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PSEUDO-DYNAMIC SEISMIC TESTING OF STRUCTURAL TIMBER ELEMENTS

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Pseudo-Dynamic Seismic Testing of Structural Timber Elements

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Abstract

The best method of determining the seismic capacity of a bracing element is to test it by racking it with cycles of increasing displacement. The maximum mass it can restrain is then assessed analytically but this requires verification with a dynamic test. The pseudo-dynamic test method is now well established as an alternative to shake table testing. It provides increased accuracy and enables much larger specimens to be tested. Currently, the most common method of conducting the dynamic simulation is by applying an incremental displacement to the specimen, pausing while measuring its response and calculating the subsequent displacement increment. Two significant modelling errors are introduced because relaxation reduces the load after the displacement increment is applied and the specimen is subjected to high acceleration pulses at the beginning and end of the displacement increment. A continuous test system, which keeps the specimen moving while the computation for the subsequent increment takes place, has been developed at BRANZ to overcome these errors. The BRANZ test facility is described and a proposed research programme is briefly outlined. The effect of time scale (or loading rate) on the measured loads is also discussed.

Keywords: Analysis, Earthquakes, Mechanical Tests, Pseudo-dynamic, Relaxation, Seismic Rating.

Introduction

One acceptable and reliable method of determining the mechanical behaviour of a structural component (e.g. a simple beam) or subassemblage of components is to subject it to physical testing. Structural components or sub assemblages are normally tested either:

- to verify that they are capable of meeting a required (codified or calculated) level of performance; or
- to assess or rate their performance in order to assign design properties.

These two situations are reasonably similar but the methods of testing and evaluating their performance are significantly different. To illustrate this, consider the following two test methods applied to a bracing wall. For the first, the maximum lateral force to be applied to the wall is calculated. This force is factored to account for statistical variability and applied as a proof load to a sample wall specimen (or to a series of similarly constructed specimens). The wall is deemed adequate if it successfully resists the proof load. The advantage with the proof load test is that the specimen remains unbroken if it performs satisfactorily.

The proof load test gives no indication of the degree of safety over and above its proof load. (Also, it gives no indication of the strength variability needed to calculate the proof load.) Therefore the performance of the bracing wall is often characterised using an alternative method in which the applied load is increased until the sample fails. A characteristic strength of the sample (normally the lower fifth percentile) is then obtained statistically from the failure load(s).

These two example tests are commonly used to verify or assess the specimen strength. The physical test arrangement is similar for both tests, with a lateral load, P, applied to the top of the specimen anchored to a suitable foundation (Figure 1). A typical lateral load-displacement (P-Δ) response of the specimen to these monotonic tests is depicted within the Figure 1a test specimen.

A different form of test is required to assess the inelastic deformation capacity, commonly called 'ductility', of a specimen subjected to earthquake shaking. The reverse cyclic test (Figure 1b), with one or more complete cycles at each of a series of incrementally increasing displacements, is often used to characterise ductility. The difficulty with characterising it in this manner is that previous test cycles affect the response and the rating.

The pseudo-dynamic and shake table tests (Figure 1c and 1d respectively) are used to verify the behaviour of a specimen subjected to earthquake shaking. These tests subject the specimen to the same motion as it would experience in a nominated or design earthquake, although the pseudo-dynamic test provides a number of advantages as will be shown later. Currently, neither test directly rates the wall so a series of tests is used to both rate and verify the inelastic deformation capacity of a bracing wall.

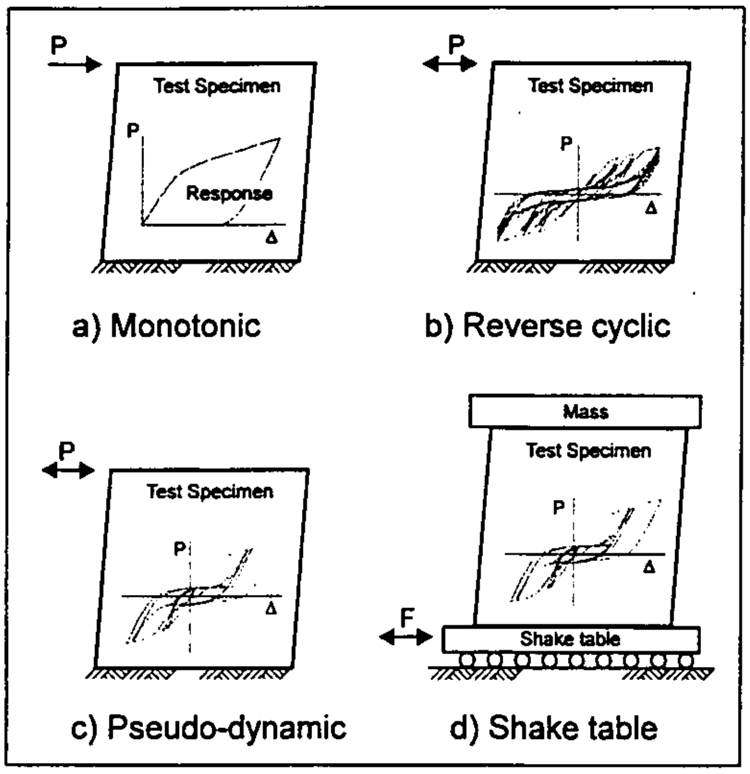


Figure 1. Specimen test methods

Deam and King (1994) have shown that it is more appropriate to rate degrading bracing elements in terms of the greatest mass they can restrain without collapse in a given earthquake than to assign an artificial yield point and ductility. The following procedure is proposed as a method of both rating and verifying the mass able to be restrained by a particular bracing element for a design earthquake.

1. Conduct a monotonic racking test (Figure 1a) with one specimen to determine its ultimate strength. This is required to determine the maximum force it can impose upon its restraint components.
2. Subject a second identically constructed specimen to a reverse-cyclic racking test (Figure 1b). This may have some cycles to a service level load (i.e. to about 8 mm deflection for a 2.4 m high specimen) followed by pairs of cycles at each subsequent deflection increment.
3. Fit an analytical model to the response of the second specimen and use this to determine the mass which can be restrained by the specimen during a design level earthquake. The details and a computer program suitable for this step are reported elsewhere (Deam and King 1994 and Deam 1996).
4. Conduct a pseudo-dynamic proof test with a third specimen to verify that it is capable of restraining the rated mass.

At the time of writing, this rating procedure itself is not completely defined or verified but it is included here to show where it is placed as a test method.

Relaxation introduces one of the greatest difficulties in realistically testing timber components. It is well known that the strength of timber increases as the rate of loading increases. It is likely that the strength at a seismic loading rate is higher than at a quasi-static rate because there is no relaxation rather than because the material strength increases.

The effects of relaxation are illustrated in Figure 2. Here the load-displacement response of a timber component loaded using a hand operated actuator shows drops in load during the pauses while the pump handle is lifted.

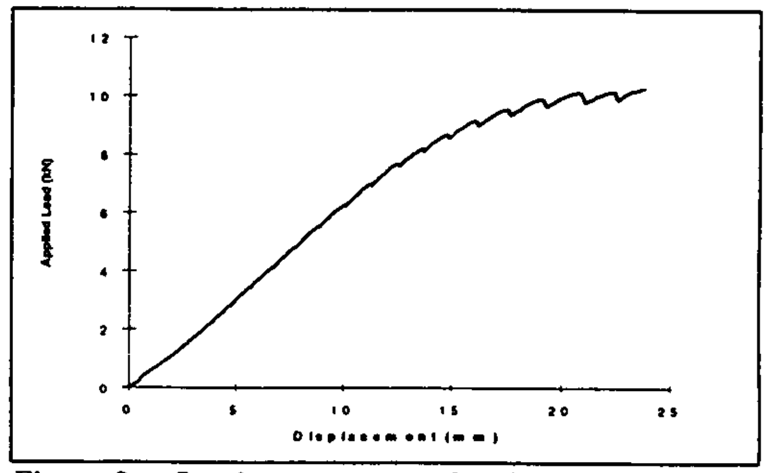


Figure 2. Specimen response showing relaxation.

The remainder of this paper describes the pseudo-dynamic test method and how it was adapted and implemented at BRANZ to overcome the difficulties traditionally encountered using this method due to relaxation. Preliminary test results from the BRANZ continuous test facility will be presented at the conference.

The Pseudo-dynamic Technique

The pseudo-dynamic test method simulates the inertial response of the mass in a shake-table test by racking the test specimen. It only requires the test specimen itself as the mass and other physical aspects are modelled analytically.

The pseudo-dynamic test method offers several significant advantages over the physically equivalent shake table test method:

- the duration of the test may be conveniently extended to allow more detailed observation of the specimen;
- the earthquake record can be adapted during the test in response to the behaviour observed during earlier parts of the test.
- it does not require a mass to be attached to the specimen (which also increases the safety for those observing the test);
- the fidelity of the reproduction of the ground motion is greatly improved and the specimens may be physically much larger because the hydraulic equipment is not required to move the mass and shake table at the dynamic rate; and
- the specimen may be tested so that it responds as though it is within a complete structure because the remainder of the structure can be modelled analytically.

In spite of these advantages over shake-table testing, the pseudo-dynamic method was first employed as a test method for timber structures (Kamiya 1988) more than a decade after the method was first described (Takanashi et al. 1974). Unfortunately, the pseudo-dynamic test is not realistic for facade specimens, such as masonry walls, which do not restrain floors and have their mass distributed throughout the specimen.

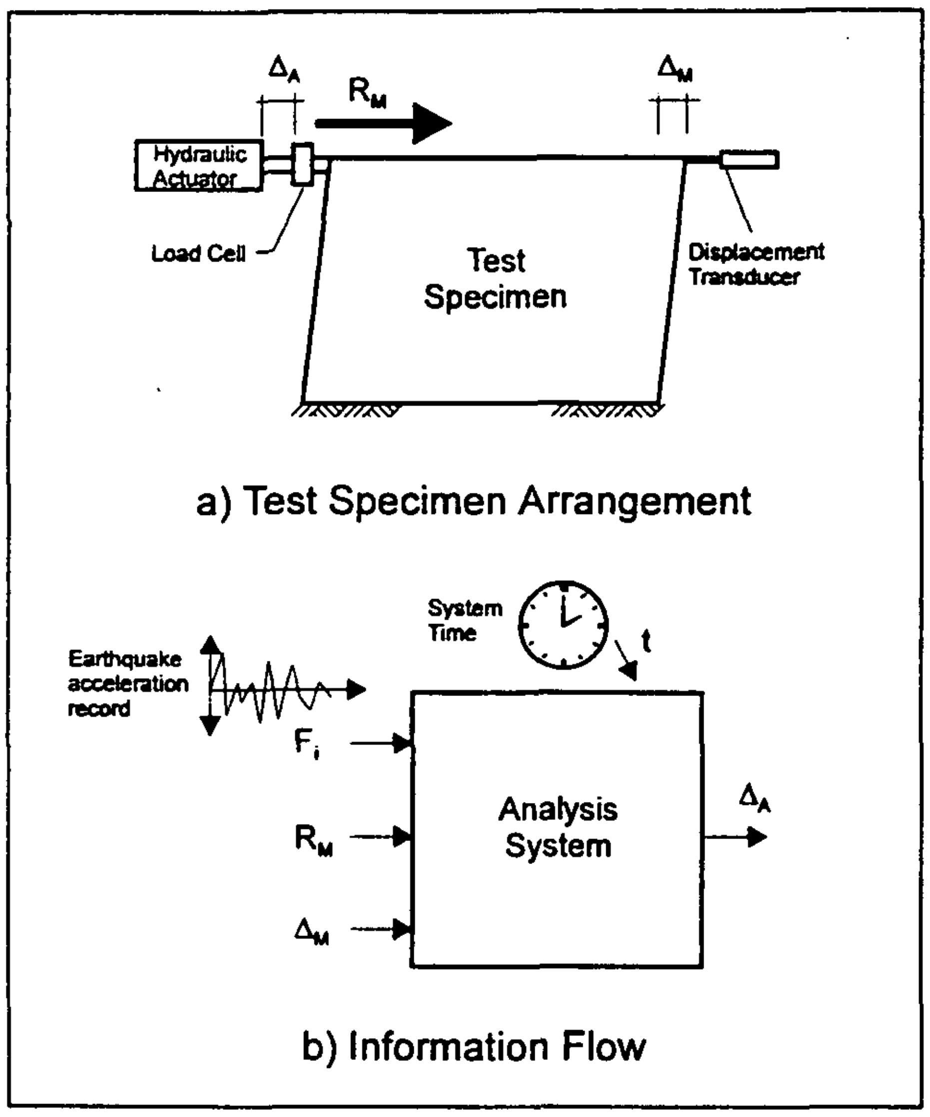


Figure 3. The pseudo-dynamic method.

The equipment used for a pseudo-dynamic test is essentially the same as is used for a monotonic or reverse cyclic test (Figure 3a). The test specimen is racked using a servo-hydraulic actuator to apply displacement Δ_A. The load, R_M, and specimen displacement, Δ_M, are measured by a precision load cell and displacement transducer respectively. (Strains in the equipment and supports often make Δ_A and Δ_M different.) The analysis system (Figure 3b) combines the earthquake record with the measured load and displacement to generate the subsequent actuator displacement. The analysis is synchronised by a system clock.

The analysis system, the heart of the method, has been implemented in a variety of ways by previous researchers. All of the methods are based on the solution to the classical equation of motion for a single-degree-of-freedom system (Equation 1) which relates the acceleration, a, velocity, v, and displacement, d, of mass M to the instantaneous stiffness, K, of the element, the seismic force, F, and a viscous damping term, C:

$$Ma + Cv + Kd = F \qquad (1)$$

Equation 1 is normally solved using numerical integration to obtain the velocity and displacement from the acceleration. There are many algorithms available for performing the numerical integration, most using a finite difference approach. Each algorithm introduces or amplifies one or more types of error when performing the integration so the algorithm is chosen to minimise the errors in the most important aspects.

Equation 1 itself is commonly modified to improve the accuracy of the solution when used within a pseudo-dynamic system. A particularly useful improvement in accuracy can be obtained by replacing the stiffness term, Kd, with the measured force, R_M. This significantly reduces measurement errors, particularly for very stiff specimens, because the stiffness can not be measured directly and is normally calculated from the load and displacement measurements. Further modifications are necessary when the specimen is tested as part of an analytical structure.

It is almost essential that the measured force be used for timber specimens because relaxation makes calculation of the stiffness even more prone to error.

A second common modification to Equation 1 is to replace the viscous damping, Cv, with dissipation (i.e. damping) within the integration scheme itself (e.g. Thewalt and Mahin 1995). (Damping is required to reduce numerical errors or instability in the higher modes of vibration when Equation 1 is extended to multiple degrees-of-freedom as well as to model its physical presence.) The damping is indirectly defined with dissipation because it is controlled by less obvious parameters within the solution algorithm.

Dissipation is often used in place of damping because Equation 1 artificially couples the vibration modes together in a manner which may cause the higher frequency modes to distort the more useful lower frequency modes (Nakashima and Kato 1987). Shing and Mahin also reported that constant viscous damping produces 'unexpected results' in non-linear tests (Thewalt and Mahin 1995). The 'unexpected results' are most likely to occur because the damping, based on the mass and initial specimen stiffness, remains high when the specimen degrades and the stiffness reduces. This could be more significant in timber because the stiffness is more consistently lower than it is in other materials (in these it only reduces when the specimen is 'yielding').

Hilber, Hughs and Taylor's (1977) variation on Newmark's integration algorithm was chosen for the BRANZ test facility because it is able to provide dissipation when required. The algorithm consists of a series of equations which are solved to give d, v and a at discrete times or steps during the course of the test. For a single degree-of-freedom system, the algorithm has the following set of equations (Thewalt and Mahin 1995):

$$Ma_{i+1} + Cv_{i+1} + (1+\alpha)R_{M.i+1} - \alpha R_{M.i} = F_{i+1} \quad (2)$$

$$d_{i+1} = d_i + \left[v_i + \left((0.5-\beta)a_i - \beta a_{i+1}\right)\Delta t\right]\Delta t \quad (3)$$

$$v_{i+1} = v_i + \left((1-\gamma)a_i - \gamma a_{i+1}\right)\Delta t \quad (4)$$

where the i subscripts denote the time at step $i\Delta t$ and α, β and γ are the integration parameters. Stability and desirable dissipation properties are achieved by setting β and γ to the following functions of α:

$$\beta = (1-\alpha)^2 / 4 \quad (5)$$

$$\gamma = 0.5 - \alpha \quad (6)$$

The useful range of α is from -1/3 to 0 with $\alpha = 0$ giving Newmark's trapezoidal rule (with no dissipation). The dissipation and period error both increase as the time step, Δt, increases relative to the natural period, T, as shown in Figure 4 (Hilber et al. 1977). Figure 4 also shows that the period error can be quite considerable when the time step approaches the natural period.

The sequence of events traditionally used for each step during a pseudo-dynamic test are illustrated in Figure 5 (Mahin and Shing 1985). The step begins with a 'hold' (where the specimen is held stationary) immediately after the previous step is completed. Load and displacement measurements are acquired and used in Equations 2 to 4 above to determine the target displacement, d_{i+1} , at the end of the step. The servo-actuator then applies the target displacement at a constant velocity to complete the step. (This part of the step is termed 'ramp'.)

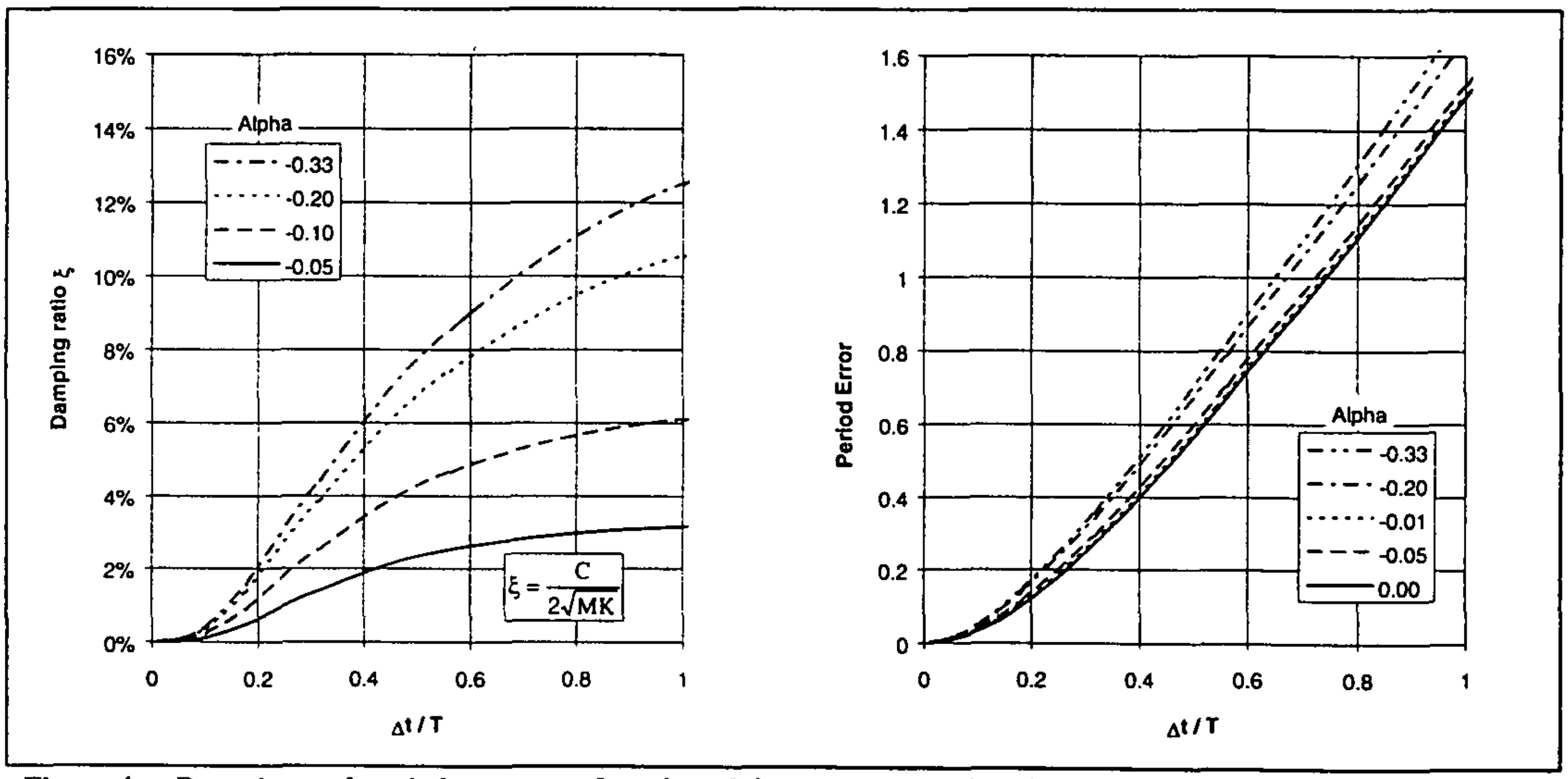


Figure 4. Damping and period error as a function of time step, natural period and α (Hilber et al. 1977).

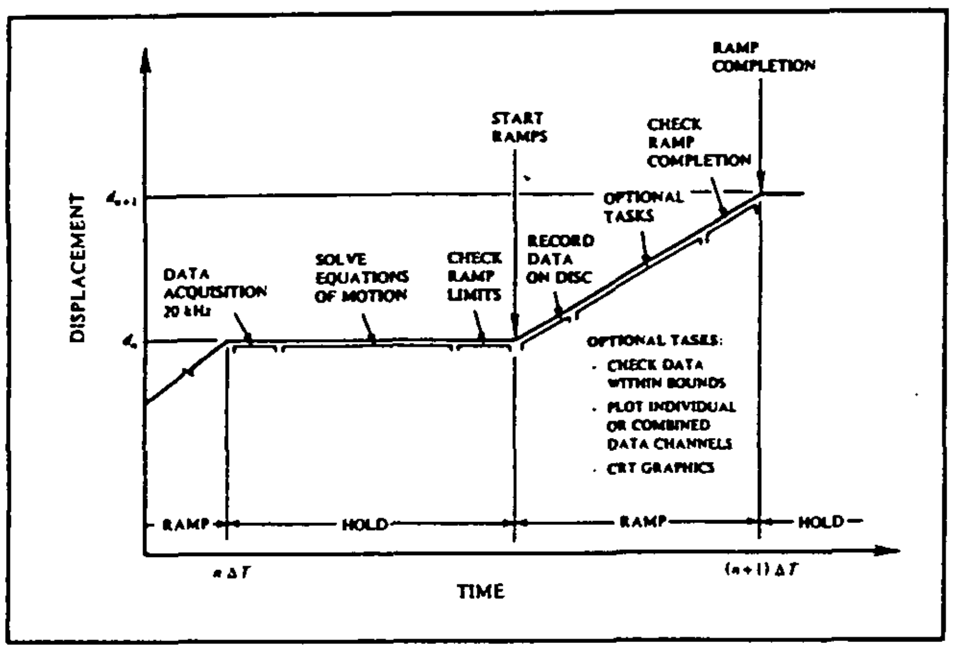


Figure 5. Tasks performed in each step of a pseudo-dynamic test (Mahin and Shing 1985).

This process is reasonably straight forward for a single degree-of-freedom (DOF) specimen but a multiple DOF system requires separate control for each actuator or axis. The ramp velocities for each axis are set so the new positions are attained simultaneously at each axis but the interaction between the axes, particularly where the specimen is very stiff (Seible, Hegemier and Priestley 1991), affects the load distribution within the specimen. To overcome this, the multiple axis test was simplified to a single mode by Seible et al. who conducted a pseudo-dynamic test using the response of the top storey only. The two lower axes on their 3 storey specimen were arranged to apply a fixed portion of the force at the top.

The analysis system (Figure 3b) adopted by most experimenters to date calculates the target displacement for the end of the step using the force acquired at the beginning of the step. This can make Equation 1 unbalanced at the end of the step when the specimen stiffness changes during the step. This is normally corrected in the subsequent step but the error may accumulate when this occurs over a large number of steps.

Thewalt and Mahin (1995) observed that the load (or a representative voltage) is available throughout the ramp (Figure 5) even though it has not been acquired by the computer. They reasoned that this force could be used to modify the applied displacement, correcting it for non-linear specimen behaviour while the ramp is in progress. To do this (Figure 6), they separated the Equation 2-4 algorithm above into implicit and explicit components. The explicit component was calculated once at the beginning of the ramp and held constant throughout the ramp. The axis command displacement was then continuously updated during the ramp using an analog computer to add the explicit component to the implicit component derived from the measured force.

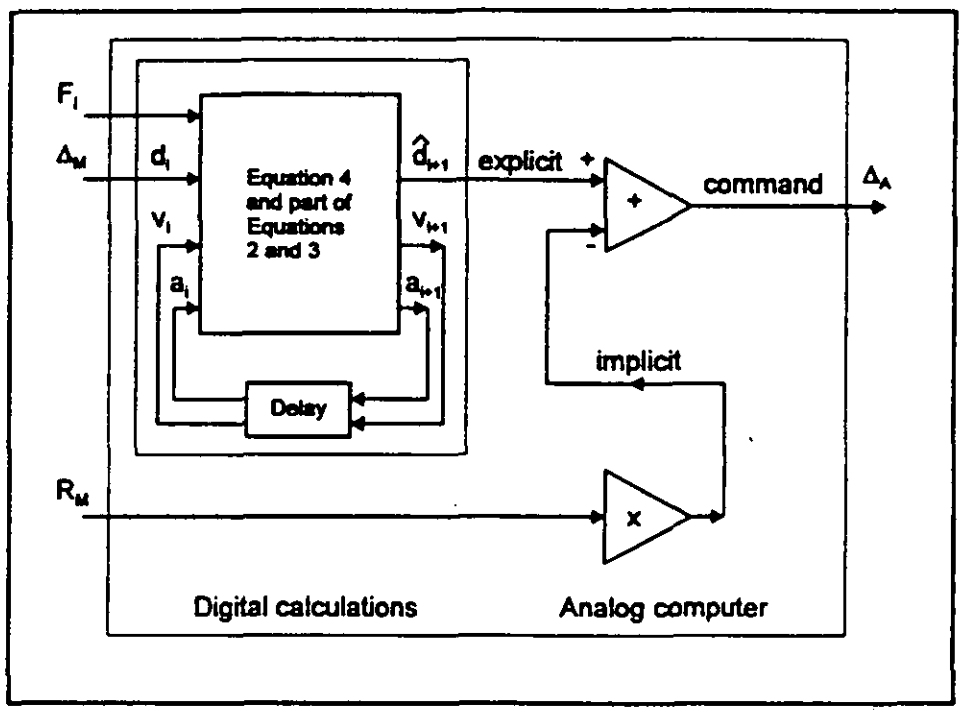
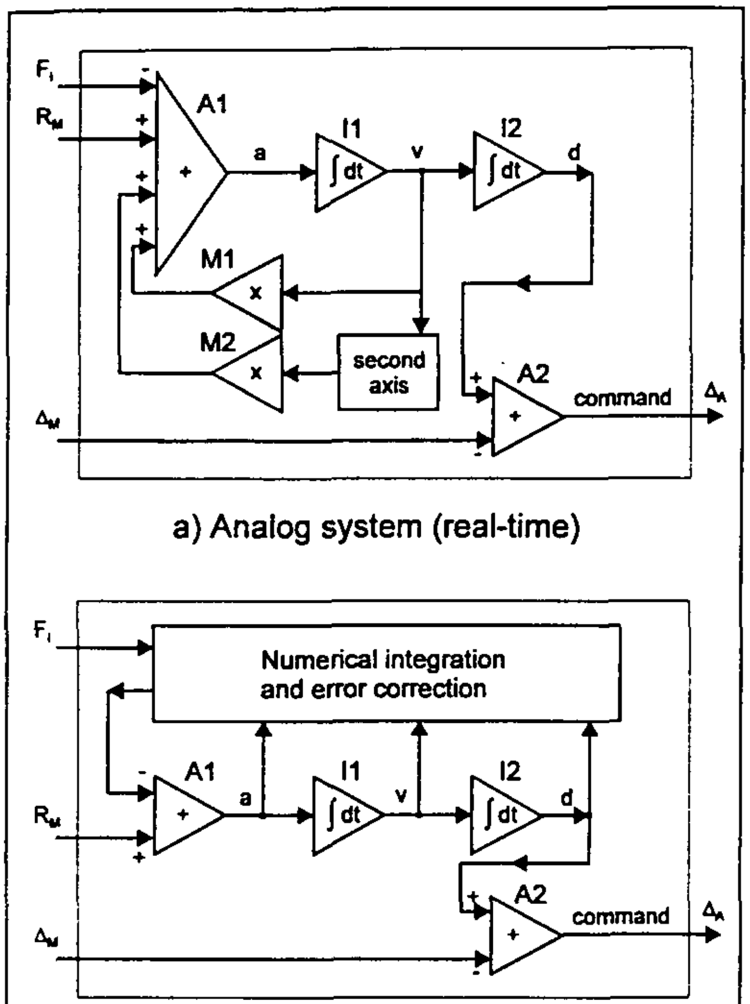


Figure 6. Thewalt and Mahin's analysis system.

BRANZ Continuous Test Facility

A continuous pseudo-dynamic test facility has been developed at BRANZ which will be capable of testing components or sub assemblages susceptible to relaxation. The continuous test eliminates the possibility of relaxation during the hold phase of the traditional ramp and hold method (Figure 5). Recent advances in computing power have significantly reduced the time required for the hold period but it still allows relaxation. The continuous method also avoids applying acceleration pulses to the specimen at the beginning and end of the ramp.

The analysis system is implemented in the two forms shown in Figure 7. In the first, the integration is performed by an analog computer to give continuous control over the acceleration, velocity and displacement of each axis. The information flow for the analog system is given in Figure 7a for one of two axes. The system for the second axis is identical. Adder A1 is used to obtain the acceleration using Equation 2 above for each force increment F_i. This is integrated twice using I1 and I2 to obtain the velocity and displacement respectively (analogous to Equations 3 and 4). Multipliers M1 and M2 return the damping forces from each axis to adder A1. (Multiplier M2 is not required for a single axis test.) Adder A2 is used to make Δ_M equal to the displacement command signal d. This adder is incorporated in the servocontroller in the BRANZ test facility.



a) Analog system (real-time)

b) Mixed system (scaled time)

Figure 7. BRANZ continuous analysis systems

The analog continuous analysis system is ideal for conducting real-time tests because it only requires the earthquake acceleration record to be input. The data acquisition system may be completely separated from the controller.

There are several significant disadvantages with the analog system:

- that the analog computer requires very precise adjustment to reduce drift errors. This is particularly important when the test time is extended because the drift increases;
- the damping is directly coupled between axes. This is not able to be replaced by more desirable numerical dissipation; and
- the specimen is not able to be tested so that it responds as though it is within a complete structure because the remainder of the structure can not be modelled easily.

The mixed analysis system shown in Figure 7b was developed to overcome the shortcomings with the analog system. The mixed analysis system performs numerical integration in parallel with the analog control system to give precise control over the acceleration, velocity and displacement of the specimen. It is also able to apply corrections to the acceleration fed into the analog system to virtually eliminate both drift and modelling errors.

The test time currently has to be long enough to accommodate the delay associated with measuring, calculating and applying the corrected accelerations. Faster digital signal processing equipment should be able to allow real-time earthquakes to be applied using the mixed system.

The BRANZ pseudo-dynamic test facility currently has two axes. One axis has a 90 kN actuator with 500 mm stroke and a maximum velocity of 200 mm/sec. The second axis has a 200 kN actuator with 300 mm stroke and a maximum velocity of 600 mm/sec. These are able to be bolted to a 6 m high 5 m wide reaction wall with a 400 mm grid. The specimen is attached to a 9 m long 5 m wide reaction floor, also with a 400 mm grid.

Research Plan

With the design of the BRANZ pseudo-dynamic test facility completed and the implementation in progress at the time of writing, the following research plan will be of interest to other researchers.

A series of timber framed test specimens sheathed with plaster board, plywood and cement board is currently being constructed. These will be used to verify the ratings currently assigned to them using the PhylMas program (Deam 1996).

The rate of loading (or time required for the test) has been highlighted as a significant factor in determining the strength of the specimens. Pairs of closely matched walls will be subjected to real-time earthquake and quasi-static rates of loading to investigate the differences in the magnitudes of the strength and mass able to be restrained.

The degree and form of damping (or dissipation) has been highlighted as having a significant effect upon the dynamic response of a specimen. The sensitivity will be investigated numerically and verified using the pseudo-dynamic test.

The rating system described in the introduction requires verification. One area or uncertainty is the earthquake record itself. Records are available which match the New Zealand uniform risk design spectra but it may be important to ensure that there is a degree of reserve capacity for a 'maximum credible' earthquake. It may be desirable that a fourth specimen be used to verify that the behaviour is not catastrophic when a stronger earthquake occurs.

The accuracy of the PhylMas analytical model will be improved by analysing the responses obtained in pseudo-dynamic tests of a range of degrading components.

Structural systems with a mixture of bracing and so-called non-structural elements will be able to be tested to verify that the non-structural elements do not introduce undesirable strength reductions in the bracing elements.

The response of two axis specimens either with two storeys or torsion will be analysed and verified.

Conclusions

This paper has outlined the desirability of testing bracing systems both as a means of rating and verifying their performance when subjected to seismic loading. A rating method has been proposed which uses a combination of reverse cyclic and pseudo-dynamic testing.

The relaxation present in timber components has been shown to be a problem in conducting tests. The traditional method used for pseudo-dynamic testing introduces several major errors into modelling dynamic performance.

A continuous pseudo-dynamic test method has been developed at BRANZ to overcome these shortcomings and is, at the time of writing, in the process of being implemented.

The pseudo-dynamic test facility will provide a significantly better understanding of the manner in which one and two storey construction is to be designed in order to resist earthquakes.

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