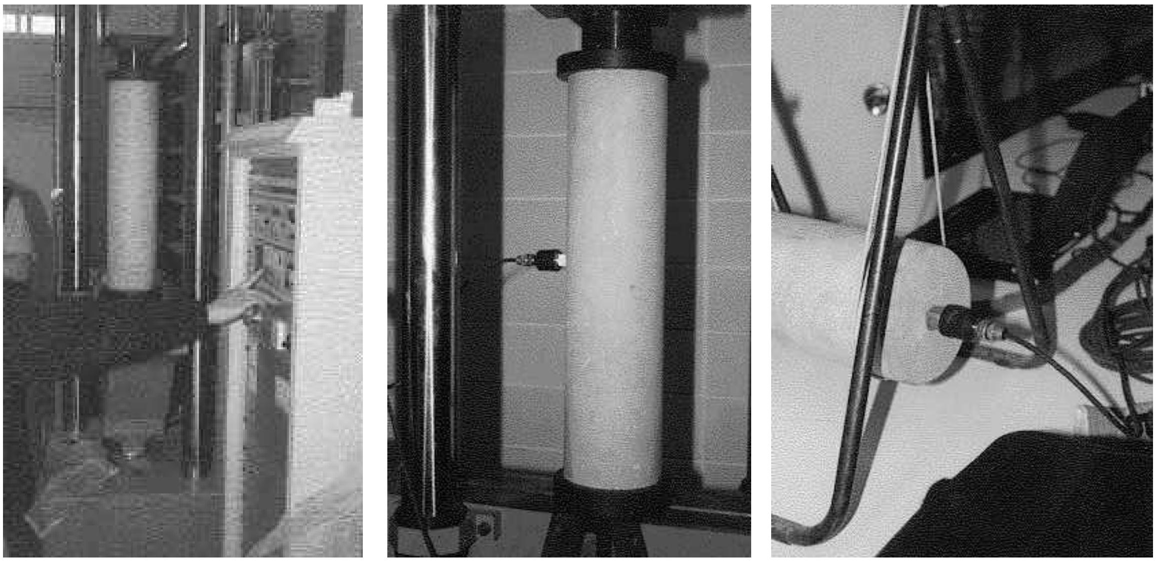
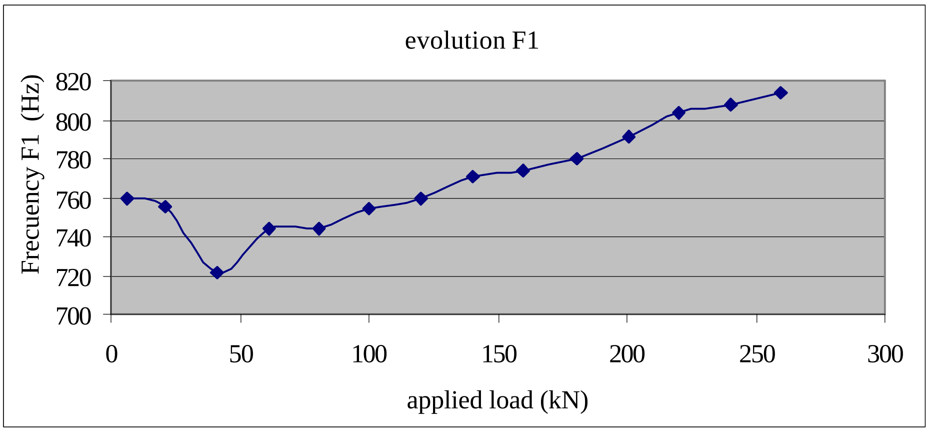


Figure 6 : Detail of test (left), attached accelerometer (middle) and dynamic modulus test (right)

A clear variation of natural frequencies was observed during the test (figure 7). First, a descending slope was presented during the first two load steps. Then, the frequencies showed a clear increasing trend. .

It is well known that the theoretical proportion between the second and first natural frequencies F2/F1 presents a constant value of 2.75 for double fixed support condition and 4.0 for a double free support condition in column-type elements (figure 9).

On developed tests, a variation between the ratio F2/F1 with applied load is clear only for the first two load steeps. Further on, the relationship between F2/F1 and the applied load remains more or less horizontal. This clearly shows that the support conditions at the ends of the column changed only during the first two steps to then stabilize in the form of a partial clamping. Further on, variation in frequencies are mostly to the variation of the modulus of elasticity.



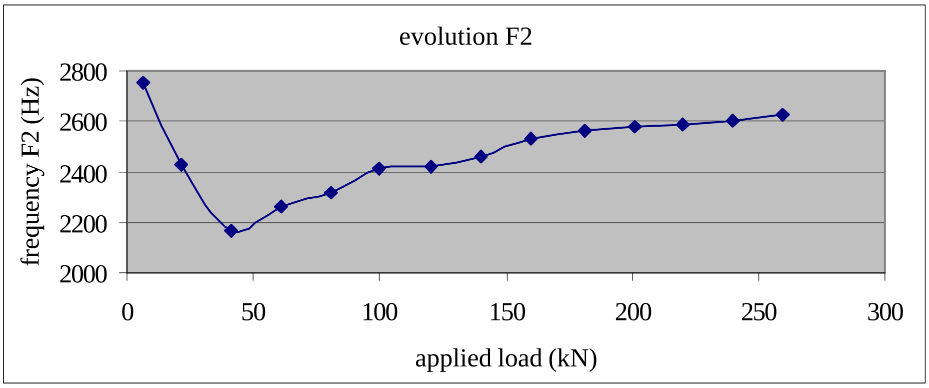


Figure 7 : Evolution of the natural frequencies with the applied axial load. First frequency (above) and second frequency (below).

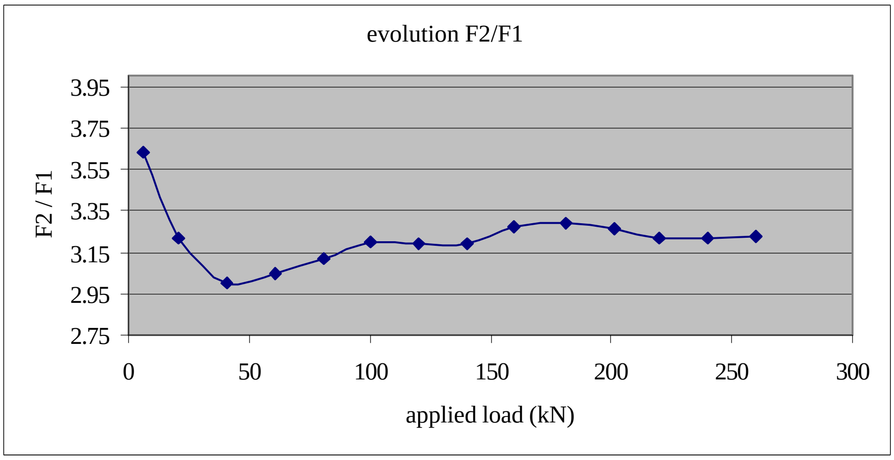


Figure 8 : Relationship between the ratio F2/F1 and the applied axial load.

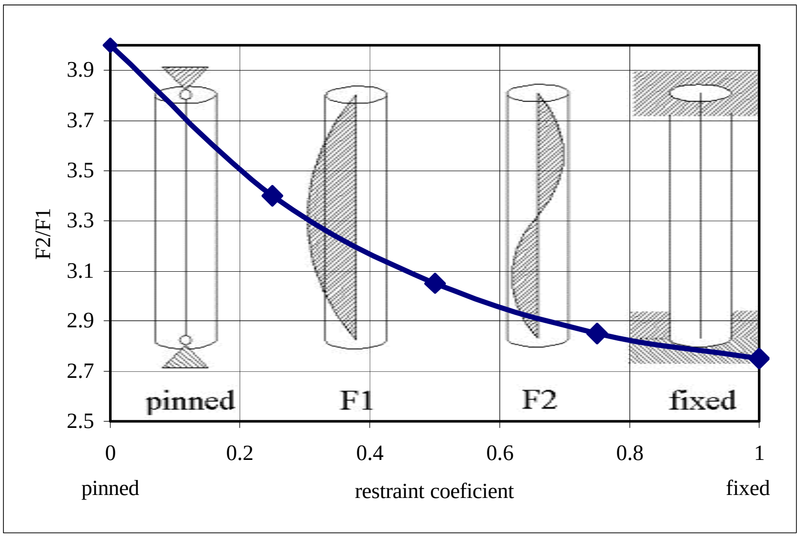


Figure 9 : Theoretical relationship between the ratio between the first and second natural frequencies (F2/F1) and a restraint coefficient measuring the level of restrain ranging form 0 (pinned) to 1 (fixed)

The dynamic modulus of deformation was evaluated by mean of the same technique used for concrete cylinder specimens (ASTM C215, figure 5 (right)). A value of 37,600 MPa was thus measured.

5. FINITE ELEMENT MODEL

A simple analytical model was created to assess the accuracy of the identification method. The model consisted of a simple column with variable support conditions at the ends. The modulus of deformation was estimated from the value obtained experimentally as dynamic modulus. A satisfactory agreement was obtained between the analytical prediction of the first natural frequencies and the measures obtained experimentally in the cloister. The agreement was obtained assuming fixed condition at the ends of the columns.

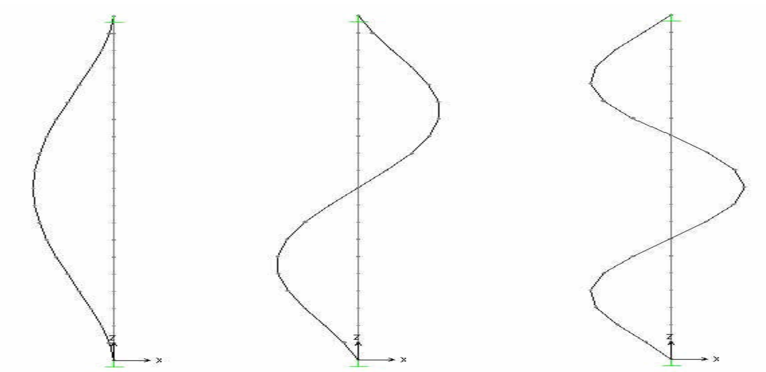


Figure 9. First modes of vibration predicted by the analytical model, corresponding to frequencies F1=370 Hz (left); F2=909 Hz (middle); F3=1700 Hz (right).

6. CONCLUDING REMARKS

The study presented constitutes a first approach of a more general investigation aimed at assessing the condition of stone columns, based on dynamic identification. In particular, the study has shown it feasible to correlate the work load sustained by the stone columns with their measured natural frequencies. A test developed in laboratory showed that a clear variation in natural frequencies appears when increasingly loading a stone column with an hydraulic actuator. The variation of the natural frequencies can be caused, in principle, either by a modification of the supporting conditions or by a modification of the intrinsic stiffness of the specimen with the amount of load. As is well known, a modification of the support conditions would force a variation of the ratio between the first two natural frequencies. In the case of the mentioned experiment, the fact that the ratio between the two first natural frequencies did not vary significantly through the loading process showed that the variation of the absolute values was essentially due to the non-linearity of the stress-strain response of the specimen, i. e, the alteration of the stiffness with the load.

The tests executed in-situ allowed the measurement of a significant variation of the natural frequencies among the stone columns of the cloister. This variation can be correlated with the location of the column and probably with the axial load supported by each column. On the other hand, columns with visible cracks showed a sensible decrease in frequency, due to loss of inertia. Further investigation is needed (and now being undertaken by the authors) to define a clear relation between natural frequencies and axial load in intact and damaged columns.

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