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Failure Potential Evaluation in Engineering Experiments Using Load/Unload Response Ratio Method

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Abstract—The Load/Unload Response Ratio (LURR) method is proposed for prediction of the failure of brittle heterogeneous materials. Application of the method typically involves evaluating the external load on materials or structures, differentiating between loading and unloading periods, determining the failure response during both periods from data input, and calculating the ratio between the two response rates. According to the method, the LURR time series usually climbs to an anomalously high peak prior to the macro-fracture. To show the validity of the approach in engineering practice, we applied it to the loading and unloading experimental data associated with a two-floor concrete-brick structure. Results show that the LURR time series of the two floors consists of the damage evolution of the structure: they are at low level for most of the time, and reach the maxima prior to the final fracture. We then attempt to combine the LURR values with damage variable (*D*) to provide the health assessment of the structure. The relationship between LURR and *D*, defined as a function of Weibull stochastic distribution, is set up to provide more detailed underlying physical means to study damage evolution of the structure. The fact that the damage evolution of the structure correlates well with the variation of LURR time series may suggest that the LURR approach can be severed as a useful tool to provide the health assessment to big scale structures or ancient buildings.

Key words: Load/Unload Response Ratio (LURR), two-floor structure, Weibull distribution, macro-fracture, structure health assessment.

1. Introduction

Research on the failure of heterogeneous brittle material is an interesting research task which relates to many important natural phenomena (e.g. earthquake, landslide, rockfall) and engineering experiments (e.g. rock, ceramics, concrete) . Failure of heterogeneous brittle material is a complicated nonlinear and discontinuous progressive process resulting from the stress concentration and transference associated with the micro-crack initiation, propagation and coalescence (BAI *et al.*, 1993, 1994). Theoretically speaking, due to the heterogeneities contained in the materials and the random distribution of pre-existing defects, it is very difficult to describe the mesoscopic structures and components accurately. To solve the problems, traditional mechanics analysis such as the constitutive equations, boundary conditions, initial conditions, history background are usually considered. However, the failure of heterogeneous brittle material, including crack propagation, interaction and coalescence, is a very complicated three-dimensional formation process. Relevant mechanical problems, except plain strain problems and plain stress problems, such as crack propagation and crack interaction, are related to many directions and cannot be simplified to two-dimensional problems (CAPPINTERI, 1986; ANDERSON, 2005). Actually, there are no proper approaches in mathematics to describe three-dimensional crack propagation even in homogenous material (KACHANOV, 1986; LEMAITRE, 1992; KRAJCINOVIC, 1996). Presently, though some understanding of rock failure process have been achieved (HOLCOMB and COSTIN, 1986; HORII and NEMAT-NASSER, 1986; ATKINSON, 1987; ASHBY and SAMMIS, 1990; DU and AYDIN, 1991; LI *et al.*, 2003), there still are many basic problems that are difficult to answered, such as regards damage localization, nucleation and growth in heterogeneous brittle materials during the process from damage to macro-fracture (BOCK, 1978; COSTIN, 1983; OHTSU, 1982; MICHAELS and PAO, 1985; DU and AYDIN, 1991).

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The formation and interactions between all kinds of weakness on different scales are so intricate that more work focuses on stress field investigation as well as failure criteria of materials. Numerical tests, such as the Finite Element Method, provide an important means to study the failure process of the materials (Liang *et al.*, 2004; Wang *et al.*, 2005). With the improvement of computing environments and the practical demands, the failure process of heterogeneous material analysis is tuning its steps to simulate the complete process of the whole structure. Therefore, the traditional finite element method should adopt new techniques and other methods to meet the need of meso-mechanics to get a satisfactory initial stress, initial strain fields or the final stress state (Linero *et al.*, 2006; Oliver and Huespe, 2004; Oliver *et al.*, 2004, 2006). On the other hand, the investigation of fracture process is much more significant than stress field investigation, in which the peak strength of the material was acquired to help practical engineering design. As a result, the rock fracture experiment is proposed as another effective method to investigate the failure of heterogeneous material (Lockner *et al.*, 1991, Lockner, 1993; Geng *et al.*, 1993). Since the first complete stress–strain curve was obtained by Cook in 1963 (Cook, 1963), large numbers of rock failure experiments were undertaken to study the rock progressive failure process (Lockner and Byerlee, 1977; Hsu *et al.*, 1977; Ceranoglu and Pao, 1981). To simulate the nature failure process of rock samples, the artificial triaxial tests are introduced in experimental investigations (Yin *et al.*, 2004; Yu *et al.*, 2006; Zhang *et al.*, 2006a). The results showed that unstable point was found after the peak strength point in the complete stress–strain curve.

In Fig. 1, we show a typical stress–strain curve of rock masses. Before failure of a rock material, it will have experienced three different phases: elasticity, damage, and failure or destabilization. For the elasticity phase, when the load is well below the yield strength of the material, the response is usually linear to the loading and unloading. However, the damage phase is irreversible and the responses of loading and unloading become quite different. Based on such a thought, a failure prediction method called the Load/Unload Response Ratio (LURR) is proposed (Yin, 1987; Yin *et al.*, 1991, 1994, 1995). Over the past two decades, the method has also been widely applied to earthquake prediction and other engineering practices (He *et al.*, 2004; Zhang *et al.*, 2006b). Results show that prior to most of the large earthquakes and the engineering catastrophes studied, anomalously high LURR values were usually observed.

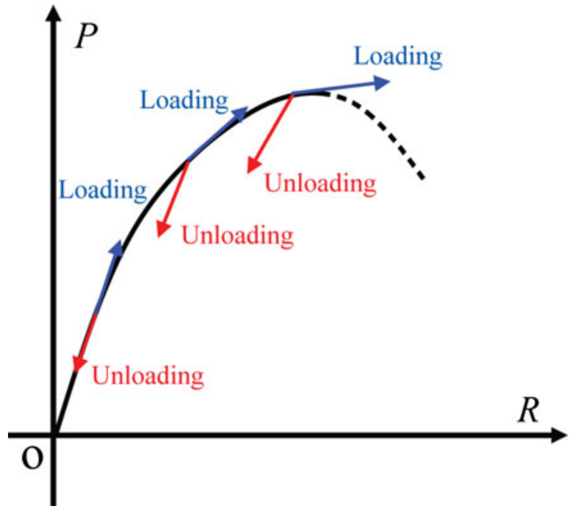


Figure 1
Schematic view of the constitutive law of a brittle mechanic system. *P* and *R* correspond to the load and response of the mechanic system. The response is linear to the *loading* and *unloading* when the load is well below the strength of the system, and becomes nonlinear when the system is close to failure

In this paper, we try to apply the approach to the change of LURR time series associated with a large engineering structures failure. To show the effectiveness of the approach, a two-floor concrete-brick structure failure experiment carried out in University of Naples Italy was chosen as the example. Relevant experimental data of this paper are supported by Prof. Federico M. Mazzolani and his research team.

2. *The LURR Method and Its Definition*

The LURR values that measure the degree of closeness to instability for a heterogeneous brittle material can be defined as

$$Y = \frac{X_+}{X_-}, \tag{1}$$

where '+' and '−' refer to the loading and unloading processes, and X is the response rate (Yin, 1987; Yin *et al.*, 1994, 1995). Suppose that P and R are respectively the load and response of the system, then

$$X = \lim_{\Delta P \to 0} \frac{\Delta R}{\Delta P}, \tag{2}$$

can be defined as the response rate, where ΔR denotes the small increment of R, resulted from a small change of ΔP on P.

When the system is in a stable state, $X_+ \approx X_-$ and LURR ≈ 1. When the system evolves beyond the linear state, usually $X_+ > X_-$, and LURR >1 (see Fig. 1). Thus, LURR can be used as a criterion to judge the state of stability for a heterogeneous system.

In practical use of the LURR method, the macro-displacements and its associated energy release within certain temporal window are usually used as data input. LURR can, therefore, be expressed as a ratio between energy released during loading and that released during unloading periods. Specifically,

$$Y_\gamma = \frac{\left(\sum_{i=1}^{N+} E_i^\gamma\right)_+}{\left(\sum_{i=1}^{N-} E_i^\gamma\right)_-}, \tag{3}$$

where E_i is energy released by the i-th micro-event. γ is a parameter to adjust influence of energy on LURR (Zhang *et al.*, 2006c). '+' and '−', denote the events that occurred during the loading and unloading stages, respectively.

3. Engineering Experiment Data Analyzing

We here introduce an interesting experiment made by the team of Federico M. Mazzolani at University of Naples Italy. As shown in Fig. 2 (personal communication), they conducted a load–unload experiment on a two-floor concrete-brick structure building. Detailed experiment equipment including the building structure, structure for distributing forces between floors, reacting frame and its associated containers are shown in Fig. 2a, whose main profile is shown in Fig. 2b. The building was loaded through a

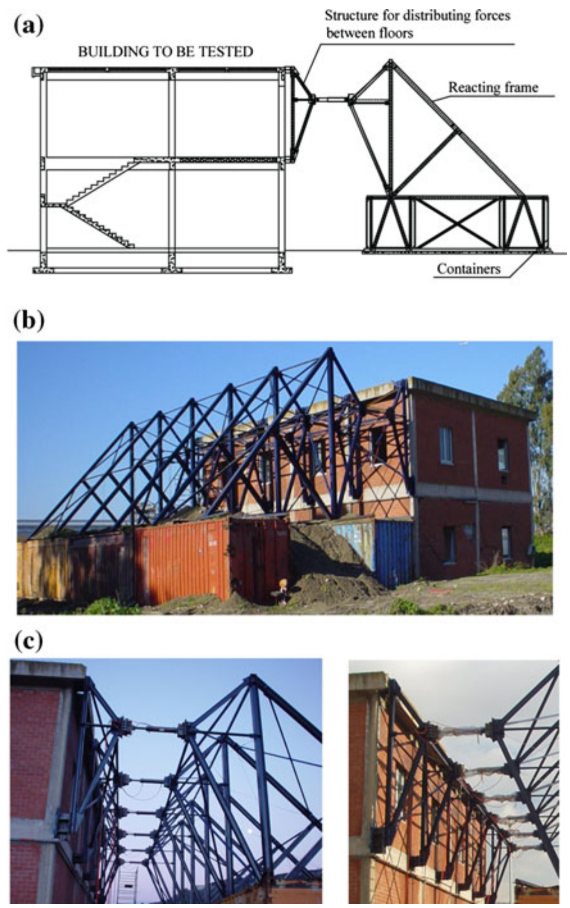
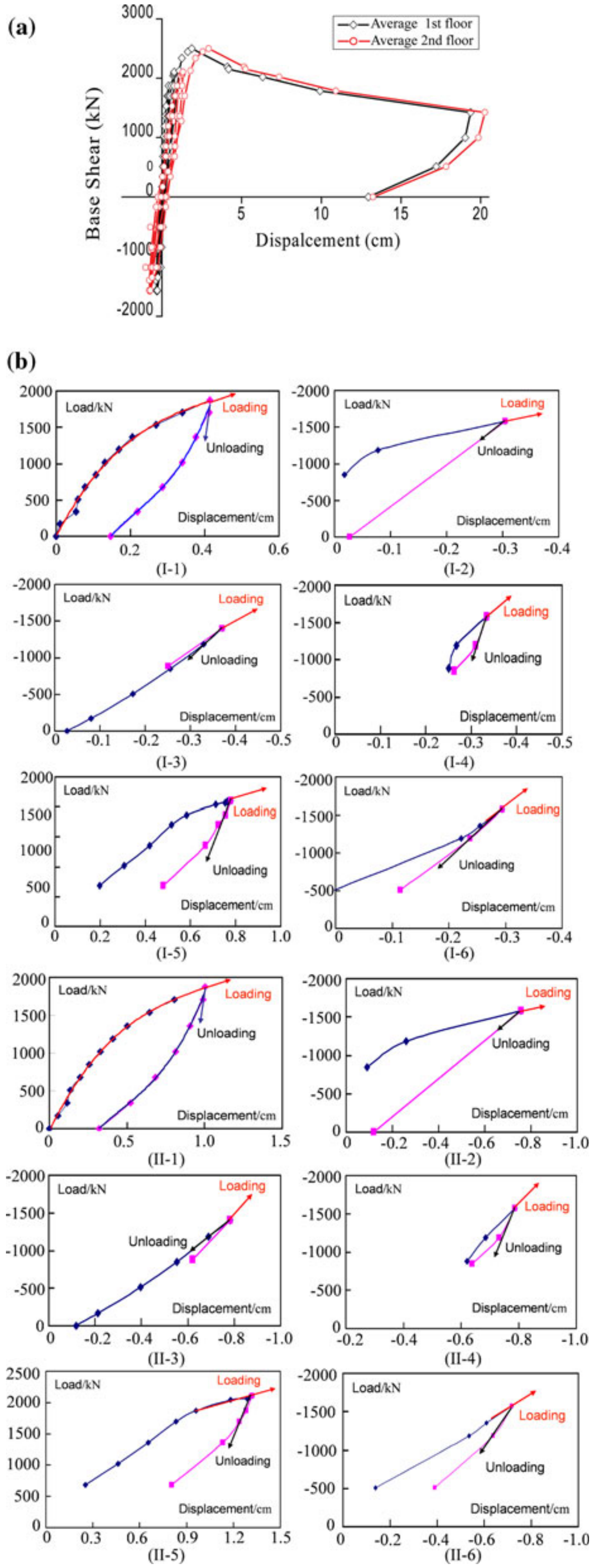


Figure 2
The sketch map of the experiment system. **a** The main vertical sections. **b** The global view of the structure. **c** The triangulated steel structures

triangulated steel frame structure at one side of the building (Fig. 2c). During the experiment, the structure was subjected to six load–unload cycles from −2000 to 2500 kN and fractured at 2501.35 kN. The whole and detailed load–displacement curves of the two floors are respectively shown in Fig. 3a, b.

In each load–unload cycle, the LURR was calculated in accordance with the change of the tangent modulus at the load–unload conversion point. For example, during the first load cycle (see Fig. 3b), the load–unload conversion points of the first and second floors were marked as I-1 and II-1, respectively. We firstly fit the loading and unloading processes at I-1 with a polynomial function. Then, we calculate the tangent slopes of the loading and unloading processes


(a)
Average 1st floor
Average 2nd floor
Base Shear (kN)
Dispalcement (cm)
(b)
Load/kN
Loading
Unloading
Displacement/cm
(I-1)
(I-2)
(I-3)
(I-4)
(I-5)
(I-6)
(II-1)
(II-2)
(II-3)
(II-4)
(II-5)
(II-6)

◀ Figure 3
The curves of load versus displacement for the building structure. **a** The whole load–displacement curves of the two floors shown by *black-diamond* and *red-circle curves*. **b** Detailed load–displacement curves for different load–unload phases. The load–unload conversion points are also shown in the figures. Loading and unloading processes are delineated by different symbol, *blue-diamond curves* for loading, and *magenta-square* for unloading, respectively. Conversion point labeled as (*I-1*) is for the first conversion point of first floor, (*II-1*) is for the first conversion point of the second floor, and the rest may be deduced by analogy

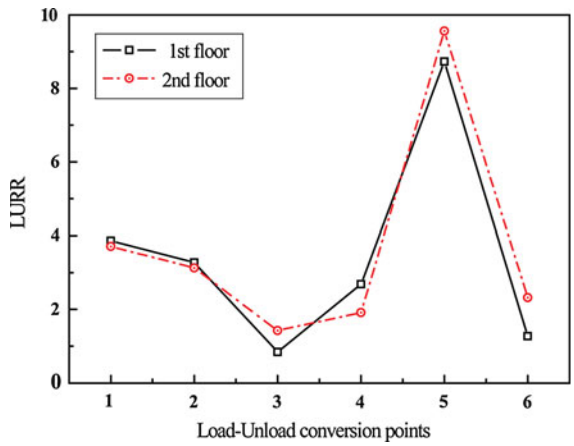


Figure 4
Time series of LURR for the six load–unload conversion points. The *black-solid* and *red-dashed curves* show the time series of the two floors, respectively

at the conversion point. The LURR value at I-1 can, therefore, be derived by evaluating the ratio between the two slopes. Using the same method, we can evaluate the LURR values for II-1 and the other five load–unload cycles. The LURR time series of the six different load cycles are shown in Fig. 4. It is clear that our algorithm yields significant anomalies prior to the final fracture of the building. The evolution of LURR time series is consistent with previous studies by Yin *et al.* (1995, 2000), which show that the LURR values were between 1.0 and 3.0 for most of time until a short time frame before the fracture when, the LURR values peaked at a high value of 9.5, and then began to drop before the final failure.

4. Damage Estimation in the Structure

We have calculated the LURR values for the load–unload conversion points shown in Fig. 3. Comparing the LURR values of different load–unload cycles, it is clear that with increase of the load level the LURR value enhanced obviously. However, we would still care about the damage level at each conversions point and its associated effects on failure of the structure. To solve the problem, we calculate the relationship that exists between the LURR (Y) and the damage variable (D) as bellow.

According to the definition of damage mechanics (Kachanov, 1986; Lemaitre, 1992), we know that

$$\sigma_n = \sigma_a(1 - D), \tag{4}$$

where, σ_a and σ_n are respectively the actual and nominal stresses, D is the damage variable. And the total differential of σ_n can be expressed as

$$\mathrm{d}\sigma_n = \mathrm{d}\sigma_a(1 - D) - \sigma_a \mathrm{d}D. \tag{5}$$

If we assume that $\mathrm{d}D$ is 0 when the material stays in an unloading state (Zhang *et al.*, 2010), then

$$\begin{aligned} \mathrm{d}\sigma_{n(+)} &= \mathrm{d}\sigma_{a(+)}(1 - D) - \sigma_a \mathrm{d}D \\ \mathrm{d}\sigma_{n(-)} &= \mathrm{d}\sigma_{a(-)}(1 - D), \end{aligned} \tag{6}$$

where "+" and "−" represent loading and unloading, respectively.

On the other hand, in terms of the definition of Hooke's law, we have

$$\begin{aligned} \mathrm{d}\sigma_{a(+)} &= E_0 \mathrm{d}\varepsilon_{(+)} \\ \mathrm{d}\sigma_{a(-)} &= E_0 \mathrm{d}\varepsilon_{(-)}, \end{aligned} \tag{7}$$

where $E_0$is the initial Young's modulus.

From Eqs. 6 and 7, the loading and unloading responses are, therefore, expressed as:

$$\begin{aligned} X_+ &= \frac{\mathrm{d}\varepsilon_{(+)}}{\mathrm{d}\sigma_{n(+)}} = \left(E_0(1 - D) - \frac{\sigma_a \mathrm{d}D}{\mathrm{d}\varepsilon_{(+)}}\right)^{-1} \\ X_- &= \frac{\mathrm{d}\varepsilon_{(-)}}{\mathrm{d}\sigma_{n(-)}} = (E_0(1 - D))^{-1}. \end{aligned} \tag{8}$$

Combining with Eq. 1, the LURR can be rewritten as:

$$Y_E = \frac{X_+}{X_-} = \frac{1}{1 - \frac{\varepsilon}{(1-D)} \frac{\mathrm{d}D}{\mathrm{d}\varepsilon_{(+)}}}. \tag{9}$$

On the other hand, suppose that the fracture limitations of materials (ε_c) follow the same function of Weibull distribution

$$h(\varepsilon_c) = m\varepsilon_c^{m-1}\exp\left(-\varepsilon_c^m\right), \tag{10}$$

where m is the Weibull modulus which definite the heterogeneous of the material, ε_c is the strain at the critical failure point (Reichl, 1980; Wei *et al.*, 2000; Abbasi *et al.*, 2006). The damage function $D(\varepsilon)$ can then be integrated as:

$$D(\varepsilon) = \int_0^{\varepsilon} h(\varepsilon_c)\mathrm{d}\varepsilon_c = 1 - \mathrm{e}^{-\varepsilon^m}. \tag{11}$$

Substitute Eqs. 9 with 11, then

$$Y_E = \frac{1}{1 - m\varepsilon^m}. \tag{12}$$

If we let $\varepsilon_F = \left(\frac{1}{m}\right)^{\frac{1}{m}}$, we can get

$$Y_E = \frac{1}{m\left(\varepsilon_F^m - \varepsilon^m\right)}. \tag{13}$$

And the damage degree at the failure point can also be obtained by combining with Eq. 11

$$D_F = 1 - \mathrm{e}^{-\frac{1}{m}}. \tag{14}$$

Eliminating ε in Eqs. 11 and 12, we can establish the relationship between LURR (Y_E) and damage variable (D). Specifically,

$$Y_E = \frac{1}{1 - m\varepsilon^m} = \frac{1}{1 + m\ln(1 - D(\varepsilon))}. \tag{15}$$

And the damage level of the structure can be expressed as:

$$D = 1 - \mathrm{e}^{\frac{m(1-Y_E)}{Y_E}}. \tag{16}$$

We know that the heterogeneities of different materials are given by different m values. It is hard to set up a uniform scale to evaluate the D values associated with different materials. In Fig. 5, we list the relationships between ratio of D/D_F and Y_E when Weibull modulus is $m = 1, 2, 4, 8$, respectively. It is obvious that with increase of the damage the LURR value is enhanced, the spread of the function also depends on the value of m: the larger m values, the higher D/D_F becomes.

During the experiment that we show above, the structure was destroyed at 2500 kN (see Fig. 3a). If we let damage level at this point be the critical damage D_F, the relative damage for each load–unload cycle (at the conversion points shown in Fig. 3b) can be evaluated using Eq. 16. The damage statistics for the six load–unload conversion points of the two-floor structure with the change of its associated LURR value are listed in Table 1. In this study $m = 2$ is used to depict the heterogeneity of the material, which is the suitable value for the statistics of the Weibull distribution (Wei *et al.*, 2000). Results show that the change of LURR time series with increase of external load could provide a relatively more precise estimation of the damage level of the structure: the higher is the LURR value, the larger is the damage.

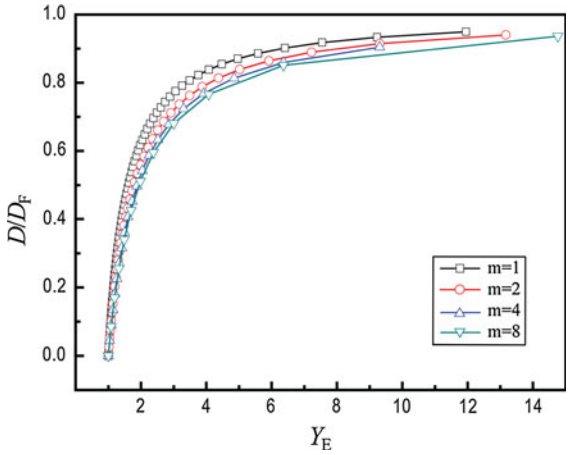


Figure 5
The relationships between D/D_F and Y_E when Weibull modulus $m = 1, 2, 4, 8$. D_F is the critical damage for different heterogeneity (m) materials

Table 1

Damage statistic of the two floors structure with change of the LURR

LURR analysis of the 1st floor				LURR analysis of the 2nd floor			
No.	Load (kN)	LURR	D/D_f	No.	Load (kN)	LURR	D/D_f
1	1871.76	3.8667	0.7872	1	1871.76	3.7139	0.7779
2	−1583.40	3.2780	0.7460	2	−1583.40	3.1275	0.7328
3	0	1.7942	0.5050	3	0	1.3407	0.3033
4	−1572.09	2.6869	0.6847	4	−1572.09	1.9108	0.5389
5	2105.73	8.7333	0.9092	5	2105.73	9.5638	0.9173
6	−1572.09	1.2696	0.2560	6	−1572.09	2.3175	0.6288
7	2175.5	∞	1.0	7	2175.2	∞	1.0

5. Discussion

Over the past 20 years, the LURR method has been developed by Yin and others (e.g. Yin *et al.*, 1995, 2000, 2006; Wang *et al.*, 2004; Yu *et al.*, 2010, 2011; Zhang *et al.*, 2006a, c, 2010). Prior to occurrence of a large earthquake, the LURR time series usually climb to an anomalously high value. This phenomenon can be used as an important precursor to evaluate potential of large failure (Yin *et al.*, 1995, 2000). In this study, we transplanted the idea of LURR from seismology into mechanics to investigate the damage evolution of the brittle heterogeneous systems. Comparing the LURR time series of the two-floor, it is clear that both curves have yielded significant anomalies prior to the ensuing major failure. The LURR time series of both algorithms are at a low level for most of the time, and reach maxima a few times before the failure. These results are consistent with previous studies by Yin *et al.* (2000, 2002), who indicated that the LURR values were between 0 and 3 for many load–unload cycles until the last cycle before the failure when, the LURR values peaked at a high value (~ 9), and then began to drop to 1, short before the final fracture.

The LURR method is based on the methodology of system theory. We can study the relationship between the input and output signals of the system (i.e. research on the response to the input signal) to achieve the purpose of understanding the system behavior. As an example that we show above, we first calculate the displacement as response to evaluate the LURR time series. Then we establish the relationship between LURR and damage variable D with Weibull distribution as probability function input. It is quite interesting that with increase of the external load the damage within the structure increased. During the one load cycle when the anomalous high LURR occurred, the damage reaches a relatively high level. The fact that LURR correlates well with the damage level of the structure may suggest the critical triggering of the approach: when the stress is low, it is difficult to generate any large damages, so that LURR must be low. On the other hand, when the stress is at a high level, the source material will be sensitive to any tiny extrinsic disturbance, and damages can easily be created, so that LURR must be anomalously increased. Knowing the unique characteristic of the approach, we may use that for testing various kinds of structure failure in the future.

For a given structure, if its inner damage or deformation information effective to dictate its stress state is loaded with anomalously high stress, it will tend to be driven toward failure. The two-floor structure failure experiment we show above is such an example, whose high stress state is detected by the anomalously high LURR prior to the failure. Because the load–unload cycles are specifically devised for testing the final fracture of the structure, the ones with LURR values at a lower level (whose the stress change may be less effective in manifesting the damage change of the structure), are excluded from the failure potential estimation (such as the LURR values of the I $\sim$ IV load–unload conversion points shown in Fig. 3b), the sensitivity of the LURR method is therefore implemented. On the other hand, because we have set up the relationship (Eq. 16) between the damage (D/D_{F}) and LURR (Y_{E}), the damage level of each stage can therefore be evaluated using its associated LURR value. Moreover, from the anomalous high LURR value, the critical damage level to assess failure of the structure may also be defined. Hence, the damage evolution with anomalously increased LURR values can provide a natural health assessment and critical estimation to the large scale structures.

6. Conclusion

The approach presented in this paper allows us to systematically search for the failure of the structures if response signals and external loads setting are known. Analysis of the anomalies in the LURR time series may provide us with failure potential evaluation with estimates of all the crucial parameters of the health assessment such as failure location, time, magnitude. The two-floor concrete-brick structure failure experiment that we show above has indicated that anomalous increase in the time series of LURR was observed prior to failure of the structure. And even if such a priori anomaly is not detected, one could still estimate all the possible damage scenarios of the structure by applying the approach to evaluate the LURR and corresponding damage (D) to provide the health assessment of the large structures.

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REFERENCES

ABBASI, B., JAHROMI, A. H. E., ARKAT, J., and HOSSEINKOUCHACK, M. (2006), *Estimating the parameters of Weibull distribution using simulated annealing algorithm*, Applied Mathematics and Computation, *183*(1):85–93.

ANDERSON, T. L. (2005), *Fracture Mechanics: Fundamentals and Applications*, Third Edition, Structural Reliability Technology, Boulder, Colorado, USA.

ASHBY, M. F., and SAMMIS, C. G. (1990), *The damage mechanics of brittle solids in compression*, Pure and Appl. Geophys., *133*(3):489–521.

ATKINSON, B. K. (Ed.) (1987), *Fracture Mechanics of Rock*, Academic Press, New York, p. 534.

BAI, Y. L., LU, C. S., KE, F. J., and XIA, M. F. (1994), *Evolution induced catastrophe*, Phys. Lett. A, *185*(2):196–200.

BAI, Y. L., XIA, M. F., KE, F. J., LU, C. S., and LING, Z. (1993), *Analysis and simulation of evolution induced catastrophe*, Chinese Phys. Lett., *10*(3):155–158.

BOCK, H. (Ed.) (1978), *An Introduction to Rock Mechanics*, James Cook University of North Queensland, Townsville, Australia, p. 342.

CAPPINTERI, A. (1986), *Mechanical Damage and Crack Growth in Concrete Plastic Collapse to Brittle Fracture (Engineering Applications of Fracture Mechanics)*, Vol. 5, ISBN: 978-90-247-3233-3, Springer.

CERANOGLU, A. and PAO, Y. H. (1981), *Propagation of elastic pulses and acoustic emission in a plate, parts 1, 2, and 3*. J. Appl. Mech., *48*(1):125–147.

COOK, N. G. W. (1963), *The basic mechanics of rockbursts*, Journal of the South African Institute of Mining and Metallurgy, *64*(3):71–81.

COSTIN, L. S. (1983), *A microcrack model for the deformation and failure of brittle rock*, J. Geophys. Res., *88*(B11):9485–9492.

DU, Y., and AYDIN, A. (1991), *Interaction of multiple cracks and formation of echelon crack arrays*, Int. J. Numerical and Analytical Methods in Geomechanics, *15*(3):205–218.

GENG, N. G., CUI, C. Y., and DENG, M. D. (1993), *The remote sensing observation in experiments of rock failure and the beginning of remote sensing rock mechanics*, Acta Seismologica Sinica, *6*(4): 971–980. doi: 10.1007/BF02651832

HE, K. Q., ZHOU D. Y., and WANG S. J. (2004), *Features of Load-Unload Response Ratio and its significance in prediction of colluvial landside by rainfall*. Chinese Journal of Rock Mechanics and Engineering, *23*(16):2665–2670 (in Chinese with English abstract).

HOLCOMB, D. J., and COSTIN, L. S. (1986), *Detecting damage surfaces in brittle materials using acoustic emissions*. J. Appl. Mech., *108*:536–544.

HORII, H., and NEMAT-NASSER, S. (1986), *Brittle failure in compression: splitting, faulting and brittle-ductile transition*. Philos. Trans. R. Sot. London, A, *319*(1549):337–374.

HSU, N. N., SIMMONS, A., and HARDY, S. C. (1977), *An approach to acoustic emission signal analysis*. Mater. Eval. *35*:100–106.

KACHANOV, L. M. (1986), *Introduction to Continuum Damage Mechanics*. Martinus Nijhoff, Dordrecht

KRAJCINOVIC, D. (1996), *Damage Mechanics*, 1st ed. North-Holland Elsevier Amsterdam: Netherlands press, 1–774.

LEMAITRE, J. (1992), *A Course on Damage Mechanics*, Springer-Verlag Berlin Heidelberg.

LI, L., LEE, P. K. K., TSUI, Y., THAM, L.G., and TANG, C. A. (2003), *Failure Process of Granite*, International Journal of Geomechanics, *3*(01-02):84–98.

LIANG, Z. Z., TANG, C. A., LI, H. X., XU, T., and ZHANG, Y. B. (2004), *Numerical simulation of 3-d failure process in heterogeneous rocks*. International Journal of Rock Mechanics and Mining Sciences, *41*(Supp. 1):323–328.

LINERO, D. L., OLIVER, J., HUESPE, A. E., and PULIDO, M. D. G. (2006), *Cracking modeling in reinforced concrete* via *the strong discontinuity approach*. Computational Modeling of Concrete Structures: proceeding of the EURO-C 2006. Meschke, G., Borst, R., Mang, H., Bicanic, N. (eds), Mayrhofen, Tirol (Austria).

LOCKNER, D. A., BYERLEE, J. D., and KUKSENKO, V. (1991), *Quasi-static fault growth and shear fracture energy in granite*. Nature, *350*:39–42.

LOCKNER, D. (1993), *The role of acoustic emission in the study of rock fracture*. International Journal Rock Mechanics and Mining & Geomechanics Abstracts, *30*(7):883–899. doi:10.1016/0148-9062(93)90041-B

LOCKNER, D., and BYERLEE, J. D. (1977), *Hydrofracture in Weber sandstone at high confining pressure and differential stress*. J. Geophys. Res. *82*(14):2018–2026.

MICHAELS, J. E., and PAO, Y. H. (1985), *The inverse source problem for an oblique force on an elastic plate*. J. Acoust. Soc. Am. *77*(6):2005–2011.

OHTSU, M. (1982), *Source mechanism and waveform analysis of acoustic emission in concrete*. J. Acoust. Emission. *1*(2):103–112.

OLIVER, J., HUESPE, A. E., BLANCO, S., and LINERO, D. L. (2006), *Stability and robustness issues in numerical modeling of material failure with strong discontinuity approach*. Computer Methods in Applied Mechanics and Engineering, *195*(52):7093–7114.

OLIVER, J., HUESPE, A. E., SAMANIEGO, E., and CHAVES, E. W. V. (2004), *Continuum approach to the numerical simulation of material failure in concrete*. International Journal for Numerical and Analytical Methods in Geomechanics, *28*:609–632.

OLIVER, J., and HUESPE, A. E. (2004), *Theoretical and computational issues in modeling material failure in strong discontinuity scenarios*. Computer Methods in Applied Mechanics and Engineering, *193*(27–29):2987–3014.

REICHL, L. E. (1980), *A Modern Course in statistical Physics* (University of Texas).

WANG, S. H., TANG C. A., ZHANG, Y. B., and LI, L. C. (2005), *Numerical study on cracking process of masonry structure*, Advanced Materials Research, *9*:117–126.

WANG, Y., MORA, P., YIN, C., and PLACE, D. (2004), *Statistical tests of Load-Unload Response Ratio signals by Lattice Solid Model:*

Implication to tidal triggering and earthquake prediction. Pure Appl. Geophys., *161*(11–12):1829–1839.

Wei, Y. J., Xia, M. F., Ke, F. J., Yin, X. C., and Bai, Y.L. (2000), *Evolution induced catastrophe and its predictability*, Pure and Appl. Geophys., *157*:1945–1957.

Yin, X. C., and Yin, C. (1991), *The precursor of instability for nonlinear system and its application to earthquake prediction*, Science in China (Series B), *5*:512–518 (in Chinese).

Yin, X. C., Yu H. Z., Kukshenko V., Xu, Z. Y., Wu, Z. S., Li, M., Peng, K. Y., Elizarov, S., and Li, Q. (2004), *Load-Unload Response Ratio (LURR), Accelerating Energy release (AER) and State Vector evolution as precursors to failure of rock specimens*. Pure and Applied Geophysics, *161*(11–12):2405–2416.

Yin, X. C., Zhang L. P., Zhang H. H, Yin, C., Wang, Y. C., Zhang, Y. X., Peng, K. Y., Wang, H. T., Song, Z. P., Yu, H. Z., and Zhuang, J. C. (2006), *LURR's Twenty Years and Its Perspective*. Pure Appl. Geophys., *163*(11–12), 2317–2341.

Yin, X. C., Mora, P., Peng, K. Y., Wang, Y. C., and Weatherley, D. (2002), *Load-unload response ratio and accelerating moment/energy release critical region scaling and earthquake prediction*. Pure and Appl. Geophys, *159*(9), 2511–2523.

Yin, X. C., Chen, X. Z., Song, Z. P., and Yin, C. (1995), *A New Approach to Earthquake Prediction-The Load/Unload Response Ratio (LURR) Theory*. Pure and Appl. Geophys., *145*(3/4), 701–715.

Yin, X. C., Chen, X. Z., and Song, Z. P. (1994), *The load/unload response ratio (LURR) theory and its application to earthquake prediction*. Journal of Earthquake Prediction Research, *3*(3), 325–333.

Yin, X. C., Wang, Y. C., Peng, K. Y., Bai, Y. L., Wang, H. T., and Yin, X. F. (2000), *Development of a new approach to earthquake prediction: Load/Unload Response Ratio (LURR) theory*. Pure and Appl. Geophys., *157*(11–12), 2365–2383.

Yin, X. C. (1987), *A new approach to earthquake prediction*. Earthquake Research in China, *3*(1):1–7 (in Chinese).

Yu, H. Z., Yin, X. C., Zhu, Q. Y., and Yan, Y.D. (2006), *State Vector—a new approach to prediction of the failure of brittle heterogeneous media and large earthquakes*. Pure and Applied Geophs., *163*(11–12):2561–2574.

Yu H. Z. and Zhu Q. Y. 2010, *A probabilistic approach for earthquake potential evaluation based on the Load/Unload Response ratio method*. Concurrency and Computation:Practice and Experience, *22*, 1520–1533.

Yu H. Z., Zhu Q. Y. and Wan Y. G. 2011, *Stress accumulation and Load Unload Response Ratio change before large earthquakes—example of the 2008 Mw7.9 Wenchuan earthquake*. Nat Hazards, doi:10.1007/s11069-010-9664-9.

Zhang, H. H., Yin, X. C., Liang, N. G., Yu, H. Z., Li, S. Y., Wang, Y. C., Yin, C., Kukshenko, V. Tomiline, N., and Elizarov, S. (2006a), *Acoustic Emission Experiments of Rock Failure Under Load Simulating the Hypocenter Condition*. Pure Appl. Geophys., *163*(11–12):2389–2406.

Zhang, L. P., Yin, X. C., and Liang, N. G. (2010), *Relation between Load/Unload Response Ratio and Damage Variable and its application*, Concurrency and Computation:Practice and Experience, *22*(12):1534–1548. doi:10.1002/cpe.1513.

Zhang, W. J., Chen, Y. M., and Zhan, L. T. (2006b), *Loading/Unloading response ratio (LURR) theory applied in predicting deep-seated landslides triggering*. Engineering Geology, *82*, 234–240.

Zhang, Y. X., Yin, X. C., Peng, K. Y., Wang, H. T., Zheng, J. C., Wu, Y. J., and Zhang, L. P. (2006c), *LURR and the San Simeon M 6.5 Earthquake in 2003 and the Seismic Tendency in CA*. Pure Appl. Geophys., 163(11–12):2343–2351.

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