# DESIGN OF MASONRY STRUCTURES FOR EARTHQUAKE IN AUSTRALIA

Rod Johnston

Principal of Electronic Blueprint
Principal of Quasar Management Services Pty Ltd
(Consultant to the Concrete Masonry Association of Australia)

## SUMMARY

This paper deals with the design of masonry buildings for earthquake loads in Australia, in the context of the publication of AS 1170.4-2007 and AS 3700 Amendment 3. It covers:

- Probability of exceedance of load and probability of failure.
- Design of masonry at base of the building for in-plane base shear
- Design masonry walls for out-of-plane face load
- Geometric limitations on masonry building height.

## BACKGROUND

Until the 1970's, there was no comprehensive design standard controlling the design of masonry buildings in Australia. These were designed by a combination of engineering judgement, rule of thumb and experience. Over the last thirty years, piecemeal introduction of loading rules and capacity rules has led to a situation where, using AS 3700-2001 *Masonry structures* with AS 1170.4-1993 *Earthquake loads*, traditional construction can no longer be justified in many cases. The simultaneous publication of AS 1170.4-2007 and AS 3700 Amendment 3 seeks to redress these anomalies.

## APPROPRIATE PROBABILITY OF EXCEEDANCE FOR VARIOUS LOADS

Extreme wind loading occurs reasonably frequently, and the BCA (Building Code of Australia) has the following requirements. For wind load, BCA Vol 2 requires housing to be designed to AS 4055. This infers an annual probability of exceedance of 1 in 500. For wind load, BCA Vol 1 requires other buildings to be designed for an annual probability of exceedance of:

1 in 500 Importance Level 2
1 in 1000 Importance Level 3
1 in 2000 Importance Level 4

Earthquakes occur infrequently in Australia, but perhaps more often than is commonly appreciated. For earthquake load, BCA Vol 2 requires housing to be designed to AS 1170.4-1993. This infers an annual probability of exceedance of 1 in 500. However, AS 1170.4-2007 will exempt most houses from design for earthquake. For earthquake load, BCA Vol 1 requires other buildings to be designed for an annual probability of exceedance of:

1 in 500 Importance Level 2
1 in 500 Importance Level 3
1 in 800 Importance Level 4

The apparent anomalies between the treatment of earthquake and wind loads give rise to the following comments.

- There should be more consistency in the BCA for probability of exceedance for various loads.
- Exemptions within the AS 1170 loading standards (e.g. the exemption of AS 1170.4-2007 Appendix A for earthquake design of housing) should not undermine the specified BCA probabilities of exceedance for loads.
- BCA specifies probabilities of exceedance of load, but not probabilities of collapse. In other words, BCA defines the loads, but not the capacities. It relies on Australian Standards and various other manuals to do this.

## OBJECTIVES OF AS 1170.4-2007

The Draft Commentary to AS 1170.4-2007 stated that the earthquake loading standard has three objectives. These are reproduced in Appendix 1. A simplification of these objectives is presented below:

- Remain serviceable under earthquake loads likely to be exceeded once in approximately 10 years
- Resist collapse under earthquake loads likely to be exceeded once in approximately 500 years
- Maintain a reduced probability to resist collapse when subjected to a “strong” earthquake.

## DETERMINATION OF EARTHQUAKE LOADS

Set out below are the principal steps involved in determining the earthquake loads in accordance with AS 1170.4-2007.

1. Annual probability of exceedance and $k_p$ .
   Using AS 1170.0 and the BCA, determine the acceptable annual probability of exceedance for earthquake loads for the particular building Importance. Using Table 3.1, determine the appropriate Probability Factor, $k_p$. For example, for earthquake load acting on a building of Importance Level 2, the design event for safety has an annual probability of exceedance of 1 : 500 and $k_p$ = 1.0.

2. Hazard factor, z
   Using Section 3, determine the Hazard Factor, z, for the particular location.
   For example, in Hobart z = 0.03, in Brisbane z = 0.05, in Sydney, Melbourne and Canberra z = 0.08, in Perth z = 0.09, in Adelaide z = 0.10 and in Newcastle z = 0.11.

3. Housing?
   If the structure meets the specified limitations for domestic structures (housing) with a height not greater than 8.5 m, use Appendix A to determine any design and/or detailing requirements. Otherwise proceed as below. Only housing in locations with a hazard factor, z, greater than 0.10 need to have any specific design or detailing for earthquake load.

4. Subsoil
   Using Section 4, determine the Site Subsoil Class. These may be described approximately as: A = Strong rock, B = Rock, C = Shallow soil, D = Deep or soft soil, E = Very soft soil.

5. Earthquake Design Category
   Using Section 2, including Table 2.1, determine the appropriate Earthquake Design Category (EDC). This will depend on Hazard Factor (location), Site Subsoil Class, Height and Importance.

6. EDC I
   For EDC I, use Clauses 5.2 and 5.3 to determine base shear and horizontal forces up the building, which are taken as 10% of the seismic weight, $W_i$, at the particular level.

7. EDC II
   For EDC II, use Clauses 5.2 and 5.3 and Section 6 to determine the horizontal forces by static analysis. This considers:
   - Probability Factor, $k_p$ ,
   - Hazard Factor, z,
   - Ductility, μ,
   - Structural Performance Factor, $S_p$, and
   - Spectral Shape Factor, $C_{1(T)}$, which depends on:
     - Sub Soil Class and
     - Period of vibration.

8. EDC III
   For EDC III, use Clauses 5.2 and 5.3 and Section 7 to carry out a dynamic analysis to determine the horizontal forces.

9. Parts
   Using Section 8 where appropriate, determine the earthquake forces on the Parts (those members that are not part of the seismic force resisting system)

## ANALYSIS METHOD

The simplest and most common analysis for simple masonry structures will be the equivalent static method, which ignores cyclic reversal of loads and the short period of application of loads. The equivalent static analysis method ignores the displacement history under load, and is considered to be conservative in many cases, particularly for high frequency earthquakes that produce small displacements.

## FUNDAMENTAL PERIOD

The Fundamental Period of a building, $T_1$, is the natural period of vibration of the building, determined using the maximum of:

$T_1$ = 1.25 $k_t h_n^{0.75}$
$T_1$ = 0.4 seconds for site sub-soil class A, B or C, or
$T_1$ = 0.6 seconds for site sub-soil class D, or
$T_1$ = 1.0 seconds for site sub-soil class E

It is reasonable to assume that masonry buildings up to 15.0 m high are stiff elastic brittle structures, $k_t$ = 0.05, commonly leading to a Fundamental Period of 0.4 seconds. On the other hand, buildings over 15.0 m high generally include moment-resisting concrete frames or steel frames, $k_t$ = 0.075.

## SPECTRAL SHAPE FACTORS

Spectral Shape Factors $C_{h(T)}$, are used in the determination of acceleration at the centre of weight of the building.

| **Spectral Shape Factors, $C_{h(T)}$** | | | | | |
|---|---|---|---|---|---|
| Period (seconds) | A Strong Rock | B Rock | C Shallow Soil | D Deep or Soft Soil | **E Very Soft Soil** |
| 0 < T ≤ 0.1 | 0.8 + 15.5 T | 1.0 + 19.4 T | 1.3 + 23.8 T | 1.1 + 25.8 T | **1.1 + 25.8 T** |
| 0.1 < T ≤ 1.5 | min (0.704/T, 2.35) | min (0.88/T, 2.94) | min (1.25/T, 3.68) | Min (1.98/T, 3.68) | **Min (3.08/T, 3.68)** |
| T > 1.5 | 1.056/T2 | 1.32/T2 | 1.874/T2 | 2.97/T2 | **4.62/T2** |
| **Where T is the calculated period of vibration** | | | | | |

## STRUCTURAL DUCTILITY FACTOR AND STRUCTURAL PERFORMANCE FACTOR

Masonry buildings up to and including four storeys high commonly have an earthquake resisting system that is provided by the unreinforced masonry, with or without contribution by a concrete shear core (e.g. four storey brickwork home units). The following factors are designated in AS 1170.4-2007.

Structural Ductility Factor, $\mu$ = 1.25
Structural Performance Factor, Sp = 0.77

Buildings over four storeys high (with or without masonry elements) most often have an earthquake resisting system that consists essentially of reinforced concrete frames and the isolated unreinforced masonry, e.g. high rise concrete framed buildings with or without shear walls and with isolated masonry partitions or cladding. The masonry does not normally provide a substantial contribution to the earthquake resisting system. The following factors are designated in AS 1170.4-2007.

Structural Ductility Factor, $\mu$ = 2.0
Structural Performance Factor, Sp = 0.77

## SEISMIC WEIGHT

For face loads on masonry walls, the Seismic Weight, $W_t$ , is taken as the mean weight of the particular masonry leaf. In order to minimise shear load transferred at the base and top of the inner leaf of cavity walls, the external leaf of cavity masonry should be fixed directly to each concrete floor slab or bears on a shelf angle at each floor. This is often the case in external cavity walls of high rise construction, but is not common in medium rise construction. For shear at the base of the building, the Seismic Weight, $W_t$ , is taken as the mean weight of the floors above, factored by:

Dead load factor 1.0
Live load factor 0.3
Uniform live load 2.0 kPa

## BASE SHEAR AND ACCELERATION AT VARIOUS HEIGHTS

The Base Shear, V, is given by: $V = k_p Z C_{h(T1)} S_p / \mu \,.W_t$

The Force at any floor is given by $F_i = \dfrac{W_i h_i^{\,k}}{\Sigma_{ni=1} (W_i h_i^{\,k})}$.

Where the exponent is dependent on structure period.

When $T1 \le 0.5$, $k = 1.0$
When $T1 \le 2.5$, $k = 2.0$
When $0.5 < T1 < 2.5$, k is linearly interpolated between 1.0 and 2.0

It is assumed that the buildings being analyzed comprise reasonably similar floors, without soft storeys. The horizontal acceleration at any particular floor is given by the horizontal design action coefficient, $C_{d(T1)}$, multiplied by the factor R. The values of Acceleration Factor at various heights, $K_s$, are the product of Height Amplification factor and Spectral Shape Factor. $K_s = R_{floor}\ C_{h(T1)}$

| Proposed Values for $K_s$ for Table 5.1 | | | | | | |
|---|---|---|---|---|---|---|
| | | 5th | 4th | 3rd | 2nd | 1st |
| 5 | A | 1.8 | 1.4 | 1.0 | 0.7 | 0.3 |
| | B | 2.2 | 1.8 | 1.3 | 0.8 | 0.4 |
| | C | 3.2 | 2.5 | 1.8 | 1.2 | 0.6 |
| | D | 5.0 | 3.9 | 2.9 | 1.9 | 0.9 |
| 4 | A | | 2.9 | 2.2 | 1.5 | 0.7 |
| | B | | 3.7 | 2.8 | 1.8 | 0.9 |
| | C | | 5.2 | 3.9 | 2.6 | 1.3 |
| | D | | 5.9 | 4.4 | 2.9 | 1.5 |
| 3 | A | | | 3.4 | 2.3 | 1.1 |
| | B | | | 4.3 | 2.9 | 1.4 |
| | C | | | 5.5 | 3.7 | 1.8 |
| | D | | | 5.5 | 3.7 | 1.8 |
| 2 | A | | | | 3.1 | 1.6 |
| | B | | | | 3.9 | 2.0 |
| | C | | | | 4.9 | 2.5 |
| | D | | | | 4.9 | 2.5 |
| 1 | A | | | | | 2.4 |
| | B | | | | | 2.9 |
| | C | | | | | 3.7 |
| | D | | | | | 3.7 |

## DESIGN MASONRY WALLS FOR OUT-OF-PLANE FACE LOAD IN AUSTRALIA

The table below summarises the horizontal face load as a proportion of wall weight, at the top of a masonry building, calculated using method EDC II for various Hazard Factors, z, and Sub-soil Classifications (A to E).

**Out-Of-Plane Face Load / Seismic Weight**
$F_{ph}$ / $W_{p\ \ uning}$ EDC II

| z | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.10 | 0.11 | 0.12 | 0.13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.05 | 0.06 | 0.08 | 0.09 | 0.11 | 0.12 | 0.14 | 0.15 | 0.17 | 0.18 | 0.20 |
| B | 0.06 | 0.08 | 0.09 | 0.11 | 0.13 | 0.15 | 0.17 | 0.19 | 0.21 | 0.23 | 0.25 |
| C | 0.08 | 0.11 | 0.13 | 0.16 | 0.19 | **0.22** | 0.24 | 0.27 | 0.30 | 0.32 | 0.35 |
| D | 0.11 | 0.15 | 0.19 | 0.23 | 0.26 | 0.30 | 0.34 | 0.38 | 0.42 | 0.45 | 0.49 |
| E | 0.11 | 0.15 | 0.19 | 0.23 | 0.26 | 0.30 | 0.34 | 0.38 | 0.42 | 0.45 | 0.49 |

The values under 0.10 (shaded) represent a combination of low seismicity (low z) and/or relatively stable sub-soil conditions (A, B or, in one case, C). In these cases, the calculations by EDC II yield a more optimistic result than the simplistic 0.10 (10%) for EDC I. This is as it should be. However, for the majority of cases, this is not the situation. The performance of EDC II calculations, yields a more conservative result than 0.10, leading to the question; "Is EDC I too optimistic to be included in AS 1170.4?"

If one assumes that the weight of a typical masonry leaf is approximately 175 kg/m$^2$, the values calculated above translate to the following earthquake inertia unit forces.

**Out-Of-Plane Face Load (kPa)**
$F_{ph}$

| z | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.10 | 0.11 | 0.12 | 0.13 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 0.08 | 0.10 | 0.13 | 0.16 | 0.18 | 0.21 | 0.23 | 0.26 | 0.29 | 0.31 | 0.34 |
| B | 0.10 | 0.13 | 0.16 | 0.20 | 0.23 | 0.26 | 0.29 | 0.33 | 0.36 | 0.39 | 0.42 |
| C | 0.14 | 0.18 | 0.23 | 0.28 | 0.32 | **0.37** | 0.42 | 0.46 | 0.51 | 0.55 | 0.60 |
| D | 0.19 | 0.26 | 0.32 | 0.39 | 0.45 | 0.52 | 0.58 | 0.65 | 0.71 | 0.78 | 0.84 |
| E | 0.19 | 0.26 | 0.32 | 0.39 | 0.45 | 0.52 | 0.58 | 0.65 | 0.71 | 0.78 | 0.84 |

For the most common case, z = 0.08 (Sydney, Melbourne and Canberra) on subsoil C (shallow soil) the calculated out-of-plane earthquake inertia is 0.37 kPa. This is the level load that might be applied to internal partition walls to account for accidental loading or light wind. It can be seen that, for most common applications, the earthquake inertia load on a single masonry leaf is considerably less than the wind load that might be expected on an external wall.

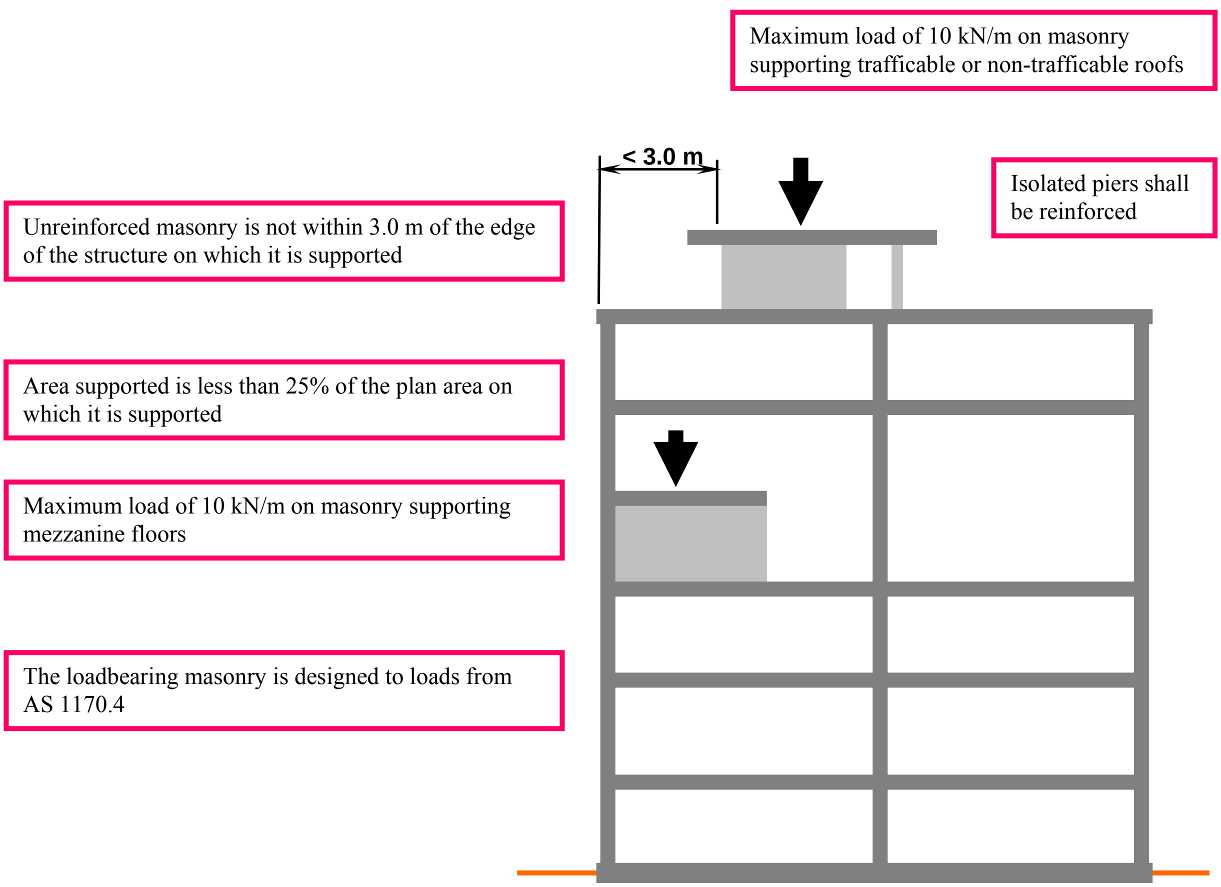
## HEIGHT LIMITS ON LOAD-BEARING MASONRY BUILDINGS

It is possible (but uncommon) to do detailed complex calculations that consider the strengths and stiffness of masonry in a building, its interaction with other members such as concrete floors and shear cores, the deflections and interstorey drifts, and the deterioration of the masonry with the repeated load reversal associated with an earthquake. It may be possible to demonstrate that some relatively tall unreinforced loadbearing masonry buildings are sufficiently robust to remain standing during the relatively benign earthquake behaviour assumed for design purposes in Australia.

However, the committees preparing AS 1170.4 (earthquake loads) and AS 3700 (masonry structures) have agreed that it is prudent to place limits on the heights of buildings that incorporate loadbearing unreinforced masonry. AS 3700 Amendment 3-2007 includes a new Appendix AA, with typical masonry details. It also limits on the height of buildings constructed of loadbearing unreinforced masonry, for various combinations of Hazard Factor, z, and Subsoil Classifications (A to E). These height limits are not intended to restrict buildings that incorporate non-loadbearing unreinforced masonry or reinforced masonry.

| **Height Limits on Load-bearing Masonry Buildings** (metres) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| z | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.10 | 0.11 | 0.12 | 0.13 |
| A | 15 | 15 | 15 | **15** | **15** | **15** | **15** | **15** | **12** | 12 | 12 |
| B | 15 | 15 | 15 | **15** | **15** | **15** | **15** | **12** | **12** | 12 | 12 |
| C | 15 | 15 | 15 | **15** | **15** | **15** | **12** | **12** | **12** | 12 | 12 |
| D | 15 | 15 | 15 | **15** | **15** | **12** | **12** | **12** | **10** | 10 | 10 |
| E | 12 | 12 | 12 | **12** | **12** | **12** | **12** | **10** | **10** | 10 | 10 |

The limits on heights of buildings incorporating loadbearing masonry are relaxed when the particular loadbearing masonry meets all of the following criteria.



## CONCLUSIONS AND RECOMMENDATIONS

1. The BCA (Building Code of Australia) does not overtly regulate the probability of building failure, only the exceedance of loads. There are inconsistencies in the probabilities of exceedance of various loads (e.g. wind and earthquake load) in the BCA.

2. It is suggested that designers consider detailing housing to resist racking forces due to moderate earthquake, even though AS 1170.4-2007 exempts most houses.

3. Horizontal loads assumed using EDC I to be equal to 10% of seismic weight are often less than the corresponding values calculated using EDC II.

4. When considering the use of loadbearing unreinforced masonry, adhere to the height limits of AS 3700 Appendix AA.

5. For minor masonry structures and mezzanine floors supported by loadbearing unreinforced masonry within larger buildings, adhere to the restrictions in AS 3700 Appendix AA.

6. AS 3700 Appendix AA includes typical details for the incorporation of masonry into building subject to earthquake loads. It is suggested that reinforced masonry or reinforced concrete shear cores be incorporated into buildings supported by unreinforced loadbearing masonry.

7. The design process should include a check of vertical load capacity of all loadbearing unreinforced masonry elements (including piers), when subjected to the expected inter-storey drift.

## REFERENCES

AS 1170.4-2007 Earthquake actions in Australia, Standards Australia

AS 1170.4-1993 Minimum design loads on structures – Part 4 Earthquake loads, Standards Australia

AS 3700-2001 Masonry structures, Standards Australia (Including Amendment 3 published 2007)

BCA 2007 Building Code of Australia Volumes 1, Class 2 to 9 Buildings, Australian Building Codes Board, May 2007.

BCA 2007 Building Code of Australia Volumes 2, Class 1 and Class 10 Buildings, Australian Building Codes Board, May 2007.

## APPENDIX 1 - OBJECTIVES OF AS 1170.4-2007

The Draft Commentary to AS 1170.4-2007, (partially prepared, but yet to be published) states that the earthquake loading standard has three objectives.

1. Remain serviceable under earthquake loads likely to be exceeded once in 10 years
"Resist frequent earthquake shaking with a low probability of damage, sufficient to prevent the structure from being used as originally intended without repair. …. For a building of normal usage and importance, shaking is assumed to be that which has an annual probability of exceedance of approximately 10%. That is it might be expected to be exceeded approximately 5 times during a 50 year design life ….". It is assumed that if the masonry is designed using AS 3700 for Objective 2, this criterion will be met. It is noted that serviceability design is not mandatory in Australia.

2. Resist collapse under earthquake loads likely to be exceeded once in 500 years
"Withstand major earthquake shaking with a reasonable margin against:

(a) Structural collapse
(b) Failure of parts and elements which would be life threatening to people within or around buildings.
(c) Failure of parts and elements whose function is critical for the safe evacuation of people from the building.
(d) Failure of systems within importance category 4 buildings, which would render them unable to undertake the roles for which the category was assigned. ……..

For a building of normal usage and importance, major earthquake shaking is assumed to be that which has a 10% probability of exceedance in the assumed design life of the structure. For a 50 year design life, this level of shaking has a return period of approximately 475 years. A reasonable margin against collapse is assumed to be provided through the adoption of the requirements of the appropriate materials standard and the specified value of Sp. ….." It is assumed that this is the principal design criterion. Provided this criterion is satisfied, the other two objectives will be achieved. Reliance on the "appropriate materials standards" assumes (incorrectly) that there is a degree of uniformity in the levels of safety provided by the various materials standards for the same loads. The purpose of this project is to estimate the probability of masonry failure (and corresponding safety index) for earthquake load.

3. Maintain a reduced probability to resist collapse when subjected to strong earthquake.
"Withstand the most severe earthquake shaking that the structure is likely to be subjected to, with a small margin against collapse. ……. For Australia an appropriate event might be a magnitude 6 earthquake, at mean plus 1 standard deviation , at an epicentral distance of 40 km. Under this level of shaking the margin against collapse is intended to be much less than for Objective 2 and therefore Sp could also be reduced. …".