CRITERIA FOR ESTABLISHING A DYNAMIC TEST LOADING PATTERN FOR MASONRY.

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SUMMARY

This research project focuses on the evolution of the damage mechanic properties for un-reinforced masonry panels under dynamic inplane loads. A statistical determination of the evolution of the damage mechanic requires, for a ceramic material, the development of a time varying load pattern. The pattern should pass the criteria of similarity to existing patterns, provide time for the measurement of the damage evolution and bear a resemblance to the characteristics of relevant earthquake loading on realistic masonry buildings. This paper looks at the filtering process from epicentre to shear wall element. The interest lies in developing a pattern that yields a reasonable representation of the filtered event at the point of loading the panel, not at the epicentre or at a recording station. One has to make compromises in the procedure. This document is about describing the process, the analysis, the compromises and the decisions. The criteria suggested from this analysis consists of: a pattern of several frequencies, each frequency is applied for a set period at a constant amplitude, quiescent periods are allowed between load applications, differing frequencies may occur in sequence, but not concurrently and the amplitude will increase in steps with time.

1 INTRODUCTION

The movement of the world is an ongoing process. In this process, the earth's surface has been folded, faulted and subsumed to varying degrees. Sedimentary rock and alluviums overlay large areas of continental rock. The world's surface layer is an anisotropic material with random and varying fracture planes, generating earthquakes at interplate boundaries on a regular basis and intraplate less frequently. Each earthquake has a characteristic signature. The surrounding ground is also unique and acts as a filter. Micro-tremor measurements demonstrate the effect of foundation conditions on a building’s response to dynamic loads.

Buildings are located in a random fashion across large areas of the world's surface. Substantial proportions of these buildings are constructed of unreinforced masonry. These buildings act as the final filter to the earthquake strain energy.

This research proposes the use a single loading pattern for investigating the time evolution of the damage mechanic properties of masonry. Loading patterns, used in earlier masonry experiments, were designed to model or copy dynamic seismic events. These patterns provide a framework of principles or criteria for selecting a single pattern for this study.

Fast Fourier Transform techniques will be used to investigate the amplitude, phase and frequency properties of a range of earthquake traces from interplate, intraplate and synthetic sources. Each earthquake trace set will be reviewed to select a series of earthquakes ranging from M 5.5 to M 8 for use in the development of criteria for selecting the loading pattern. The set of earthquake traces will be used as a dynamic loading for a three-
dimensional transient, dynamic, elastic, finite-element model of separate two and seven storey masonry buildings. Acceleration traces can be established for a number of nodal points in the buildings with a Finite Element Package.

The trace results can be translated to the frequency domain using FFT methods. This FFT information from the earthquakes provides a guide to the filtering of each earthquake trace by the building and information on the characteristics of the element loading.

A process that starts with strain release ends with strain damage in a building.

2 EARTHQUAKES

Rock strength limits earthquakes to a maximum magnitude of approximately M8. Well-constructed masonry should be able to withstand a M5.5 event of reasonable duration. These two limits provide a suitable range for considering earthquakes that will affect masonry shear walls (Richter [1], Page [2]).

Examples of tuned building’s response to earthquakes include the walls of Jericho and the Mexico City buildings. This problem highlights the need to consider both the time and frequency domain in reviewing earthquake traces.

The work of Atkinson and Boore [3] for Eastern North America (ENA) provides one interesting data set. The two specific events detailed in this work were at Saguenary, Quebec and Nahanni, Northwest Territories. The new ground motion relations provided by Atkinson and Boore cover the peak ground motions and response spectra for Eastern North America events in the range of M 4 to 5. Atkinson and Boore noted that this analysis is consistent with the data from the Nahanni and Saguenary earthquakes.

Earthquake data from Japan, California, Europe and Australia provides a range of events within the magnitude bounds of interest. Earthquake data was obtained from a number of sources—Griffith [4], Horton, Barstow and Jacobs [5], Benedetti [6], and Sinadinovski et.al.,[7]. These particular earthquakes are of interest to masonry researchers or are earthquake traces that have been in common use for a long period. The earthquake details provided are:

- the name of the location of the earthquake,
- the recording location,
- the date of the event
- and the duration of the record

Earthquakes reviewed in the study are:

- Marked Tree, Arkansas:40 (Synthetic)
- Nahanni Station 1, Iverson, Ca, 23/12/85:12
- Nahanni St 3, Battlement Ck, Ca, 23/12/85:20
- Saguenary St 8, La Malbaie, Ca, 25/11/88:20
- Saguenary St 16, Chicoutimi Nord PQ, Ca, 25/11/1988:15
- Irpinia, Calatrini, Italy, 23 November 1980:70
- Newcastle, Australia, 28/12/1989:6 (Synthetic)
- Miramichi, Loggie Lodge, Ca, 6 May 1982:1.
- Imperial Valley, El Centro, USA, 18/5/40:30
- Imperial Valley(2), El Centro Peknold, USA, 18 May 1940:28
- Migayi-Ken-Oki, Sensai City, Japan, 12/6/78. :35
- Parkfield, California, USA, 27 June 1966:20
- San Francisco, Cholame St, California, USA, 22 March 1957:10
- Kern County, Taft High, California, 21/7/52, :40
- SCT, California, USA, unknown: 80.

Nichols and Totoev [8].
Jacobs’ [9] comment was ‘but there are few stable continental earthquakes with the proper M (Magnitude), r (radius) and the right site conditions’. Boore [10] commented that one is looking to use a set of earthquakes to minimize problems from holes in the frequency traces. The FFT of the time trace provides a guide to the holes in the frequency spectra. The building’s natural modes of vibration need to be reviewed against the peaks in the earthquake FFT trace to assess the applicability of a particular trace.

3 FAST FOURIER TRANSFORMS

The Fourier transform can be considered a special case of the Laplace transform. The Discrete Fourier Transform is derived in detail in Brigham [11], who outlines the development by Cooley and Tukey of the FFT algorithm in the mid-1960’s. Fourier transforms provide a linear one-to-one relationship between the time and frequency domain. The two are equivalent representations of the same waveforms. A FFT program was coded using a Numerical Recipe in FORTRAN [12] module as the FFT subroutine. Results for the Discrete FFT are determined for the amplitude (real), phase angle (complex) and magnitude (metric) for each of the earthquake time traces (Nichols and Totoev [8]). The phase plots show a reasonably constant rate of rotation for the phase angle. This result is expected from the mathematics of DFFT.

A typical example of the time trace is presented for the Nahanni Station 1 M6.8 event in Figure 1.

![Figure 1](image1.png)

**Figure 1** Nahanni Station 1 Horizontal Y Time Acceleration Trace, a 6.8M Event

A typical example of the DFFT results for the metric is presented for the Nahanni Station 1 M6.8 event in Figure 2.
These earthquake recordings have typical peak acceleration between 0.1 and 0.3 g’s. Comments on each event and the associated FFT are:

- Marked Tree, Ak: Single trace, peaked in lower freq. At M7.25, considered an upper limit event, long duration, and acceleration of 0.5g.
- Nahanni Station 1, Three traces, a bit holey at 2,3,4 and 7 Hz. Reasonable duration, but very high acceleration peaks(>1g in the time trace)
- Nahanni St 3, Duplicate event, with a poorer smoothed or attenuated signal.
- Saguinary St 8, Good design event.
- Saguinary St 16, Duplicate event, again attenuated with distance.
- Irpinia, Two traces, long duration and acceleration in range of masonry structures.
- Newcastle, Short, holey and synthetic.
- Miramichi, Single trace.
- Imperial Valley, good design event.
- Imperial Valley(2), Duplicate
- Migayi-Ken-Oki peaks at frequency of 1 Hz.
- Parkfield, short and only two components
- San Francisco, holey.
- Kern County, a good design event.
- SCT, holey.

The events used in the subsequent analysis are Marked Tree, Ak, with a M7.25, Nahanni Station 1 with an M6.8, Saguinary St 8, with
an M5.8, Irpinia, Imperial Valley, with a magnitude of 7.1, and Kern County, with an M7.6.

4 BUILDINGS

Building models can vary in complexity and edge conditions. The mathematical trick is to use a simple model, that one is confident will establish a reasonable estimate of the tensor quantities.

A building that sits on a basement is likely to have less damage than an equivalent building without a basement (Rutherford and Chekene [13]). Benedetti & Pezzoli [14] studied the dynamic response of a set of half-scale two-storey houses of typical Italian masonry and stone construction. This work has the aim of providing a design check on retrofitting protocols to be used in the seismic areas that contain these types of buildings. The accumulation of damage with time and the impact of retrofitting are evident in this study. This work was based on a standard house shown in Figure 3.

The model parameters adopted for the analysis are presented in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young’s Modulus and Poisson’s Ratio – Mortar</td>
<td>E of 1 GPa</td>
</tr>
<tr>
<td></td>
<td>v of 0.35</td>
</tr>
<tr>
<td>Young’s Modulus and Poisson’s Ratio – Brick</td>
<td>E of 20 GPa</td>
</tr>
<tr>
<td></td>
<td>v of 0.15</td>
</tr>
<tr>
<td>Young’s Modulus and Poisson’s Ratio – Stone</td>
<td>E of 50 or 20 GPa</td>
</tr>
<tr>
<td></td>
<td>v of 0.1</td>
</tr>
<tr>
<td>Young’s Modulus and Poisson’s Ratio Concrete</td>
<td>E of 10 GPa</td>
</tr>
<tr>
<td></td>
<td>v of 0.15</td>
</tr>
</tbody>
</table>

**Table 1 Intrinsic Property Constants**

Benedetti [6] supplied details of the various measured moduli for the masonry. The walls of the ISMES Building were set at 300 mm. The ISMES building was provided with a door of 1.2-m width on the ground floor and one window directly above in one model and the door and windows removed in the second. The remaining windows were not modelled. The results in this paper are from the second model. Page [15] provides details of a seven-storey masonry apartment building in Perth. This type of apartment is common in Australia in the regional cities. The building has been simplified for the analysis, with overall dimensions of the building being 23 by 14 metres, with a 170-mm RC slab and 229 thick walls. These two buildings provide a reasonable range of conditions for the study. In developing these models, the base conditions were assumed an independent block of high strength stone. The Perth building was modelled on a Salem stone (Krajcinovic [16]) and the ISMES Building on a weaker 20 GPa stone.
These boundary conditions set the natural frequencies of the models. These natural frequencies are within the range of interest for seismic modelling.

5 FINITE ELEMENT ANALYSIS

Finite Element Models were developed to model the building and it’s base conditions. A FEM analysis was completed using Strand 6.16 [17]. The linear transient dynamic solver used a Newmark-Beta method with full analysis, rather than modal superposition, and 1 percent Rayleigh damping.

Each model was created with a single degree of homogenization. Perpends were not modelled. The buildings were simplified for the analysis, modelled full size, as a rectangular box arrangement.

Figure 4 Perth Building
A typical acceleration FFT graph is shown in Fig 5.

The results for the Perth model are the first three natural frequencies for the model are 2.47, 2.97 and 4.01Hz. The analysis shows dominant sway in the long axis or X direction of 2 Hertz and the Y direction of 3 Hertz. The displacement and acceleration data are given as a metric of the magnitude and phase angle. The dominant frequencies for the orthogonal directions for the Perth Modal for two nodal points are given in Table 2.

### Table 2 Dominant Frequencies Perth.

<table>
<thead>
<tr>
<th>Node</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>3</td>
<td>2.5</td>
</tr>
<tr>
<td>B</td>
<td>2/4</td>
<td>3</td>
<td>2/5.77</td>
</tr>
</tbody>
</table>

The results are consistent with the natural frequencies. The peak FFT metric for each of these nodes and the dominant modes is presented in Table 3.

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1. A is designated 1549 in model with coordinates (0,13.8,14.4) and B is 2371 with coordinates (23,5.7,1.5) Top of the building is 19.5.
### Table 3 Maximum Metric of Magnitude & Phase Perth

Results of the peak displacements for the two nodes are presented in Table 4.

<table>
<thead>
<tr>
<th>Node</th>
<th>Axis</th>
<th>Metric</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>X</td>
<td>140</td>
<td>300</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>250/250</td>
<td>150</td>
</tr>
</tbody>
</table>

### Table 4 Peak displacements (mm) Perth

The results for the ISMES model are the first two natural frequencies for the model are 9.72 and 11.5 Hz. The analysis shows dominant sway in the long axis or X direction of 9.57 Hertz and the Y direction of 11.5 Hertz. The dominant frequencies for the orthogonal directions for the ISMES Modal for two nodal points are given in Table 5.

<table>
<thead>
<tr>
<th>Node</th>
<th>Axis</th>
<th>Metric</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>X</td>
<td>130</td>
<td>120</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>250</td>
<td>4</td>
</tr>
</tbody>
</table>

### Table 5 Dominant Frequencies ISMLES

The peak FFT metric for each of these nodes and the dominant modes is presented in Table 6.

<table>
<thead>
<tr>
<th>Node</th>
<th>Axis</th>
<th>Metric</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>X</td>
<td>11.5</td>
<td>9.6/27</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>11.5</td>
<td>9.6/27</td>
</tr>
</tbody>
</table>

### Table 6 Maximum Metric of Magnitude & Phase ISMLES

The peak FFT metric for each of these nodes and the dominant modes is presented in Table 7.

<table>
<thead>
<tr>
<th>Node</th>
<th>Axis</th>
<th>Metric</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>X</td>
<td>62</td>
<td>16/6</td>
</tr>
<tr>
<td>5</td>
<td>X</td>
<td>60</td>
<td>16/6</td>
</tr>
</tbody>
</table>

### Table 7 Peak displacements (mm) ISMLES

This metric is for comparison purposes only. This data has not been translated to SI units for this paper. The results highlight the destructive power of the dominant mode, even with a spectrum with some breaks. A single frequency dominates from the applied trace in each of the orthogonal directions.

### 6 LOADING PATTERNS

Abrams et al. [18] used a repeated simplistic cyclic pattern to model the response of clay-unit masonry to repeated compressive forces. It is analogous to the Type B pattern detailed in Tomazevic and Lutman [19]. The four patterns used by Tomazevic are presented in Figure 6.

![Loading Patterns](image)

**Figure 6** Loading Patterns (after Tomazevic.)
(a) Monotonic, (b) Cyclic Type B, (c) Cyclic Type C and (d) simulated earthquake response.

Tomazevic identified as a problem for unreinforced masonry research, the dependence of the results on the type of synthetic loading pattern used for the masonry panel tests.

There are underlying principles that reflect the development of these loading patterns. These principles provide a framework for the development of a single loading pattern to replace the four dynamic patterns used by Tomazevic.
The four patterns are a monotonically increasing load, two cyclic patterns and an earthquake pattern. The first of the true cyclic patterns, (B), uses a constant frequency with stepped increasing amplitude. The second of the patterns, (C), is a beat pattern with a dynamic frequency of 1 Hz and the final pattern is a particular earthquake. The first loading pattern is analogous to the quasistatic pattern that has been investigated by Page [20], and Ganz & Thurlimann [21]. The final loading pattern of Tomazevic is a particular earthquake. Without an FFT of the trace, it is difficult to assess the applicability of this earthquake event. Its duration is 41 seconds and the event is of Yugoslavian origin. All earthquake traces used as actuator loads suffer from the problem of unique signature, quantification of the energy being applied and the simple question of applicability to a generalized situation.

The two cyclic patterns illustrate a number of features of sound pattern design. The first feature is increasing amplitude. The second feature is relatively constant frequency or mixture of frequencies. In designing a pattern, there is an interest in mimicking a typical design earthquake scenario, encountered by a range of masonry structures. The features, from considering the analysis of the two buildings and using a number of earthquake traces are

- Buildings can be subject to multiple events that are separated in time by anything from seconds to decades.
- The damage suffered by masonry buildings accumulates with time. This damage with time is evident in structures subject to repeated events such as the recent Assisi swarm.
- The accumulator or damage mechanic suggests an increasing destruction or damage to the material with applied energy. The application of an energy regime, that is strictly quantifiable, is thus of more than passing interest. Tomazevic [22] has commented on this point.

- The pattern should span the range of frequencies likely to encountered by masonry buildings. The simplistic elastic analysis completed using Strand6 provides a reasonable guide to the likely range of events and building response to particular earthquake events. It provides limiting criteria for the development of an actuator pattern.

The pattern design should meet the criteria detailed in Table 8.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Cyclic</td>
</tr>
<tr>
<td>Format</td>
<td>Repeatable at a frequency level.</td>
</tr>
<tr>
<td>Frequency lower limit</td>
<td>1 to 2 Hz.</td>
</tr>
<tr>
<td>Frequency upper limit</td>
<td>10 to 14 Hz.</td>
</tr>
<tr>
<td>Amplitude</td>
<td>Increasing with time in a stepped pattern.</td>
</tr>
<tr>
<td>Data</td>
<td>Ability to monitor energy application.</td>
</tr>
<tr>
<td>Quiescent Periods</td>
<td>Yes of at least seconds duration or longer.</td>
</tr>
<tr>
<td>Jerk</td>
<td>Limit.</td>
</tr>
<tr>
<td>Beat Pattern</td>
<td>Not desirable.</td>
</tr>
<tr>
<td>Load Application at constant amplitude</td>
<td>10 to 80 seconds.</td>
</tr>
</tbody>
</table>

Table 8 Pattern design criteria.

The development of the pattern is predicated on meeting as many of these criteria or limits with in the limitations of the available equipment. The Instron used for the experimental work can be programmed using an external trace to the range of events listed by Tomazevic. The key point is minimizing the jerk (rate of change of acceleration with time) on the instrument and hence the panel of masonry. These criteria suggest a pattern of several frequencies, each frequency is applied for a set period at a constant amplitude, quiescent periods are allowed between load applications, differing frequencies may occur in sequence and the amplitude will increase with time. Further research work is currently being com-
completed on masonry panels to provide a formal definition for the pattern to be used in the research into the dynamic failure of masonry panels.

7 THE TEST RIG

A diamond test rig has been developed that is capable of providing non-proportional uniform compression in two normal planes and a time varying shear load. The rig details are presented in detailed design in Nichols and Totoev [23]. The rig design is based on a concept presented by Macchi [24]. A plan of the rig is shown in Figure 7. This equipment is designed to fit within an existing Instron Frame of 300 UB 3.5 metres high by 3 metres long situated on the strong floor at the Civil Engineering Laboratory at the University of Newcastle.

8 CONCLUSION

This paper has provided a summary of the set of criteria for the development of a loading pattern for the use in a dynamic inplane series of masonry experiments. The research involved collection of a set of seismic traces. These were collected from several sources. Each set of traces was analysed in the frequency domain to determine their characteristics using Fast Fourier Transforms. Two buildings were selected as representative of a range of masonry buildings. The first building is a seven-storey apartment located in Perth. The second is the two-storey ISMSE test buildings from Italy. Each building was modelled using Strand 6 FEM package. Each was analysed using different earthquake traces. The results from the Nahanni earthquake are presented in this paper. Modelling parameters were obtained from various sources. The acceleration time series output data was analysed using FFT to review the impact of each earthquake.

The criteria suggested from this analysis consists of: a pattern of several frequencies, each frequency is applied for a set period at a constant amplitude, quiescent periods are allowed between load applications, differing frequencies may occur in sequence, but not concurrently and the amplitude will increase in steps with time.

9 REFERENCES

Acapulco, Mexico, Elsevier Science Ltd. Paper 1302


