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Toward new seismic evaluation methods with the C1SMA real-scale experimental approach

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Abstract: In France, as elsewhere, many buildings are regularly demolished as part of urban renewal policy. These buildings have constructive systems which usually reflect our real estate holdings. We set forth a mechanical device made to excite these buildings before demolition in order to define their dynamic behavior for high acceleration responses. Features and target performances of this device as well as intended application in the field of seismic evaluation of Guadeloupien architectural heritage are presented here.

Keywords: seismic evaluation; seismic rehabilitation; building demolition; real-scale experimentation; forced oscillations; architectural heritage

1. Introduction

The theoretical foundations of earthquake engineering are generally inspired or validated by in situ observations or in the laboratory.

In the first case, building behaviours may be analysed in the context of significant seismic events but, for most of the buildings, consequences are observed afterwards and neither soil nor structural motions have been measured. Building behaviours may also be analysed in the context of a planned measurement campaign, either with ambient (Ivanovic et al., 2000) or forced vibration experiments (Hans et al., 2005) but amplitude excitations are generally too weak to produce building responses whose amplitude would be comparable to those induced by strong earthquake (Trifunac, 1972). Whereas the recent needs@UCLA Mobile Field Laboratory theoretically permit to produce up to 2 g acceleration responses according to Nigbor et al. (2012), maximal response acceleration produced on a four storey RC building was only 0.09 g according to Yu et al. (2006).

In the second case, the studies are imperfect reproductions of physical phenomena (small-scale models incorrectly accounting for building production methods or or real-scale models incorrectly accounting for production conditions or material ageing...) but experimental protocols lead to a better control and measurement of phenomena.

The C1SMA (Constructions à l'échelle 1 Instrumentées soumises à un Séisme Modéré Artificiel) research project, initiated in 2014, co-financed by ENSA-Marseille and the PACA region, is a combination of two approaches: it is meant to reproduce the ground vibration effects on real buildings while benefiting from laboratory conditions. One to ten story buildings, intended for demolition in urban renewal operations and well instrumented, go through oscillations of increasing amplitude through a mechanical device reproducing on each floor the inertia forces that would be generated by an acceleration at basement level. Before or after complete demolition of the building, using excavators or explosives, samples from rubbles should allow to better characterize the nature of the lateral force resisting system.

Whereas the scope of C1SMA device is theoretically wide, intended applications firstly concerns quite pragmatic seismic evaluation of Guadeloupe architectural heritage of the 1930's with the aim of safeguarding it with the minimum possible resources.

2. General description of excitation device

2.1 Unbalanced mass mechanical vibration exciter principle

The excitation device consists in equipping each slab of the studied building with two counter-rotating eccentric masses. Thus each story is subjected to a unidirectional sinusoidal force, the intensity of which depends on the turning radius, angular frequency and mass (Equ. 1).

Both vertical drive trains are located in such a way that point of application of the resultant force (F) corresponds to the building's center of gravity (exact position being previously evaluated through ambient noise measurements). If slabs meet all the criteria to be considered as rigid diaphragm, the excitation produced by the unbalanced masses may then be considered as equivalent to inertial forces that would be produced by sinusoidal ground accelerations.

$$F(t) = 2mR\omega^2 \cdot \sin(\omega t) \quad (1)$$

where $F(t)$ = force exerted on slab; m = rotating eccentric mass ; R = turning radius; and ω = angular frequency.



Figure 1. Force exerted by unbalanced masses on concrete slab

Several eigen modes may be alternately excited (even combined) by managing at the same time fine-tuning of angular frequency, mass values and turning radius at each story.

2.2 Target performances

Table 1 presents, for different number of stories (n), the expected responses in terms of acceleration and displacements at the top of the building, as well as some of the data used to pre-size the device: fundamental period of building (T_0), each of the $2n$ unbalanced masses, turning radius ($M.R$), force exerted by each pair of unbalanced masses (F), maximum torsion torque applied to each vertical drive shaft on ground floor (T), motor power required (P).

Table 1. Expected responses and data used for pre-sizing.

n	T_0 (s)	$M.R$ (kg.m)	F (kN)	T (kN.m)	P (kW)	a (g)	d (cm)
1	0.07	7	60	41	8	0.6	0.07
2	0.13	26	62	317	30	0.75	0.3
3	0.2	39	43	477	30	0.55	0.6
5	0.3	72	26	758	30	0.35	1
10	0.7	142	13	1404	30	0.18	2

The previous estimations are based on the following assumptions: whole story mass of 200 tons, damping: 5%, fundamental period supposed to be equal to $n/15$.

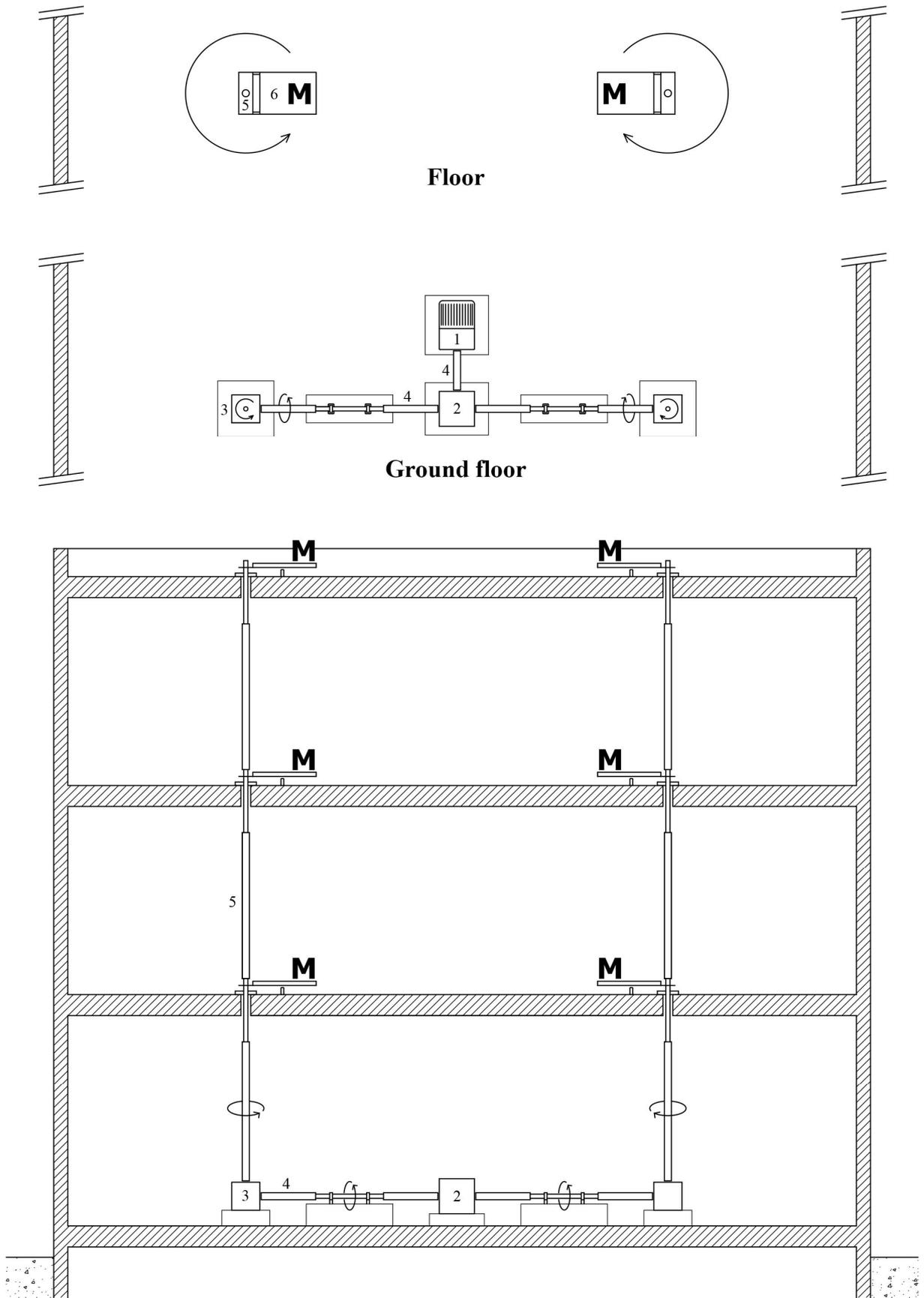


Figure 2. Mechanical device: asynchronous motor (1), angular gearboxes with reduction ratio (2 & 3), horizontal drive shaft (4), vertical drive shaft (5), eccentric mass structure (6)

3. Technical description

3.1 Unbalance exciter

The mechanical device, which can be dismantled after each use and stored in a container (Figure 2), is essentially composed of the following elements:

- An asynchronous motor controlled by a variable speed drive connected to two horizontal drive shafts connected to cardan shafts and angular gearboxes with reduction ratios. All of these elements are situated on the building's ground level.
- Two vertical drive trains connected to horizontal drive trains through two angular gearboxes with reduction ratios. These devices pass through all the floors (to which they are connected by ball bearings).
- Two eccentric mass exciters per floor rotated by the vertical drives and turning at the same speed in opposite directions (the synchronization is purely mechanic). Two models of eccentric mass structures are considered. The « slow » ones are used for buildings of low-order fundamental frequencies (1 to 3 Hz). They bear masses of approximately 100-200 kg with a turning radius of 1 meter. The « fast » ones are used for buildings of high-order fundamental frequencies (4 to 15 Hz). They are made of a steel structure and bear steel masses of approximately 20-50 kg with a turning radius of 0.3 meter.

3.2 Motorisation

All of the eccentric mass vibrators are driven by the same three-phase electric motor. Two rotation speed ranges can be obtained by interchangeable reducers. For each configuration, the excitation frequency can be adjusted by the variable speed drive. The rated power of the motor is 30 kW.

Each testing includes three phases: the start-up phase with a progressive increase of the rotation speed and distance of the moving masses, a phase of steady-state (rotation frequency of the unbalanced masses slightly equal to the building's natural frequency), and a phase of progressive breaking.

3.3 Vertical drive trains

Both vertical drive trains consist of a succession of steel round bars and tubes connected to each other by cone clamping elements. This connection system allows one not only to transmit high torques but also to adapt the device to a large range of floor-to-floor heights.

Connections between vertical trains and eccentric masses structures (fabricated in steel for the fast version and in wood for the slow version) are also performed by cone clamping elements while connections between vertical drive train and slab are performed by steel plates and bearings on each side of the slab.

3.4 Instrumentation

The basic instrumentation allowing one to characterize the building's dynamic behavior before, during, and after the mechanical excitation is composed of:

- An acquisition chain, based on 2 CMG-40T three-axis seismometers, intended for ambient vibration measurements, before and after the mechanical excitation.

- An acquisition chain, based on 8 single axis low-frequency accelerometers (sensitivity of 1 V/g) intended for acceleration measurement under mechanical excitation.
- Some digital cameras allowing one to characterize damage mechanisms of bearing walls.

Other sensors might be mounted on the tested buildings or in its surroundings according to goals of testing and resources of firms and laboratories involved in the operation.

3.5 Testing protocol

In principle, each testing protocol is specific, depending on objectives that have been set with partners. For each tested building, however, the general testing protocol should be approximately the following:

- 1 day for initial ambient noise measurements: estimation of first mode shapes, period and damping for low top floor accelerations.
- 3 to 5 man-days to set up the device according to building dimensions.
- 1 day for forced oscillations measurements
- 2 man-days days for final ambient vibration measurements, dismantling the device and storing it in its container.
- Collection of steel and concrete samples for laboratory tests before and during the demolition stage.

4. Current project status and intended applications

The C1SMA research project was initiated in 2014. A first financial help of ENSA Marseille and the PACA region allowed to design and produce a first prototype of the excitation device as well as to get seismometers and accelerometers acquisition chains. Excitation device was first successfully assembled and tested in December 2018 on a small wooden structure that had been built for this purpose in the ENSA Nantes premises.

It was installed for the first time on a real building in August 2020 and in a second (and last) time in June 2021. Both tests was funded by the Direction des Affaires Culturelles (DAC) of Guadeloupe and was carried on a former single-story school located in Guadeloupe and slated for demolition. This building, as well as among 100 other ones, was built by the architect Ali Tur in the 1930's as a consequence of huge damages caused by the cyclone of 1928. As all Ali Tur's building was built at the same time with the same constructive system (RC MRF with concrete masonry infill), tests carried on some of them could permit to enhance seismic evaluation of other ones.

The aim of past and next few ones is two-fold: (1) finalising the development of C1SMA device; (2) characterising the mechanical behavior of lateral-force-resisting system of Ali Tur's building under high harmonic loads.

Tests conducted in 2020 and 2021 made it possible to measure a 0.15 g acceleration response on the roof of the building. Two problems was encountered not allowing to reach higher accelerations. The first one, relating to the anchoring of bearing in the concrete hollow-core slab have been fixed in the meantime. The second ones relates to the misalignment of vertical drive trains conducting to its uncontrolled vibrations for rotation speed exceeding about 10 Hz whereas the fundamental natural frequency (according to ambient noise measurements) in the transversal direction is about 14 Hz.



Figures 3a & 3b.



Figures 4a & 4b.



Figures 5a & 5b.

New mechanical parts have recently be designed and produced in order to simultaneously reduce the initial misalignment and increase the lateral stiffness of the vertical drive shafts. A test bed is currently being set up in the ENSA Nantes premises in order to validate the

new vertical drive shaft design. In case of success of these preliminary tests it would be reasonable to expect significantly higher accelerations. In view of the lightness of the building (approximately 70 tons), 0.6 g or higher acceleration is expected. That would be at a same level if not higher than design acceleration imposed by the regulatory framework for new buildings in Guadeloupe. Next in situ tests in the same building should be carried in 2022.

If these tests were successful, namely building acceleration response reached 0.5 g or higher values, it would be possible to forecast new prospects for the seismic evaluation and low-cost safeguard of French architectural heritage. That will require building specific procedural and theoretical framework permitting to “extrapolate” experimental data obtained from a few buildings to other buildings whose lateral-load resisting system are similar enough.

5. Conclusions

A new mechanical device has been under development since 2014 and the two first in situ tests have been carried out in 2020 and 2021 in order to finalize its development and, at the same time, characterizing the mechanical behaviour of Guadeloupien buildings of the 1930's. We hope to achieve the first phase of development in 2022, allowing to expect the set up of new seismic evaluation methods and then permitting low-cost safeguard of architectural heritage.

Acknowledgements

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