Probability of fatigue failure in brick masonry under compressive loading

I.S. Koltsida[a,1], A.K. Tomor[a], C.A. Booth[b]

[a] University of the West of England, Bristol, Faculty of Environment and Technology, Division of Civil & Environmental Engineering, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK

[b] University of the West of England, Bristol, Faculty of Environment and Technology, Architecture and the Built Environment, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK

[1] Corresponding author. Tel.: +44 (0) 1173283049. E-mail addresses: Iris.Koltsida@uwe.ac.uk, iris.koltsida@gmail.com.

ABSTRACT

Long-term fatigue tests under compressive loading were performed on low-strength brick masonry prisms under laboratory conditions. The number of loading cycles to failure were recorded and used to investigate the suitability of the logarithmic normal distribution to describe fatigue test data and to develop a probability based mathematical expression for the prediction of the fatigue life of masonry. The proposed model incorporates the applied maximum stress level, stress range, number of loading cycles and probability of survival. From the mathematical model a set of curves for stress level - cycles to failure - probability of survival (S-N-P) were identified to allow the fatigue life of masonry to be predicted for any desired confidence level. Upper limit, lower limit and mean curves were proposed. The prediction curves were compared with the test data and proposed expressions from the literature and proved to be suitable to predict the fatigue life of masonry. It is surmised that S-N-P curves provide a useful tool to help evaluate the remaining service life of masonry arch bridges at different confidence levels, based on material properties. The proposed mathematical model can be incorporated into existing assessment methodologies, such as SMART to quantify the residual life of brick masonry arch bridges for failure modes associated with compressive loading.

Keywords: Brick Masonry, Fatigue, S-N curve, Probability

1. Introduction

Understanding and predicting the effect of fatigue for masonry is imperative for the preservation and maintenance of masonry arch bridges. Masonry arch bridges represent a significant part of the European railway and highway system. The increased weight, speed and density of traffic impose higher levels of fatigue loading on the structure and can lead to premature deterioration [1, 2, 3, 4, 5].

Models to predict the fatigue life of masonry have been proposed in the form of S-N (Stress-Number of cycles) curves [1, 2, 4]. The models were developed based on a limited number of experimental test data and no guidance has been available to apply them for different types of masonry.

Roberts *et al.,* [1] defined a lower bound fatigue strength curve for dry, submerged and wet brick masonry based on a series of quasi-static and high-cycle fatigue tests on brick masonry prisms (Equation 1). This equation relates the number of loading cycles with the maximum applied stress, the compressive strength and the stress amplitude.

$$F(S) = \frac{(\Delta\sigma\sigma_{max})^{0.5}}{f_c} = 0.7 - 0.05\, log\, N \qquad (1)$$

Where F(S) is the function of the induced stress, $\Delta\sigma$ is the stress range, σ_{max} is the maximum stress, f_c is the quasi-static compressive strength of masonry and N is the number of load cycles. After reprocessing the test data, Wang *et al.,* [5] suggested that Equation 1 is not a true lower bound and reflects a combination of different factors influencing the fatigue behaviour of masonry.

Casas [2, 6] post-processed and analysed the experimental data of Roberts *et al.,* [1]. Assuming the two parameter Weibull distribution for the fatigue life of masonry under a given stress level, Casas [2] proposed a probability-based fatigue model for brick masonry under compression for a range of confidence levels (Equation 2).

$$S_{max} = A \times N^{-B(1-R)} \qquad (2)$$

Where S_{max} is the ratio of the maximum loading stress to the quasi-static compressive strength ($S_{max} = \sigma_{max}/f_c$), N is the number of cycles to failure and R is the ratio of the minimum stress to the maximum stress ($R = \sigma_{min}/\sigma_{max}$). Coefficients A and B are given in Table 1 for different values of the survival probability L as reported by Casas [2].

Table 1 Parameters for Casas [2] fatigue equation for different survival probabilities

L	**0.95**	**0.90**	**0.80**	**070**	**0.60**	**0.50**
A	1.106	1.303	1.458	1.494	1.487	1.464
B	0.0998	0.1109	0.1095	0.1023	0.0945	0.0874

During analysis of the test data, Casas [2] ignored the values for two maximum stress levels (S_{max} = 0.65 and S_{max} = 0.6) and for high values of survival probability, the values of regression coefficient are quite low, suggesting that the correlations are not very good [5]. Based on Casas [2], and on the review performed by Wang *et al.*, [5], it is suggested that the suitability of the Weibull distribution to describe fatigue needs to be further investigated, due to the fact that the correlations are not very good (low) and because the number of samples that was used was limited.

Finally, Tomor and Verstrynge [4] developed a joined fatigue-creep deterioration model. A probabilistic fatigue model was suggested by adapting the model proposed by Casas [2, 6]. A correction factor C was introduced to allow interaction between creep and fatigue phenomena to be taken into account and to adjust the slope of the S-N curve (Equation 3).

$$S_{max} = A \cdot N^{-B(1-C\cdot R)} \qquad (3)$$

Where S_{max} is the ratio of the maximum stress to the average compressive strength, N the number of cycles, R the ratio of the minimum stress to the maximum stress, parameter A was set to 1, parameter B was set to 0.04 and C is the correction factor. This model also includes quasi-static tests and was intended to represent the mean fatigue life of masonry. The correction factor C, however, depends on the set of experimental data and the equation may not be used as a prediction model.

The aim of this research is to investigate the suitability of the logarithmic normal distribution to describe fatigue test data and to propose a model for S-N curves to predict the fatigue life of masonry at any required confidence level. A family of S-N curves are generated with mean, lower limit and upper limit for the fatigue life.

2. Materials and experimental test data

A total of 64 brick masonry prisms have been tested to failure under compressive fatigue loading at various maximum stress levels to investigate the fatigue life of masonry in relation to the stress level. Stack-bond brick masonry prisms were built from full-size bricks and mortar joints according to ASTM standards [7]. The total dimensions of the prisms were 210 x 100 x 357 mm^3 (five handmade solid bricks and four 8 mm mortar joints). The tests were performed using a 250 kN capacity servo-controlled hydraulic actuator to apply static or long-term fatigue loading. The detailed experimental design and results are presented in [8].

The handmade low-strength solid 210 x 100 x 65 mm^3 Michelmersh bricks (denoted B1) have an average compressive strength of 4.86 N/mm^2 and 1823 kg/m^3 gross dry density. The mortar, denoted M01, was 0: 1: 2 cement: lime (NHL3.5): sand (3 mm sharp washed) mix by volume. The mean compressive strength of masonry was 2.94 N/mm^2 (0.10 N/mm^2 Standard Deviation).

Tests under compressive long-term fatigue loading were conducted at 2 Hz frequency with sinusoidal load configuration. Before commencing the fatigue tests, load was applied quasi-statically up to the mean fatigue load. The load was subsequently cycled between a minimum and a maximum stress level defined as percentages of the mean compressive strength of masonry recorded under quasi-static loading [9]. The minimum stress level represents the dead load of the structure and was set to 10% of the compressive strength of masonry (mean strength of quasi-static tests) as the worst-case scenario for fatigue loading [3, 8]. The maximum stress level represents live loading (e.g. similar to traffic on a bridge) and varied between 55% and 80% of the compressive strength of masonry. The number of load cycles until failure is shown in Table 2 for all prisms (prisms are denoted as B1M01 according to brick and mortar type). Prisms failed between 7 and $3.5x10^6$ loading cycles. The experimental test data, including a specimen (B1M01-45) that did not fail up to 10^7 loading cycles, were used to develop the probabilistic model,.

The fatigue data presented in Table 2 exhibit large scatter. The phenomenon of scatter for fatigue test data under the same loading conditions is well known and attributed to differences in the microstructure for different specimens [10]. Potential sources of scatter could be the specimen production and surface quality, accuracy of testing equipment, laboratory environment and skill of laboratory technicians [11]. Scatter is generally larger for low stress amplitudes [11]. For the presented test data, large scatter is also observed for 80% maximum applied stress. This, however, is due to the small number of tests performed at this stress level. Similar scatter of the fatigue data in terms of magnitude is observed in the test data by Clark [12] and Tomor *et al.*, [3].

Table 2 Fatigue tests in compression on B1M01 type prisms.

Specimen Name	Stress Range	Number of Cycles N	Specimen Name	Stress Range	Number of Cycles N	Specimen Name	Stress Range	Number of Cycles N
B1M01-18	0.29-2.33 N/mm^2 10-80%	2,566	B1M01-53	0.29-2.00 N/mm^2 10-68%	134	B1M01-82	0.29-1.85 N/mm^2 10-63%	34728
B1M01-48		14,073	B1M01-54		3,541	B1M01-83		3355
B1M01-49		2,832	B1M01-55		5,994	B1M01-84		256
B1M01-50		456	B1M01-56		212	B1M01-86		59921
B1M01-66	0.29-2.14N/mm^2 10-73%	253	B1M01-57		1,100	B1M01-87		543
B1M01-67		200	B1M01-58		31000	B1M01-88		4809
B1M01-68		413	B1M01-59		69537	B1M01-89		881
B1M01-69		53	B1M01-60		34	B1M01-26	0.29-1.76 N/mm^2 10-60%	25,342
B1M01-70		55	B1M01-61		71342	B1M01-28		2,646,302
B1M01-76		7	B1M01-62		11754	B1M01-29		122,762
B1M01-77		104	B1M01-63		37938	B1M01-30		1,268,627
B1M01-78		240	B1M01-64		33752	B1M01-31		3,528,118
B1M01-85		93	B1M01-65		250000	B1M01-32		986,325
B1M01-19	0.29-2.00 N/mm^2 10-68%	1,800	B1M01-71	0.29-1.85 N/mm^2 10-63%	718	B1M01-33		796,744
B1M01-20		3,600	B1M01-72		11038	B1M01-34	0.29-1.62 N/mm^2 10-55%	56,562
B1M01-21		13,000	B1M01-73		269	B1M01-40		412,774
B1M01-22		17,350	B1M01-74		2515	B1M01-41		1,088,560
B1M01-23		18,651	B1M01-75		1104	B1M01-43		2,200
B1M01-24		18,276	B1M01-79		266	B1M01-44		4,864
B1M01-35		3,000	B1M01-80		19203	B1M01-45*		10,225,676
B1M01-36		6,737	B1M01-81		54	B1M01-46		1,724,587
						B1M01-47		1,672,237

* No failure-Terminated

3. Probabilistic model

Fatigue test data are normally presented as stress - number of cycles (S-N) curves. Due to the relatively large variation and statistical nature of the test data, results may be more conveniently presented in a three-dimensional format using stress- number of cycles- probability of failure or probability of survival (S-N-P) curves. The S-N-P relationship indicates curves for the lower bound, upper bound and the mean of the data points.

Logarithmic normal distribution has been used by several researchers to indicate the fatigue life of metals and concrete [12, 13, 14, 15, 16] at constant stress amplitude. To identify the suitability of logarithmic normal distribution to describe the fatigue data for masonry, the probabilities of failure for each stress level were calculated. Equation 4 gives the probability density function (PDF) of the fatigue life for the logarithmic normal distribution [16].

$$f(N) = \left({}^{1}\!/_{\sigma\sqrt{2\pi}} \right) exp\left[{}^{-(\log N - \mu^2)}\!/_{(2\sigma^2)} \right] \quad (4)$$

Where N is the number of loading cycles to failure, σ is the standard deviation and μ is the mean of logN. The cumulative density function (CDF) can be obtained by integrating the probability density function (Equation 5).

$$P(X \leq N) = \int_{-\infty}^{logN} f(x)dx \quad (5)$$

The probability of failure P_f can be calculated as a function of fatigue life by ranking the fatigue lives at each load level from low to high and by dividing the order of corresponding fatigue life by n+1, where n is the total specimen number for each loading level. In Figure 1 the calculated probabilities of failure at every stress level are plotted against the number of loading cycles to failure (N) in a semi-logarithmic scale (N-P plot), together with the cumulative density function curves. The CDF curves were extrapolated to cover the whole probability range. The curves provide a good approximation of the fatigue test data and suggest a logarithmic normal distribution is suitable for describing the probability of failure.

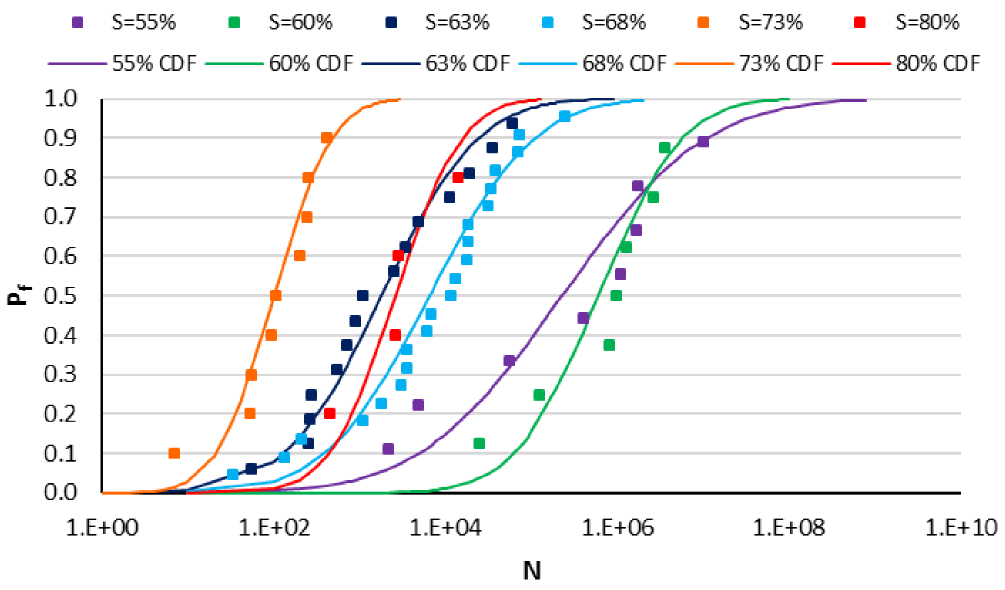

Figure 1 Variation of failure probability with the loading cycles for different stress levels

The fatigue lives corresponding to various probabilities of failure at each stress level can be calculated from the N-P plot in Figure 1 to generate the S-N-P curves. S-N-P curves are shown in Figure 2 for 0.05, 0.1, 0.5, 0.9 and 0.95 probabilities of failure. The S-N curves were identified based on a power law best fit according to Equation 6.

$$S_{max} = A \times N^B \quad (6)$$

Where S_{max} is the ratio of the maximum loading stress to the quasi - static compressive strength (S_{max} = σ_{max}/f_c) and N is the number of cycles to failure. A and B are parameters depending on the probability of failure (Table 3).

Table 3 Parameters A and B for different probabilities of failure

Parameter \ (P_f)	0.05	0.10	0.50	0.90	0.95
A	0.779	0.802	0.868	0.905	0.925
B	0.028	0.030	0.030	0.028	0.027

Even though the 50% failure probability curve provides a good approximation of the mean test data, the 5% and 10% failure probability curves do not represent reliable lower bounds. This could be due to the fact that only a few specimens were tested at 80% maximum stress and results indicated greater fatigue lives than for 73% stress level. Additionally, extrapolation of the distributions to low probabilities resulted in intersection of the cumulative density function curves. This intersection produced the anomaly that below a certain probability, specimens tested at lower stress levels have shorter fatigue lives. More test data are required for high stress levels to develop more accurate relationships for lower bound S-N curves.

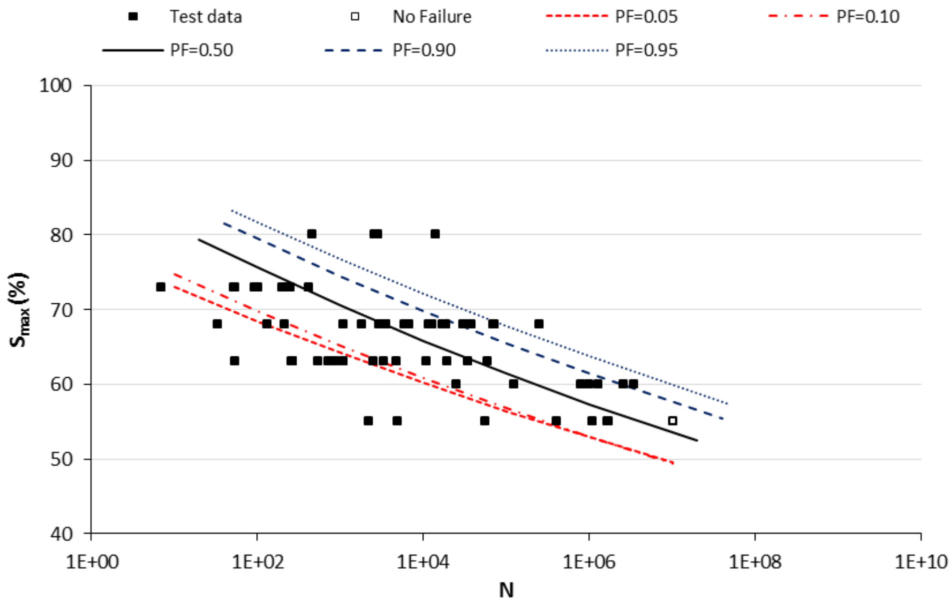

Figure 2 Experimental data and predicted S-N curves for different probabilities of failure

McCall [13] used a logarithmic mathematical model to describe the S-N-P relationship for fatigue of plain concrete under reverse bending loading (Equation 7).

$$L = 10^{-a{S_{max}}^{b}(\log N)^{c}} \quad (7)$$

where L is the probability of survival, a, b and c are experimental constants, S_{max} is the ratio of the maximum applied stress over the quasi-static compressive strength, N is the number of cycles for fatigue failure. The probability of survival L is equal to 1-P_f (P_f is the probability of failure) and is used instead of the probability of failure to simplify the equation. In Equation 7 the following limits are valid:

$$L = 1 \text{ for } N = 1$$

$$L \rightarrow 0 \text{ for } N \rightarrow \infty$$

$$L = 1 \text{ for } S_{max} = 0$$

$$L \rightarrow 0 \text{ for } S_{max} \rightarrow 1$$

To investigate the suitability of this model to describe the behaviour of masonry under fatigue compressive loading, parameters a, b and c have to be calculated based on available experimental data. To account for different stress ranges ΔS, as well as for the maximum stress level, the term $S_{max}\Delta S$ will be used, instead of S_{max}. Equation 7 can, therefore, be transformed to Equation 8.

$$L = 10^{-a(S_{max}\Delta S)^b(\log N)^c} \quad (8)$$

Where L is the probability of survival, S_{max} is the ratio of the maximum applied stress over the quasi-static compressive strength, ΔS is the stress range and N is the number of cycles for fatigue failure.

To transform Equation 8 into a linear form, the logarithms of the logarithms of each side of the equation were taken.

$$\log(-\log L) = \log a + b\log(S_{max}\Delta S) + c\log(\log N) \quad (9)$$

By substituting log(-logL) by Y, loga by A, $\log(S_{max}\Delta S)$ by X and log(logN) by Z the following linear form is obtained:

$$Y = A + bX + cZ \quad (10)$$

or

$$Z = A' + B'X + C'Y \quad (11)$$

where $A' = {}^{-A}/_{c}$, $B' = {}^{-b}/_{c}$ and $C' = {}^{1}/_{c}$.

In order to work with the variables measured from the samples, the following equation was derived from Equation 11.

$$\sum Z = \sum A' + B'\sum X + C'\sum Y$$

$$\frac{1}{n}\sum Z = A' + B'\frac{\sum X}{n} + C'\frac{\sum Y}{n}$$

$$\bar{Z} = A' + B'\bar{X} + C'\bar{Y} \quad (12)$$

By subtracting Equation 12 from Equation 11, the subsequent expressions are attained:

$$Z - \bar{Z} = B'(X - \bar{X}) + C'(Y - \bar{Y})$$

or

$$z = b'x + c'y \quad (13)$$

where $\bar{X}$, $\bar{Y}$, and $\bar{Z}$ are the average values of X, Y and Z respectively and in Equation 13, $z = Z - \bar{Z}$, $x = X - \bar{X}$ and $y = Y - \bar{Y}$.

Using least square normal equations, expressions (14) and (15) are obtained:

$$b'\sum x^2 + c'\sum xy = \sum xz \quad (14)$$

$$b'\sum xy + c'\sum y^2 = \sum yz \quad (15)$$

Analysing the experimental fatigue data based on this set of equations, the required statistical terms were calculated.

$\sum x^2 = 0.553$ $\sum xy = 0.002$ $\bar{X} = -0.440$

$\sum y^2 = 11.595$ $\sum yz = 3.026$ $\bar{Y} = -0.580$

$\sum z^2 = 2.089$ $\sum xz = -0.566$ $\bar{Z} = 0.547$

Substitution of these statistical terms in Equations 14 and 15 allows the calculation of parameters $b^{'}$ and $c^{'}$. Equation 13, using the calculated $b^{'}$and $c^{'}$ parameters will become, therefore:

$$z = -1.0243x + 0.2601y$$

Parameter $A^{'}$ can now be calculated by substitution of $B^{'}$ and $C^{'}$, as well as, $\overline{X}$, $\overline{Y}$ and $\overline{Z}$ in Equation 12. Equation 11 is now expressed as:

$$Z = 0.2474 - 1.0243X + 0.2609Y$$

Finally, after having computed all the required parameters, Equation 8 may be rewritten for masonry under compressive fatigue loading in the following form (Equation 16):

$$L = 10^{-0.1127(S_{max}\Delta S)^{3.9252}(log\, N_f)^{3.8322}} \quad (16)$$

Equation 16 can be used to evaluate the S-N curves for masonry under compressive cyclic loading for any preferred confidence level of survival. It can also be used to evaluate the mean, upper limit and lower limit fatigue life of masonry.

4. Application

In Figure 3, the S-N-P curves for 99%, 95%, 50%, 5% and 1% probabilities of survival are indicated for the experimental fatigue data under study. The curve for 0.50 probability is a reliable estimate of the mean cycles to failure for each stress level and curves for 0.01 and 0.99 probability are good upper and lower limits as well. The 0.05 and 0.95 probability curves could also be used for upper and lower limits if a less conservative solution is desired.

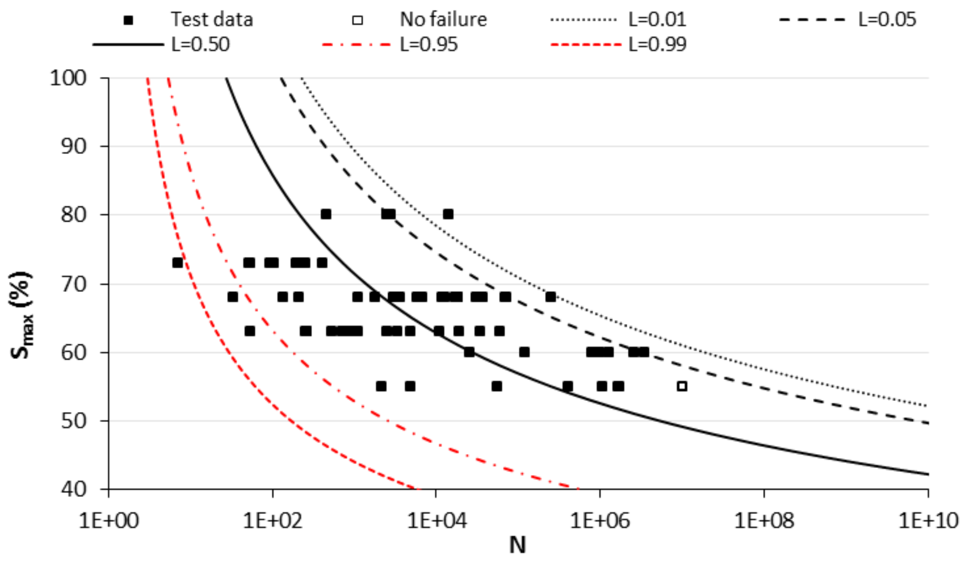

Figure 3 S-N-P curves for masonry under compressive fatigue loading at 2Hz, 10% S_{min} and various S_{max} levels

To establish the suitability of the proposed model to describe masonry under fatigue compressive loading for various masonry types and loading conditions, fatigue data were collected and analysed from the literature. Figure 4 presents the experimental data by Clark [17] on brick masonry prisms under fatigue loading. Dry and wet masonry prisms were loaded at 5 Hz frequency up to 5 million cycles under 5% minimum stress. Prisms that did not fail were subsequently tested under quasi-static loading to failure. The S-N-P curves proposed in Equation 16 are also included in Figure 4. The proposed model seems to be a reliable estimate for dry masonry prisms but is less representative for saturated specimens that fall under the 0.50 probability of survival curve. Test data for saturated specimens should, therefore, be analysed separately and a modified equation should be proposed. The available experimental data are, however, too limited to perform statistical analyses and propose a modified model. Additionally, the test data were performed under different loading rates. The effect of frequency has not been, however, specifically studied for masonry [5] and designated experimental data are required to incorporate this effect within a mathematical model.

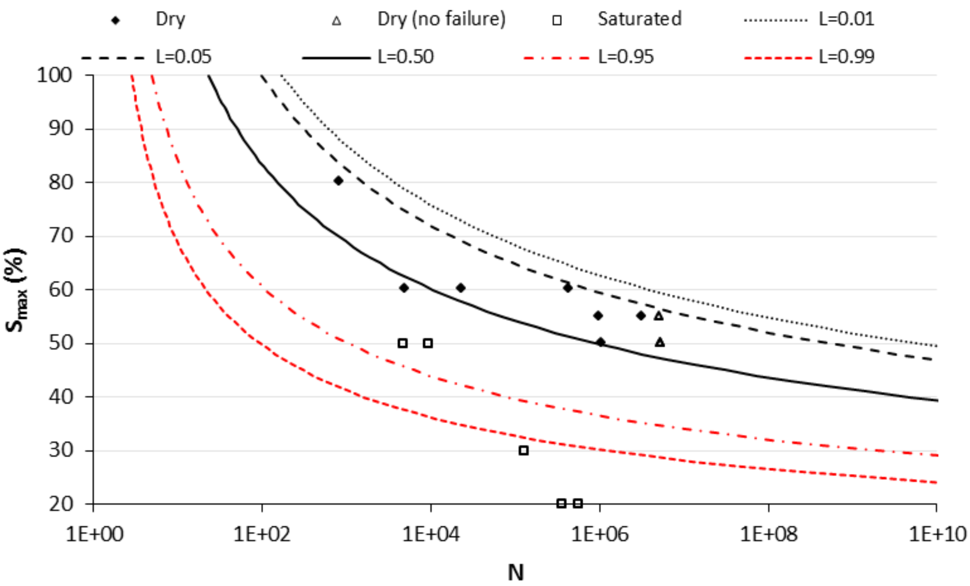

Figure 4 Experimental data by Clark [17] coupled with the proposed S-N-P curves.

Tomor *et al.*, [3] tested a series of masonry prisms under fatigue loading at 2 Hz frequency and 10% minimum stress. Prisms tested under stress levels lower than 58% did not fail and testing was terminated. The test data are presented in Figure 5 together with the S-N-P curves. Disregarding the prisms that did not fail under fatigue loading, the 0.50 probability curve is a reliable estimate of the test data, while the 0.95 probability of survival curve consists a lower limit. The 0.99 probability curve may also be used as a more conservative lower limit.

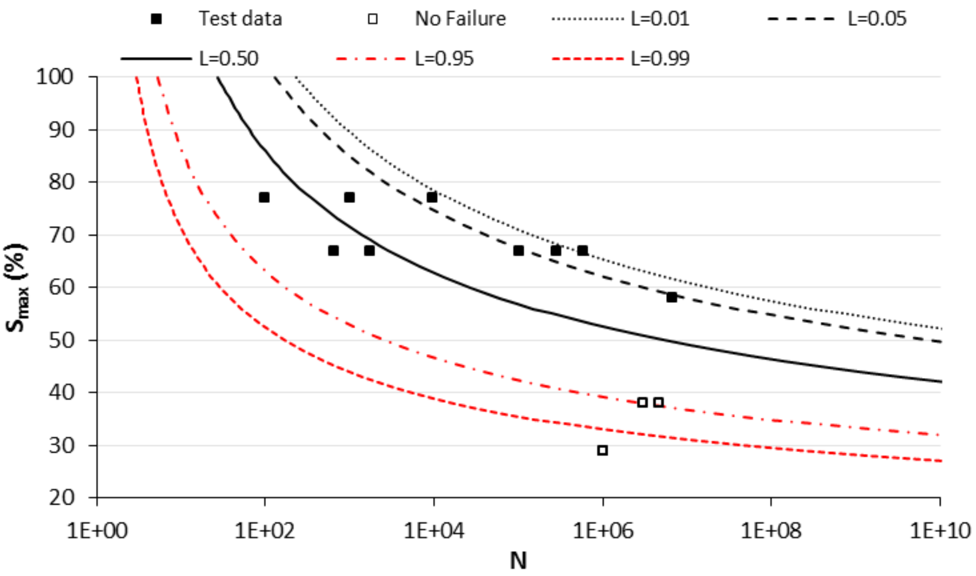

Figure 5 Experimental data by Tomor *et al.*, [3] coupled with the S-N-P curves.

Comparison of available experimental data with the proposed prediction model indicates Equation 16 can be satisfactorily used to predict the fatigue life of brick masonry under compressive loading at any desired confidence level. In every case, the curve corresponding to 0.50 probability of survival indicated the mean fatigue life of dry brick masonry. As a lower limit, the 0.95 probability curve can be considered as a good representation, while the 0.99 curve offers a more conservative solution. For the upper limit, the 0.01 probability curve generally provided a reliable estimate. For wet and saturated masonry, further experimental data are needed to develop probability models.

The presented masonry prisms were tested under slightly different minimum stress levels, σ_{min}/f_c=5% by Clark [17] and σ_{min}/f_c=10% by Tomor *et al.*, [3], although the proposed S-N-P model appears to be a good estimate for all test data, regardless of the minimum stress level. Further test data is needed for identifying the effect of minimum stress on the probability of survival.

Comparison of the proposed S-N-P model with models presented in the literature is carried out separately for the lower limit and mean fatigue life.

For lower limit the current test results (Table 2) and proposed model for 0.95 probability of survival (Equation 16) are shown in Figure 6 together with proposed models by Casas [2] for 0.95 probability and Roberts *et al.*, [1]. The linear lower limit by Roberts does not seem to be a satisfactory fit for the data, underestimating the data in some regions and overestimating in other regions. The model by Casas [2] displays a better fit but does not provide a lower bound, especially for maximum stress levels 60-80%. The proposed prediction model in Equation 16 presents a satisfactory fit, lower limit, as well as offers the flexibility of identifying any suitable probability of survival.

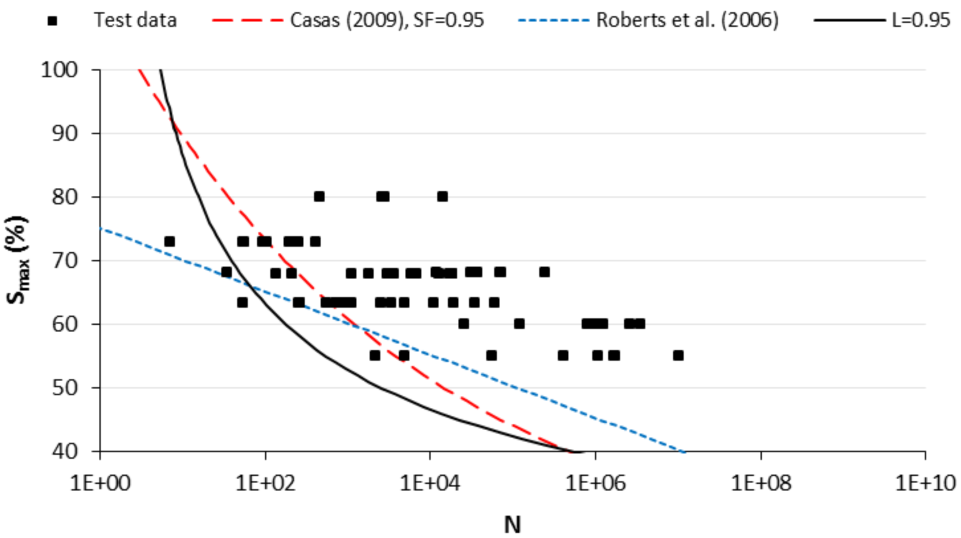

Figure 6 Test data (Table 2) with lower limit from a) Equation 16 for P_f=0.95, b) Casas [2] for P_f=0.95 and c) Roberts *et al.*, [1]

For prediction of the mean fatigue life the current test results (Table 2) and proposed model for 0.5 probability of survival (Equation 16) are shown in Figure 7 together with proposed models by Casas [2] for 0.5 probability and Tomor & Verstrynge [4]. The model by Casas [2] is notably overestimating the fatigue life of masonry prisms at any stress level. The model by Tomor & Verstrynge [4] with correction factor C=-1.5 (identified to best fit current set of test data) seems to provide a good estimate of the mean test data but the curve does not follow the data points very closely. The model cannot be considered as a prediction model as parameter C depends on the data set. The proposed prediction model in Equation 16 presents a satisfactory fit of the mean fatigue life, following the test data closely.

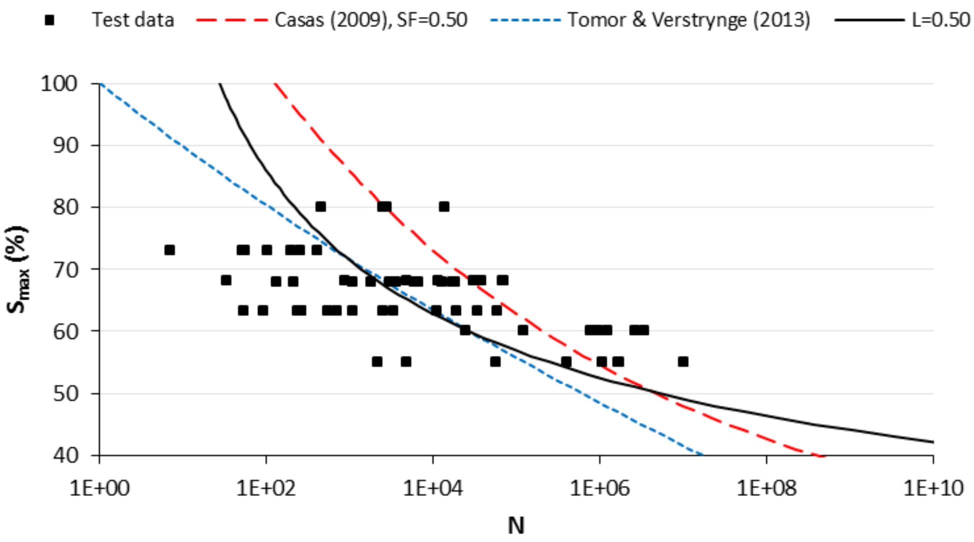

Figure 7 Test data (Table 2) mean fatigue life from a) Equation 16, b) Casas [2] and c) Tomor & Verstrynge [4]

5. Discussion

The prediction model by Casas [2] can provide S-N curves for a limited set of survival probabilities (between 0.50 and 0.95) but does not offer an upper limit or flexibility of adjusting the confidence level for best fit. The S-N curves by Roberts *et al.*, [1] and Tomor & Verstrynge [4] do not account for confidence levels. Roberts *et al.*, [1] offer a lower bound limit for the fatigue life of masonry, while Tomor and Verstrynge [4] offer an expression for the mean fatigue life. The proposed model is currently the only model that allows the S-N curves to be identified for masonry at any confidence level.

For bridge management, information on the rate of deterioration and remaining service life is essential to optimise assessment and inspection techniques and minimise the cost of maintenance. S-N-P curves can provide a useful tool to help evaluate the remaining service life of masonry arch bridges at different confidence levels, based on material properties and traffic load levels. Optimising the weight, speed and frequency of traffic could also help reduce deterioration and extend the remaining service life, particularly in older and weaker bridges.

The proposed mathematical model for the S-N curves can also be fed into the SMART method

(Sustainable Masonry Arch Resistance Technique) [18] for failure modes associated with compressive loading (crushing). The SMART method can be used, therefore, to quantify the residual life of brick masonry arch bridges.

6. Conclusions

A mathematical model is proposed to describe the fatigue life of masonry using S-N-P curves, based on the model used for concrete by McCall [13]. The model, given in Equation 16, takes the stress range and maximum stress level into account and allows the prediction of the fatigue life expectancy of masonry to be defined for any desired confidence level.

The proposed model is presented together with the experimental test data [17, 3] and is compared with models from the literature [1, 2, 4]. The model provides a good estimate for the S-N-P curves for dry masonry. The curve corresponding to 0.50 probability of survival can be used to predict the mean loading cycles to failure, while curves corresponding to 0.95 or the 0.99 probabilities of survival can be used to predict lower limits for any type of dry masonry. In addition, the shape of the proposed curve seems to fit the exponential configuration of the experimental data. Further test data is needed to adapt Equation 16 for wet or submerged masonry specimens.

Acknowledgement

The work reported in this paper was supported by the International Union of Railways (UIC). The technical and financial support provided, is gratefully acknowledged by the authors.

References

[1] T. Roberts, T. Hughes, V. Dandamudi and B. Bell, "Quasi-static and high cycle fatigue strength of brick masonry," *Construction and Building Materials*, vol. 20, no. 9, pp. 603-614, 2006.

[2] J. R. Casas, "A probabilistic fatigue strength model for brick masonry under compression," *Construction and Building Materials*, vol. 23, no. 8, pp. 2964-2972, 2009.

[3] A. Tomor, S. De Santis and J. Wang, “Fatigue deterioration process of brick masonry,” *Journal of the International Masonry Society,* vol. 26, no. 2, pp. 41-48, 2013.

[4] A. Tomor and E. Verstrynge, “A joint fatigue–creep deterioration model for masonry with acoustic emission based damage assessment,” *Construction and Building Materials,* vol. 43, pp. 575-588, 2013.

[5] J. Wang, A. K. Tomor, C. Melbourne and S. Yousif, “Critical review of research on high-cycle fatigue behaviour of brick masonry,” *Construction and Building Materials,* vol. 38, pp. 602-609, 2013.

[6] J. R. Casas, “Reliability-based assessment of masonry arch bridges,” *Construction and Building Materials,* vol. 25, no. 4, pp. 1621-1631, 2011.

[7] ASTM, “Standard test method for compressive strength of masonry prisms,” in *Annual Book of ASTM Standards*, vol. 4.05, ASTM, Ed., West Conhohocken, ASTM International, pp. 889-895, 2014.

[8] I. Koltsida, A. Tomor and C. Booth, “Experimental evaluation of changes in strain under compressive fatigue loading of brick masonry,” *Construction and Building Materials,* vol. 162, pp. 104-112, 2018.

[9] A. Medeiros, X. Zhang, G. Ruiz, R. Yu and M. De Souza Lima Velasco, “Effect of the loading frequency on the compressive fatigue behavior,” *International Journal of Fatigue* , vol. 70, p. 342–350, 2015.

[10] T. Xuesong, “Scatter of fatigue data owing to material microscopic effects,” *Physics, Mechanics & Astronomy,* vol. 57, no. 1, pp. 90-97, 2014.

[11] J. Schijve, Fatigue of Structures and Materials, 1st ed., London: Kluwer Academic, 2001.

[12] G. Sinclair and T. Dolan, “Effect of stress amplitude on statistical variability in fatigue life of 75S-T6 aluminium alloy,” *Transaction of the A.S.M.E.,* vol. 75, no. 5, pp. 867-872, 1953.

[13] J. McCall, “Probability of fatigue failure of plain concrete,” *Journal of the American Concrete Institute*, vol. 55, no. 8, pp. 233-244, 1958.

[14] A. Stagg, “An Investigation of the Scatter in Constant Amplitude Fatigue Test Results of Aluminium Alloys 2024 and 7075. Report number: ARC CP 1093,” Her Majesty's Stationary office, London, 1970.

[15] P. Forrest, Fatigue of metals, 2nd ed., London: Pergamon Press, 1970.

[16] M. Zhao, X. Fan, Q. Fang and T. Wang, “Experimental investigation of the fatigue of closed-cell aluminum alloy foam,” *Materials Letters,* vol. 160, no. 1, pp. 68-71, 2015.

[17] G. Clark, “Bridge analysis testing and cost causation project: serviceability of brick masonry,” British Rail Research Report LR CES 151, 1994.

[18] C. Melbourne, J. Wang and A. Tomor, “A new masonry arch bridge assessment strategy (SMART),” *Journal of Bridge Engineering,* vol. 160, no. 2, pp. 81-87, 2007.