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# A Precision and Bias Study Of Four Masonry Flexural Stress Bond Wrenches

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## Abstract

Prior to 1980, one of the constraints in the use of unreinforced and reinforced masonry in earthquake and high wind areas was the relative paucity of design information on the tensile properties of masonry. Wind and earthquake loads induce curvatures in a masonry wall, usually resulting in tensile stress being developed in parts of the wall. If the applied tensile stress field exceeds the capacity of the masonry to resist the stress field the wall will crack and potentially fail, often with fatal results for the inhabitants. Two Victorian researchers, at the Brick Development Research Laboratory in Melbourne in 1980, developed the masonry bond wrench. The bond wrench provides an indirect method of measuring the tensile capacity of masonry in bending. This seminal instrument significantly advanced the ability of scientists to understand the response of masonry to wind and earthquake loads. The purpose of this study is to investigate the precision and bias of four bond wrenches, two of which are commonly used in masonry research and two new wrenches which follow the design concepts of the Italian masonry researchers who study ultralow strength lime based mortars in historic buildings. The principal conclusion, from the research, is that the two international standard wrenches, the Australian Standard AS 3700 Bond Wrench and the ASTM C1072 Bond Wrench exhibit an unacceptable bias and poor precision. The two new wrenches, IB and IUB, based on the conceptual ideas from the Italian research provide a significant improvement on the precision and exhibit only a moderate bias.

## Introduction

A bond wrench is used to determine the ability of masonry to resist out of plane loads and is an essential tool for the design of modern thin masonry. This paper reviews the development of four bond wrenches, each modified from the first practical example given by Hughes and Zsembery (1980). The review covers construction issues and the statistical issues of bias and precision of the test results for the four wrenches. The paper presents a brief review of the relevant literature, provides a summary of the key design changes for the four wrenches, outlines the methods used in the research, and provides results with some conclusions.

## Literature Review

The first recorded failure of buildings during an earthquake can be attributed to the battle of Jericho as told in the Book of Joshua (Joshua 6:1 – 27, KJV). Clearly the trumpets with a frequency far exceeding the natural frequency of the building could not have caused that level of damage and one can reasonably conclude that the earthquake roar sounded like trumpets to someone who had not experienced a previous earthquake. Clarke (1869) provides an excellent summary of the potential impact of earthquakes on the young colony of NSW, but it is a pity that so much of this data was lost from this early work. A more complete understanding of the 1804 Parramatta earthquake would assist in judging current risk in Sydney. Cotton (1921) studied the 1919 Kurrajong earthquake, which occurred on the northern outskirts of modern Sydney, although at the time the region was quite remote from the city proper. The 1919 event was an order of magnitude smaller than the 1804 event according the eyewitness accounts of the events. One can rightly conclude that Sydney is far from immune from earthquakes and likely deaths in a future event from falling masonry.

Nichols (2006) outlined the likely problems in Sydney from a major earthquake, whilst looking at the statistics of earthquake deaths in the world. Fatality counts in earthquakes follow a generalized Poissonian process, which is a statistical method developed by Consul (1989) to study insurance problems.

Gutenberg and Richter (1954) showed that the set of world earthquakes could be subdivided into statistically similar sets for a given region, for a sufficient study time. Gutenberg and Richter (1954), Gutenberg and Richter (1956) further demonstrate the mathematical properties of the statistical distribution related to earthquakes. The fundamental property of this world earthquake data set is that it can be divided by considering various areas as distinct units over sufficient time. Hence an earthquake hazard can be determined for Sydney, Australia. In essence, if ten M5 earthquakes occur in a given period, then a M6 can be anticipated to have occurred in the same period, and so on.... The only difference between Sydney and the Kermadec Islands, which is the most earthquake prone region in the world, is the time period for the ten M5 events, as is true for every location in the world.

The study of deaths in earthquakes shows that the world cannot be divided into a neat array of independent sets based on location, as Gutenberg and Richter had showed for earthquakes. Nichols and Beavers (2008) show that the problem of very large fatal earthquakes is a world issue; there probably will be three events this century with a death toll in the region of 250,000 people, and a possible event up to one million deaths. The three smaller events can only occur in an area with at least 1 million people due to the constraint imposed by ground wave attenuation, population density and building characteristics. There are a strictly limited integer set of urban regions with one million people. This integer set gets rapidly smaller as the size of the event increases. Sydney with a large masonry stock and four million people remains in the set of all possible fatal earthquakes, as does New York as an example.

Donne (1839) wrote "*therefore never send to know for whom the bell tolls; it tolls for thee.*" In this sense one applies Donne's call to mean, every death in the series of earthquake deaths comes from the one set of people, all of us. We are in this together; we must plan and respond as one unit.

This is one of the few world fatality problems, but it requires an understanding of the world data as one set, somewhat like weather patterns and the now famous butterfly wings problem, Lorenz (1963). The problem is usually attempted to be studied as a region specific issue, which it is not. It is also considered to be an issue of the poorer countries having lower building standards, which it is not. Christchurch demonstrated both points quite well in the last few years in a swarm of events as is well documented by Ingham et al. (2011). In a series of comments they noted that the event was not expected in Christchurch by the experts, which is common comment heard by the author in reviewing such events. Silent active faults with a return period of 2500 to 10,000 years are killers in the worst possible sense, unexpected, devastating and as the Italians note in a famous proverb always occur in the middle of a snowstorm. Using the snowstorm as a metaphor, one seeks the Achilles heel, which in the case of Sydney can be viewed as masonry veneer in old buildings. One of the major reasons for fatalities in earthquakes is the failure of masonry structures in earthquakes with a magnitude greater than M5. One tragic example is the Italian masonry grade school collapse in 2002 that killed twenty two school children. This was the lowest magnitude earthquake with known fatalities ever as documented by Erbay (2004). These types of single and double storey unreinforced masonry buildings are common in many major urban areas from England, USA, Italy, China and Australia giving just a few sample locations. Understanding how these vulnerable buildings fail in earthquakes is an important step in reducing the death tolls in future earthquakes. Significant work has occurred on understanding the problem, Epperson and Abrams (1989), Erbay (2004), Griffith et al. (2004), Hadjian (1992), but the key to failure is an understanding of the tensile properties of the masonry elements.

Baker (1914) published the first significant treatise on testing masonry and bricks. A test developed at that time determined the tensile stress at failure for mortar samples. Figure 1 shows the test arrangement and the mould specimen as shown by Baker (1914). The problem in using the old mortar test device is that it did not test the bond between the brick and the mortar, which is often the constraining limit to the flexural strength as shown in recent work by Sugo (2000) completed at the University of Newcastle.

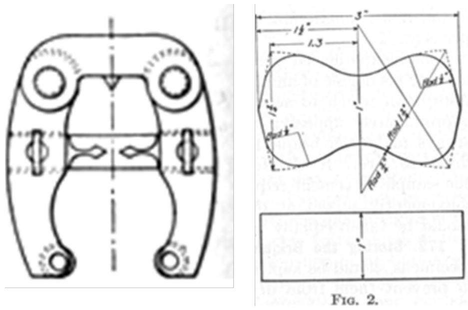


*Figure 1: Mortar test device and mould.*

Figure 2 shows the simplest beam test used to measure the flexural strength of a masonry pier.

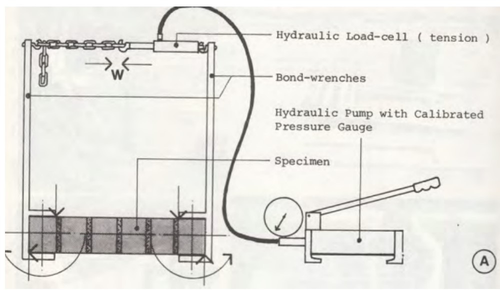


*Figure 2: Simple beam test method after Hughes and Zsembery (1980).*

The test rig shown in Figure 2 imparts a moment to the masonry prism resulting in a flexural failure in tension on the lower side of the prism. There are several issues with this test method. Each prism yields only one result and it may not be the minimum result due to the secondary moments from the mass of the prism. Establishing straight beams is quite difficult even in a laboratory and the time to manufacture the prisms is lengthy.

Hughes and Zsembery (1980) extended the simple masonry beam test to encompass a test of every joint in the beam. This device developed by these researchers is now known as the bond wrench. The bond wrench provides a better understanding of the failure strengths for masonry joints, a key step in understanding how to build better masonry. The critical design insight for the bond wrench made by Hughes and Zsembery (1980) was to allow for a two brick prism, with only one joint tested, as shown on Figure 3.

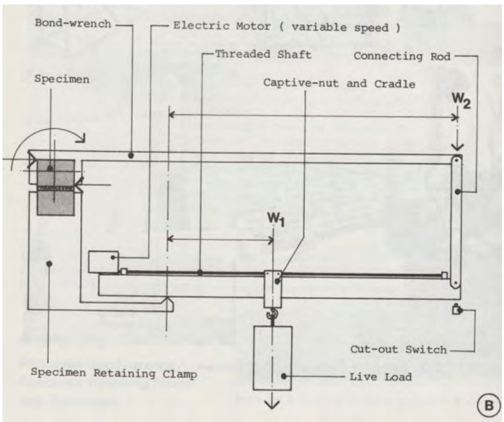


*Figure 3: Two brick masonry prism.*

The only significant conceptual variation in all subsequent bond wrench designs is to allow for stacked bricks to reduce the wastage of bricks. It is difficult to fathom why any other changes were made to the original design.

Baronio et al. (2003) studied the strength of materials used in a number of Italian buildings. Often this material is centuries old and quite weak, because of the types of pozzalonic material used at the time. The Italian research group developed a balanced bond wrench, which imparted no net bending load on the masonry prisms before the start of the test. By way of contrast the other bond wrench designs all impart a moment at the start of the test. This preload moment, given the low failure loads of lime based mortars, is a problem in trying to measure ultra-low failure stresses.

Finally, it is a commonly accepted observation that bond strength of 0.1 MPa in masonry veneer significantly reduces fatalities in earthquakes (AS 3700-2001/Amdt 2-2003; 2001). Like most early rules of thumb it provides a measureable standard that can be used to check the performance of masonry in all parts of the world, refer to Abell and Nichols (2003).

Table 1: Member Data.

| Number | Started Infants School NSW | Joined Royal Society |
|---|---|---|
| 1 | 58 | 360 |
| 2 | 61 | 450 |
| 3 | 64 | 720 |
| 4 | 63 | 240 |
| 5 | 59 | 310 |
| 6 | 60 | 285 |
| 7 | 61 | 410 |
| 8 | 59 | 500 |
| 9 | 65 | 390 |
| 10 | 66 | 560 |
| Mean | 61.6 | 422.5 |
| Standard Deviation | 2.8 | 143 |
| Variance | 7.6 | 20462 |

But in comparing results, it is critical to determine if a bias exists between testing devices so that the results are being compared on an equal footing. The standard technique used for comparing the results between different bond wrench tests is to use the Student's *t*-test to statistically compare two sets of numbers representing the measured values. Table 1 shows two sets of manufactured data. Column 1 holds the entry age in months of ten members of the Royal Society into the NSW Public School system and column 2 holds the age in months for the same members joining the Royal Society.

It is trivial to observe that the Column 1 data could be reported as having a mean of 62 ± 3 months and Column 2 data as having a mean of 420 ± 140 given a reasonable number of significant figures. For the simple hypothesis that the members joined the Royal Society after entry to Infants School, the observation that 420 – 140 >> 62 + 3 is the significant answer, given the magnitude of the means and standard deviations or in mathematical terms it is self-evident. The Student's *t*-test developed by a statistician at the Guinness Brewing Company, Miller and Freund (1976), provides a measure of the relative differences between the means allowing for the magnitude of the standard deviations. The critical number is termed the t-Stat. Many numerical packages provide a built in function to calculate results for a Student's *t*-test comparison of two data sets. The Student's *t*-test results for the data in Table 1 are shown in Table 2, assuming unequal variances.

The critical number is the |*t*-Stat| which is 7.97. The critical case is the one tailed distribution, as except in exceptional circumstances, the starting age at Infants School is going to be less than the age of joining the Royal Society. The probability that the two columns represent the same data is 1 in 88,280 in terms of odds, which is the P(T<=*t*) one-tail of $1.1 \times 10^{-5}$, confirming the reasonable hypothesis that the Royal Society does not admit infants. The critical *t*-Stat is variable, but for the average problem it has a typical value of about 2. The bias is the difference in the means and the precision is measured by the standard deviation in the modern setting or the variance originally.

Table 2: Member Data Student's *t*-test

| Description | Started Infants School NSW | Joined Royal Society |
|---|---|---|
| Mean | 61.6 | 422.5 |
| Variance | 7.6 | 20462.5 |
| Observations | 10 | 10 |
| Hypothesized Mean Difference | 0 | |
| Degrees of Freedom | 9 | |
| t Stat | -7.97 | |
| P(T<=*t*) one-tail | $1.13 \times 10^{-5}$ | |
| t Critical one-tail | 1.83 | |
| P(T<=*t*) two-tail | $2.27 \times 10^{-5}$ | |
| *t* Critical two-tail | 2.26 | |

## Bond Wrench Design

Four bond wrenches have been constructed for this research work. The first and second bond wrenches were to be based on the Australian masonry standard AS 3700-2001/Amdt 2-2003 (2001). This standard provides a conceptual plan for the wrench, rather than a proscriptive design, as used for the ASTM International (2010).

The Indian master's students, who manufactured these two wrenches, lacked the skills to craft the Australian standard wrench in either an unbalanced or a balanced configuration. The students developed two much lighter wrenches, one balanced and one unbalanced. These wrenches are termed the Indian bond wrenches. The Indian balanced bond wrench is shown in Figure 4.

*Figure 4: Indian balanced bond wrench.*

Figure 5 shows the schematic plan for the Australian bond wrench from Standards Australia (2001).

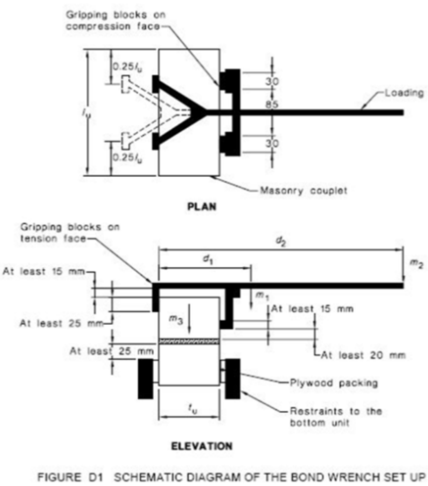


*Figure 5: Australian standard bond wrench.*

Figure 6 shows the ASTM bond wrench, documented in ASTM International (2013).

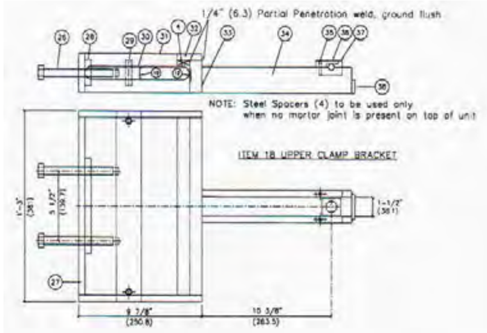


*Figure 6: ASTM bond wrench design.*

Figure 7 shows the schematic dimensions required to calculate the flexural stress at the point of failure of the specimens. Equation 1 shows the moment, applied to the specimen at the point of flexural failure:

$$M_U = P_1 L_1 + P_2 L_2 \tag{1}$$

where $L_1$ is the distance from the centre of the brick prism to the centroid of the bond wrench and $L_2$ is the distance from the applied load to the centre of the brick prism. Table 3 provides the measured mass $P_1$ for each of the four wrenches. A number has been assigned to each wrench to simplify presentation of the results. Table 4 shows the key dimensions for each of the four wrenches.

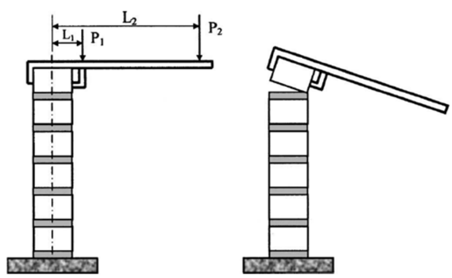


*Figure 7: Bond wrench schematic dimensions.*

Table 3: Mass of the four wrenches.

| Wrench Number | Design Basis | $P_1$ Mass (kg) |
|---|---|---|
| 1 | Indian balanced | 6.15 |
| 2 | Indian unbalanced | 6.10 |
| 3 | ASTM | 20.0 |
| 4 | Australian standard | 4.70 |

Table 4: Dimensions of the four wrenches.

| Wrench Number | Length $L_1$ mm | Length $L_2$ mm |
|---|---|---|
| 1 | 0 | 660 |
| 2 | 132 | 686 |
| 3 | 363 | 6 |
| 4 | 835 | 203 |

## Method

Three sets of experimental work have been completed on masonry prisms using this group of wrenches. The first experimental work investigated the difference in bias and precision between the Indian balanced and unbalanced wrenches. This research used an extruded brick from a local Texan brick as shown in Figure 8. The brick had an initial rate of absorption of 0.55 ± 0.04 kg/m$^2$/min, which is within the normally acceptable range for a commercial brick.

*Figure 8: Texan extruded bricks.*

Mortar was manufactured using a standard mix of six parts of sand to one part of Portland cement, Type A and one part of hydrated lime. The Portland cement and the lime act as the pozzalonic material and the sand is essentially filler between the bricks and pozzalonic material. Abell and Nichols (2003) have studied the properties of this type of mortar. Figure 9 shows a type masonry prism used for the experimental work.

*Figure 9: Masonry prisms.*

Figure 10 shows the testing arrangement for the balanced bond wrench. This work completed by Chaudhari (2010) and Singala (2010) showed a bias between the results from the two wrenches.

Nichols and Holland (2011) using the same bricks and mortar tested a set of prisms using all four wrenches. This is the second experimental series.

*Figure 10: Balanced bond wrench and prism in testing frame.*

The third experimental work was by McHargue, who used a Masonry Cement in place of the Portland Type A. This is generally considered to lower the overall flexural strength results, Page (1973), Page (1992).

Failure patterns were observed and recorded on the brick to mortar interface by McHargue. McHargue developed a system for distinguishing between the three basic failure modes. Mode 1 is a Mortar Interface failure, generally considered the weakest failure mode, Mode 2 is the Mortar Bed and Mortar Interface Failure mode and Mode 3 is a Mortar bed failure, generally considered the strongest mode.

The experimental results were analysed using standard statistical techniques as shown in Miller and Freund (1976) and Squires (2001). The critical statistical issues are the precision and the bias in the results. Precision is generally measured as the ratio of the standard deviation to the mean value assuming a normally distributed sample set. This is often termed the coefficient of variation or COV. Masonry testing undertaken on compression specimens, stiffness testing and flexural results typically has a coefficient of variation in excess of twenty percent, Hendry (2001). The bias is the difference in the mean results using two or more instruments from a common sample set.

## Results

The intent for Singala and Chaudhari's work was to study the difference in the bias and precision between an Australian Standard Bond Wrench and an Australian Standard Bond Wrench that was modified to provide a balanced wrench. Instead these researchers developed much simpler wrenches as shown in Figure 4. Fisher (1971) outlines the standard method developed for experimental design, used for the design of these experimental procedures.

These researchers each tested masonry joints using each wrench to reduce the bias due to experimenter differences in operation of the bond wrenches. The results for the mean failure load for each wrench and experimenter is shown in Table 5.

Table 5: Failure load ($m_2$) in kilograms

| Researcher | Bond Wrench | Mean $\mu \pm \sigma$ |
|---|---|---|
| I | Unbalanced | $21.46 \pm 2.8$ |
| II | Unbalanced | $21.70 \pm 3.4$ |
| I | Balanced | $21.83 \pm 2.7$ |
| II | Balanced | $21.48 \pm 3.4$ |

A Student's *t*-test analysis shows that there is no statistically significant difference between the results for the unbalanced wrench for the failure load results between the individual experimenters. A similar conclusion applies to the unbalanced to balanced comparison. The COV for the unbalanced bond wrench is 14.2% and the balanced in 13.8%. These results are exceptionally good for masonry flexural testing. There is not an experimenter induced bias in the results from the testing.

The critical result is the estimated flexural stress at the point of failure as shown in equation (1). The flexural stress at failure for each wrench and experimenter is shown in Table 6.

Table 6: Flexural stress at failure (MPa)

| Researcher | Bond Wrench | Mean $\mu \pm \sigma$ |
|---|---|---|
| I | Unbalanced | 0.72 ± 0.09 |
| II | Unbalanced | 0.73 ± 0.11 |
| I | Balanced | 0.66 ± 0.08 |
| II | Balanced | 0.65 ± 0.10 |

A Student's *t*-test analysis shows a difference that is significant at the 5% confidence level between the balanced and unbalanced stress results. A simple analysis method of taking the balanced and unbalanced stress data into descending sorted order and then performing a regression analysis on the sorted data sets shows that the data is reasonably normally distributed and the least squares ratio between the two data sets is 0.927 ± 0.03.

Nichols and Holland's results are summarized in Table 7.

Trivially there are no differences in the results for the Australian, balanced and unbalanced wrench at the 5% level, but a Student's *t*-test shows a difference between the ASTM wrench and the other three combined results for the flexural strengths.

Table 7: Flexural stress at failure (MPa)

| Wrench | Number of Specimens | Mean $\mu \pm \sigma$ |
|---|---|---|
| ASTM | 8 | 1.29 ± 0.42 |
| Australian | 7 | 0.88 ± 0.39 |
| Balanced | 6 | 0.83 ± 0.36 |
| Unbalanced | 7 | 0.84 ± 0.46 |

McHargue tested 330 joints using the ASTM and the Australian Bond wrenches. He used a randomized testing procedure, but used two different but similar brick types, one from Texas and another from Arkansas. The Arkansas brick had an IRA of 0.61 ± 0.1 kg/m²/min. The flexural results are shown in Table 8.

Table 8: Flexural stress at failure (MPa)

| Wrench | Test Set | Mean $\mu \pm \sigma$ |
|---|---|---|
| ASTM | 1 Texas Brick | 0.29 ± 0.11 |
| Australian | 1 | 0.33 ± 0.12 |
| ASTM | 2 Arkansas Brick | 0.37 ± 0.11 |
| Australian | 2 | 0.42 ± 0.10 |

The Student's *t*-test analysis shows that the flexural strength differences are statistically significant at the 5% level for the two test sets.

McHargue's results show an increase in the mean flexural stress with sample number, which suggests either improvements in manufacture or testing had some impact on the results. This result was not observed in the other tests.

The critical statistical value of interest to the design engineer is the Characteristic Flexural Strength for each brick and wrench combination. The characteristic strength ensures that 95% of all samples have a higher stress value AS 3700-2001/Amdt 2-2003 (2001). This is the value quoted in the specification for the construction of the masonry. A typical minimum value is 0.1 MPa. The characteristic values for the McHargue data are shown in Table 9.

Table 9: Characteristic Flexural Stress (MPa)

| Wrench | Test Set | Value |
|---|---|---|
| ASTM | 1 Texas Brick | 0.11 |
| Australian | 1 | 0.15 |
| ASTM | 2 Arkansas Brick | 0.14 |
| Australian | 2 | 0.19 |

The ASTM Bond Wrench for the two test sets from the McHargue data show characteristic values of the Flexural strength that are lower than the Australian standard bond wrench test results.

Finally, the ASTM wrench at twenty kilograms is heavy for use by a single individual, compared to the other three wrenches. The ASTM wrench also requires a significantly greater load to develop a comparable stress level compared to the other wrenches. A safety bar had to be fitted to the clamping device shown in Figure 10 to arrest the flight of the ASTM wrench after failure of the masonry prism.

The rather interesting argument from the designers of the main wrenches, ASTM and Australian standard is that their design has allowed for consideration of stress distribution in masonry at the point of failure. The Scottish verdict of **Not Proven** would appear to apply to this assertion, given the COV of the Indian wrenches in the original testing.

## Conclusions

Masonry provides one of the most dangerous elements for humans in an earthquake. Masonry cracks and falls causing crush injuries and death. The 1989 Newcastle earthquake redemonstrated this problem as did the recent tragic event in Christchurch, NZ. Cotton and Clarke clearly demonstrate the potential for a major earthquake in Sydney or some other major urban area. Galadini and Galli (1999) highlight the issue of silent active faults that are hard to identify and allow for in hazard mapping, Christchurch being such an example. One method to reduce the fatality rate in masonry structures in earthquakes is to implement a minimum masonry flexural characteristic strength standard of 0.1 MPa. This standard then forms a simple and relatively inexpensive method of improving quality of masonry produced using this standard.

The simplest techniques for improving the quality of masonry in flexure and to show conformance with the requisite standards is to test the masonry using a bond wrench either as the masonry walls are constructed or by certifying the mason, a technique used after the Newcastle earthquake by some.

Serendipity created the two Indian wrenches and it was not expected that such a simple and inexpensive design could yield consistently precise results with a small bias, and tight precision when compared to the ASTM wrench results. The Indian wrenches are significantly cheaper and easier to build, about $50 each, when compared to the Australian Standard wrench and the ASTM wrench, which are major undertakings for a small shop. The

Indian wrenches are safer and easier to operate.

It is extremely difficult to make significant changes to major engineering codes of practice, interestingly the key players in the modern development of the bond wrench are friends and meet on a regular basis at major masonry conferences. Yet, there is steep reluctance to let go of an entrenched system, which is really normal human behaviour for better or worse. Considering the very limited number of bond wrenches in the world, probably less than fifty, there is a need for a consistent simple and easily manufactured wrench to be used by all. The point is to develop a common standard that yields precise results, with a known relationship between the results from the equipment to the design requirements for safe masonry buildings and to the other wrenches. Neither the ASTM nor the Australian standard wrenches, the defacto world standard wrenches, meet these criteria of *simplicitate, vilis, subtilis*. As with all things it will take time and energy to push the necessary changes. This paper is a further push in that direction.

## Acknowledgements

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## References

Abell, A. B. & Nichols, J. M. (2003) *Investigation of the Rheology and Microstructure of Hydrated Lime and Sand for Mortars.*

AS3700-2001/Amdt 2-2003 (2001) *Masonry Structures*, Standards Australia, Sydney.

ASTM International (2010) *E518/E518M-10 Standard Test Methods for Flexural Bond Strength of Masonry*, ASTM International, W. Conshohocken PA.

ASTM International (2013) *C1072-13 Standard Test Method for Measurement of Masonry Flexural Bond Strength*, ASTM International, W. Conshohocken, PA.

Baker, I. O. (1914) *Treatise on Masonry Construction*, 10th edn., Wiley, New York, xiv+745.

Baronio, G., Binda, L., Tedeschi, C. & Tiraboschi, C. (2003) Characterisation of the materials used in the construction of the Noto Cathedral, *Construction and Building Materials*, 17, 8, 557-571.

Chaudhari, S. (2010) *Comparative Analysis between a balanced and unbalanced bond wrench*, Master of Science (Construction Management) thesis, Texas A&M University, TAMU.

Clarke, W. (1869) On the causes and phenomena of earthquakes, especially in relation to shocks felt in New South Wales and in other provinces of New South Wales, *Proceedings and Journal of the Royal Society of New South Wales*, 2, 51-86.

Consul, P. C. (1989) *Generalized Poisson Distributions: Properties and Applications*, Dekker, NY.

Cotton, L. A. (1921) The Kurrajong Earthquake of August 15, 1919, *Proceedings and Journal of the Royal Society of New South Wales*, 55, 83-104.

Donne, J. (1839) *The Works of John Donne vol III.*, John W. Parker, London.

Epperson, G. S. & Abrams, D. P. (1989) *Non-destructive evaluation of masonry buildings*, ATC, Urbana.

Erbay, O. O. (2004) *A methodology to assess seismic risk for populations of unreinforced masonry buildings* Ph.D. thesis, University of Illinois at Urbana-Champaign, Urbana, IL, USA.

Fisher, R. A. (1971) *The Design of Experiments*, Macmillan, London.

Galadini, F. & Galli, P. (1999) The Holocene paleoearthquakes on the 1915 Avezzano earthquake faults (Central Italy): implications for active tectonics in the central Apennines, *Tectonophysics*, 308, 143-70.

Griffith, M. C., Lam, N. T. K., Wilson, J. L. & Doherty, K. (2004) Experimental Investigation of Unreinforced Brick Masonry Walls in Flexure, *Journal of Structural Engineering*, 130, 3, 423-432.

Gutenberg, B. & Richter, C. F. (1954) *Seismicity of the Earth and Associated Phenomena*, Princeton University Press, Princeton New Jersey, 273 p. illus., maps, profiles. 28 cm.

Gutenberg, B. & Richter, C. F. (1956) Earthquake Magnitude, Intensity, Energy and Acceleration, *Bulletin of the Seismological Society of America*, 46, 105-143.

Hadjian, A. H. (1992) *The Spitak, Armenia Earthquake - Why so much damage?*, 5-10.

Hendry, A. W. (2001) Masonry walls: materials and construction, *Construction and Building Materials*, 15, 8, 323-330.

Hughes, D. M. & Zsembery, S. (1980) *A Method of Determining the Flexural Bond Strength of Brickwork at Right Angles to the Bed Joint*, 105-115.

Ingham, J. M., *Emails on the Christchurch Earthquake Deaths* (2011), Auckland.

Ingham, J. M., Biggs, D. T. & Moon, L. M. (2011) How did unreinforced masonry buildings perform in the February 2011 Christchurch earthquake., *The Structural Engineer*, 89, 6.

Lorenz, E. N. (1963) Deterministic Nonperiodic Flow, *Journal of the Atmospheric Sciences*, 20, 130-141.

Miller, I. & Freund, J. E. (1976) *Probability and statistics for engineers* 2nd. edn., Prentice-Hall, Englewood Cliffs, N.J., ix, 529 p. : ill. ; 24 cm.

Nichols, J. M. (2006) The Rule of Unintended Consequences, Sydney's Water Supply Strategy, *Built Environment*, 32, 4, 434-446.

Nichols, J. M. & Beavers, J. E. (2008) World Earthquake Fatalities from the Past -- Implications for the Present and Future, *Natural Hazards Review*, 9, 4, 179-189.

Nichols, J. M. & Holland, N. L. (2011) *A Comparative Study of Balanced Bond Wrench Testing and Unbalanced Bond Wrench Testing.*

Page, A. W. (1973) *Structural Brickwork - A Literature Review*, Department of Civil Engineering, University of Newcastle,, Newcastle.

Page, A. W. (1992) The design, detailing and construction of masonry - the lessons from the Newcastle earthquake., *Australian Civil Engineering Transactions*, 34, 4, 343-53.

Singala, J. Y. (2010) *Sensitivity Analysis of Bricks using the Bond Wrench Apparatus*, Master of Science (Construction Management) thesis, Texas A&M University, College Station.

Squires, G. L. (2001) *Practical Physics*, 4th edn., Cambridge University Press, Cambridge ; New York.

Sugo, H. O. (2000) *Strength and microstructural characteristics of brick/mortar bond* Ph.D. thesis, University of Newcastle, Newcastle, 1 v., 42 plates : ill. ; 30 cm.

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