A rapid visual screening procedure to assess the seismic resilience of RC buildings
Μια διαδικασία ταχέως οπτικού ελέγχου για την αποτίμηση της ανθεκτικότητας κτιρίων Ο.Σ. έναντι σεισμού

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Λέξεις κλειδιά: Σεισμός, Ανθεκτικότητα, Τρωτότητα, Ταχύς Οπτικός Έλεγχος

ABSTRACT: The present system of assessing the existing infrastructure for vulnerability is not enough to address the loss of life, injuries and financial loss caused by major earthquakes. Rather, society needs to be resilient to disaster and it is society's resilience that needs to be assessed. This article proposes a new rapid visual resilience assessment procedure. The concept of urban resilience is described along with factors that are considered to affect resilience. A worked example is performed and, even though a good resilience result is found, the procedure highlights areas for further improvement. It is concluded that performing a rapid visual screening procedure to assess resilience identifies the weakest links in a society's resilience to earthquake disaster and detect areas for improvement to increase urban resilience.

ΠΕΡΙΛΗΨΗ: Το σημερινό σύστημα αποτίμησης της τρωτότητας ή και αντιστρόφως της ανθεκτικότητας (resilience) των υφισταμένων υποδομών δεν επαρκεί για να αντιμετωπίσει τις πιθανές απώλειες ζωής, τους τραυματισμούς και τις οικονομικές απώλειες που προκαλούνται από μεγάλους σεισμούς. Είναι μάλλον η κοινωνία που πρέπει να είναι ανθεκτική (resilient) στην καταστροφή και είναι η αντοχή της κοινωνίας που πρέπει να αξιολογηθεί. Το άρθρο αυτό προτείνει μια διαδικασία ενός ταχέως ελέγχου της ανθεκτικότητας κτιρίων Ο.Σ. συνεκτιμώντας τις ανθρώπινες αντιδράσεις και τις κρατικές δράσεις πριν, μετά και κατά την ώρα ενός ισχυρού σεισμού. Η έννοια της κοινωνικής ανθεκτικότητας περιγράφεται μαζί με παράγοντες που θεωρούνται ότι επηρεάζουν την ανθεκτικότητα των κατασκευών. Εκτελείται ένα παράδειγμα εργασίας και, παρόλο που διαπιστώνεται καλό αποτέλεσμα ανθεκτικότητας, η διαδικασία υπογραμμίζει περιοχές για περαιτέρω βελτίωση. Συμπεραίνεται ότι η διεξαγωγή μιας διαδικασίας ταχείας οπτικής εξέτασης για την αποτίμηση της ανθεκτικότητας, εντοπίζει τους πιο αδύναμους κρίκους της ανθεκτικότητας της

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κοινωνίας, σε σεισμικές καταστροφές και εντοπίζει περιοχές βελτίωσης για την αύξηση της κοινωνικής αντοχής.

INTRODUCTION

The Centre for Research on the Epidemiology of Disasters states that in the last 20 years earthquakes and their tsunami sidekick have caused more fatalities than all the other natural hazards put together (CRED, 2015). Due to a demographic population shift, the United Nations Office for Disaster Risk Reduction estimates that 70% of the world's population will be living in cities by the year 2050 and, therefore, the risk of catastrophes caused by natural hazards is set to increase exponentially (UNISDR, 2014). According to the Atlas of the Human Planet (Pesaresi et al., 2017), between 1975 and 2015, the population in seismic prone regions has increased by 93%. 2.7 billion people (roughly 37% of the world's population) now live in seismic areas.

The above statistics are startling and, obviously, most earthquake prone countries have introduced some form of an assessment procedure to offset the major loss of life, injuries, destruction and substantial financial losses caused by major earthquakes. Such evaluation procedures concentrate on assessing the existing infrastructure for vulnerability and the rapid visual screening procedure (RVSP) is the first stage of some of these pre-earthquake assessment procedures. Here, experts initially gather all available documentation and data before going out into the field and quickly collecting crucial structural characteristic information and other parameters in the form of yes/no answers. Results from a RVSP isolate a set of buildings to be further investigated. The basic problem with RVSPs is that they assume that the factors that may affect the effectiveness of the structural system act individually on the structural system. As RVSPs have been refined by expert examination over a number of years, it is difficult to see how improvements can be made and, therefore, several authors have investigated alternative RVSPs. For example, Dritsos and Moseley (2013) have summarised the development of the fuzzy logic RVSP and observed that one advantage of such a procedure over conventional procedures may be that it considers how the identified parameters interact and may affect the overall seismic response. A second advantage noted by Dritsos and Moseley (2013) may be that the fuzzy logic procedure considers the degree to which a parameter exists. That is, the experts performing a conventional RVSP have the impossible task of making yes/no decisions when the truth may be closer to some degree of maybe.

It is clear that assessing vulnerability may not enough when considering and preparing for the effects of major earthquakes. Destructive earthquakes affect a whole region and emergency services may not be able to cope with the many high priority life threatening situations. In addition, it is the vulnerable groups, such as people with disabilities, which by far suffer the most during and after destructive earthquakes (Aroni and Durkin, 1985; Harada, 2013; Tierney et al., 1988). It has been reported for the Whittier Narrows and Loma Prieta earthquakes (Bourque et al., 1991; Jones et al., 1990) that the majority of fatalities and injuries were due to how people behaved during or immediately after the earthquake and the fatalities and injuries were caused by people being hit by non-structural elements and building contents or by people falling down. Moreover, vulnerable groups also include children, the elderly, the infirm, people with injuries, parents with small children, pregnant women, ethnic minorities, migrants, refugees, displace persons, travellers, tourists, etc. Therefore, it can be assumed that destructive earthquakes cause disproportionately many more fatalities among susceptible groups. It has been noted that if the infrastructure was designed with vulnerable groups in mind, then all society would benefit (Dritsos, 2015). Considering this may give the key to how the built environment should be assessed. For example, if a person with disabilities or a vulnerable person can easily evacuate a building after a disaster, then everybody else can do the same.

This paper introduces a new resilience assessment procedure for RC buildings. It is based on the RVSPs of the Earthquake Planning and Protection Organisation (OASP) for structural and non-structural vulnerability (OASP, 2017), the American Federal Emergency Management Agency (FEMA P-154, 2015), experience gained through developing the fuzzy logic RVSP (Dritsos and Moseley, 2013) and ideas conceived while contributing to the Council of Europe's European and Mediterranean Major Hazards Agreement. This new procedure is in its infancy and the intention of this paper is to provoke discussion and debate. A further intention is to introduce concepts beyond conventional RVSPs that should be considered to ensure that a society is resilient to earthquake disaster.

RESILIENCE

Resilience is the capacity to cope with and adapt to change. A society's resilience would involve preparing for, reacting to and recovering from a catastrophe. Resilient societies are little affected by and recover quickly from disaster. A society's resilience to disaster depends on the initial loss of functionality and the time taken to return to the previous equilibrium point. Figure 1 schematically presents resilience with regard to community recovery after an earthquake. From figure 1, it can initially be seen that the loss of functionality depends on the vulnerability or the robustness of the infrastructure and the society. In addition, a further controlling factor is the time taken to recover. Figure 1a indicates that for a constant recovery rate, a less vulnerable or more robust society recovers the quickest, while figure 1b shows that for a constant loss of functionality, it is the time taken to recover that is the dominant factor. In both figure 1 cases, the areas of the triangles define society's resilience, as the smaller the triangle the higher the resilience. Furthermore, a society may not always recover to the previous equilibrium point (the thick dashed lines of figure 1). In Greece, an example of decreased functionality would be 1953 Ionian earthquake, where most of the buildings on Kefalonia collapsed and 80% of the population left the island within two months of the disaster. A population that has no other option than to leave after a catastrophe can perhaps be considered as the worst case of non-resilience.

An example of increased functionality in Greece is the city of Volos that was devastated by a series of earthquakes in 1955. Here, the opportunity was taken to completely redesign the city with new modern facilities and a spacious layout and, today, Volos is the third largest port in Greece. It has to be noted that recovery to a decreased functionality is fairly rare, as most earthquake affected regions will eventually recover to an increased functionality.

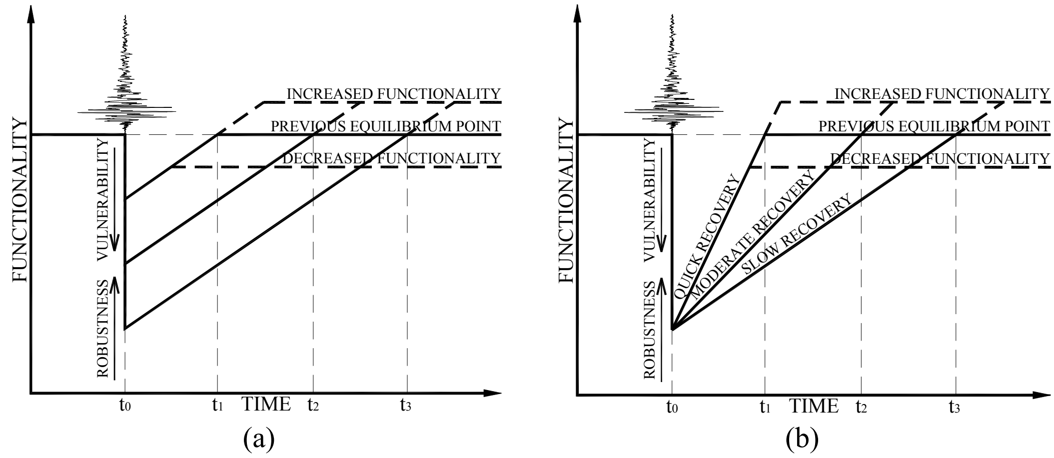

Figure 1. Recovery after an earthquake, (a) loss of functionality variable with constant recovery rate and (b) recovery rate variable (t_0 to t_1, t_0 to t_2 and t_0 to t_3 are the times taken to recover from a destructive earthquake)

ASSESSING RESILIENCE

A society's resilience to disaster depends on the following three factors: The infrastructure's performance during the disaster, the people's behaviour during and after the disaster and the readiness of plans and resources to speed recovery after the disaster. Therefore, a RVSP to assess resilience must take account of these factors. Figure 2 presents a system representation of the proposed procedure to assess resilience. Figure 2 initially lists all the parameters that are considered to affect resilience and they are grouped together to assess eight intermediate parameters. In turn, these are grouped together to obtain the two further intermediate parameters of construction vulnerability and people and State behaviour, which are then used to give a resilience result. Figure 2 is an extension of the procedure developed for the fuzzy logic RVSP (Dritsos and Moseley, 2013). In figure 2, w_i represents a weighting factor, as it can be understood that the individual and intermediate parameters may not affect resilience to an equal degree. In this new procedure, it is foreseen that screeners will collect information in the same way as for other RVSPs. Where this procedure differs is that the screeners will have the opportunity to assess the degree to which a parameter exists. A screener will allocate a value between 0 (very good) and 1 (very bad).

This is because it has been found that assessing the degree of parameter existence produces better results (Moseley and Dritsos, 2009).

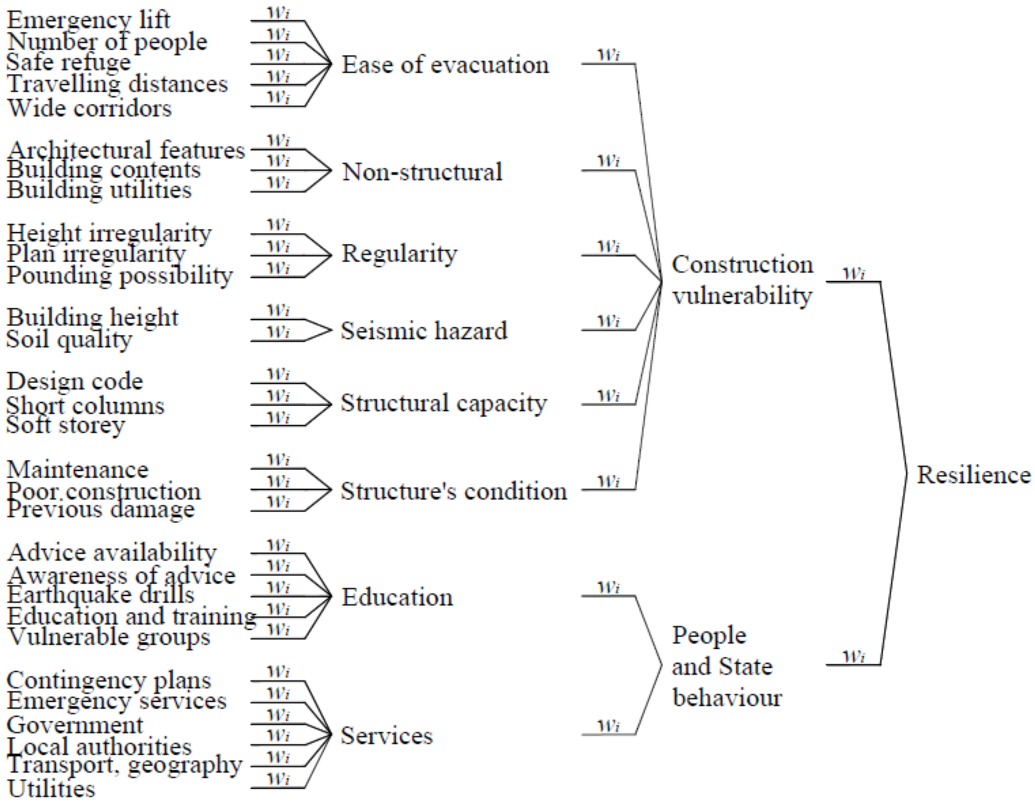

Figure 2. System representation for resilience assessment

PARAMETERS

From figure 2, guidance for assessing the individual parameters for the intermediate variables of regularity, seismic hazard, structural capacity and structure’s condition can be found elsewhere (FEMA P-154, 2015; Moseley and Dritsos, 2009; OASP, 2017). In particular, Moseley and Dritsos (2009) and to a lesser extent FEMA P-154 (2015) have defined the degree to which some parameters exist, which should serve as a model for the other parameters of figure 2. It has to be noted that some rationalisation and simplification of the individual parameters when compared to the OASP (2017) procedure has been made. For example, infill wall layout and torsion have been removed because these can be taken into account when considering the plan regularity. For the parameters of the non-structural intermediate variable, extensive guidance has been produced by OASP (2017).

When considering ease of evacuation parameters, the general advice concerning what to do after a destructive earthquake is to leave the building without using the lifts in a quick and orderly fashion. Therefore, the proper design of exit routes is essential. This requires short travelling distances to a safe refuge area that contains the stairs and an emergency lift. The possible maximum number of people that may inhabit the building at any time is also important. Ideally, buildings should be designed with one or more strong central cores. Central cores should be overdesigned structurally in order to resist any earthquake. Central cores should contain the place of safe refuge and access to exit routes in the form of stairs and emergency lifts. Emergency lifts are fire resistant and are stronger than normal lifts. They have more than one back-up battery power source and will remain operational even if the electricity fails. Emergency lifts are required because this is the only way to evacuate with dignity many classes of people with disabilities and other vulnerable groups. Corridors leading to the central cores should be straight, uncluttered and wide enough to avoid panic caused by the slowest holding up everybody else. Proper universally recognised exit route signs would be essential.

The education intermediate variable concerns peoples' behaviour. Educating the population concerning what to do before, during and after an earthquake is essential. Publication, production and dissemination of education and training material such as textbooks, booklets, leaflets, videos, posters, TV spots, e-learning, e-books, websites, seminars and tutorials is required. This would be the responsibility of the government, relevant organisations and experts. All the population must be made aware of such advice. Community leaders, the police, the fire brigade and armed forces personnel, teachers and other people or groups of people that after a disaster would play a leading role must undergo education and training. Earthquake drills must be performed on a regular basis in order to prepare for a disastrous event. Vulnerable groups must not be forgotten and advice, which may not be the same as that for the general public, should be produced in a number of languages to take into account people with learning difficulties, ethnic minorities, migrants, refugees, displaced persons, travellers, tourists, etc.

The services intermediate variable deals with recovery after a destructive earthquake and the national and local governments would play leading roles. Emergency teams and equipment must be ready to travel to an affected region at a moments notice and practiced contingency plans must be ready and in place. The government must be prepared to quickly and continually allocate resources to an affected region and emergency shelter, food and water must be on standby. Transport and geography are important parameters, as there must be alternative routes to a region, particularly in mountainous areas. In towns and cities, narrow streets could be blocked by falling debris making access very difficult. Utility companies must be prepared to go quickly to a region to restore water and electricity supplies.

WORKED EXAMPLE

An existing building has been chosen to illustrate the procedure. The building is part of a complex of buildings that make up the Department of Civil Engineering at the University of Patras. It is a three level building comprising of laboratories, lecture theatres, offices and subsidiary rooms such as storerooms, toilets, etc. Figure 3 presents a schematic plan of the building and note the adjacent building on its left hand side and corridors at the bottom that lead to other parts of the complex. It is a RC frame structure with substantial shear walls and all parts of the complex are separated by seismic gaps.

Table 1 presents the scores determined for the first intermediate parameters, while table 2 combines these scores to give a resilience value (as stated above, 0 means very good and 1 means very bad). The following provides a brief explanation of the individual parameter scores in table 1 that could be allocated during a screening procedure.

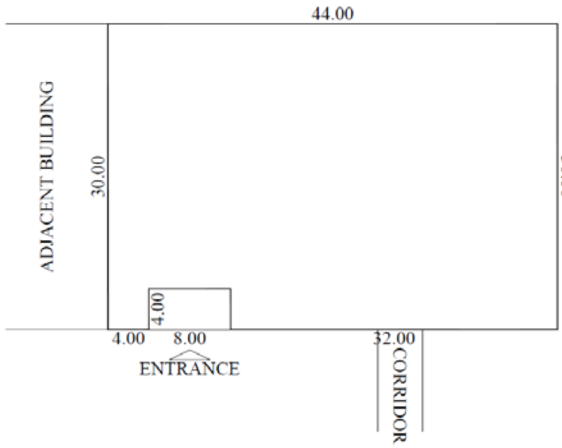

Figure 3. Schematic plan of the worked example

Considering ease of evacuation, the two lifts in the building are not emergency lifts. Normally, there are not that many people in the building but, when a lecture finishes, as much as 100 students could be passing through. The building does have something like a safe refuge on the two upper levels as there is a large space between the lifts and the stairs, which are supported by substantial shear walls. Stairs are wide, straight and split level. Travelling distances are fairly short and every level has a very wide, uncluttered, straight central corridor (a single dogleg) that all rooms, stairs and lifts lead directly onto. There are exit signs that light up when the electricity goes off.

For non-structural features, the building has false ceilings throughout which could fall, cause injuries or impede evacuation. In addition, there are large external windows, which could shatter and injure people. The offices on the upper level have large bookcases, cupboards and shelves and are full of heavy printed matter. As they are not positively attached to walls and/or floors, the bookcases and cupboards could topple, cause injuries or seriously impede evacuation. Furthermore, the contents of the bookcases are not restrained. Building utilities appear to be fairly robust but the false ceilings contain air conditioning ducts, water pipes, etc., which may fall and cause serious problems.

Concerning regularity, there is a slight height irregularity on the last level as along the top side of the building there is an open veranda but the columns and beams are in place (the top slab is missing). The building does have a serious plan irregularity as there is no consistency with the infill wall layout from level to level. The first two levels are mostly open laboratories while the last level is mostly offices with a dense infill wall layout. In addition, the top side of the building has an open covered way its full length on the ground floor. Furthermore, the shear walls associated with the lifts and stairs are not central (they are near the entrance) but a huge shear wall at the other end of the building probably prevents eccentricity between the centres of mass and rotation. Normally, these two irregularity parameters would be allocated a high score but the presence of massive shear walls throughout mean that there is a very little possibility of a change of stiffness with height or torsion affecting the performance of the building. For the pounding parameter, the building is isolated from adjacent structures through adequate seismic gaps.

Considering seismic hazard, a three level RC frame with substantial shear walls should not cause problems. The soil is an alluvium deposit consisting of well compacted, fairly well graded silt, sand and gravel. There is no evidence (subsidence, pavement cracking, etc.) that the soil should be a cause for concern.

For the structural capacity, the building was designed to the 1995 anti-seismic code but there are massive shear walls in excess of that required by the present code. There are short columns on every level and the lower two levels could be considered as soft storeys due to a lack of infill walls. It is not considered that these parameters will cause problems as the massive shear walls will inhibit drift.

Concerning the structure's condition, apart from the building badly needing a coat of paint, there is no evidence of a maintenance problem. The building appears to be very well built and there is no previous damage.

When considering education, in recent years, the OASP (2017) has made considerable efforts to produce advice concerning what to do before, during and after an earthquake. Much of this material is aimed at vulnerable groups and is in a variety of languages. The building is an educational establishment and the students are just out of school where it is known that they are informed about what to do concerning earthquakes. Most must have taken part in an earthquake drill elsewhere but an earthquake drill has never taken place at the building in question. The education and training parameter is unknown and, therefore, has been allocated the median value. Vulnerable groups may include foreign students and invited lecturers. It is unlikely that these have been informed of the dangers of earthquakes but those informed (the other students) would help out.

For services, contingency plans, government, local government and utilities are fairly unknown quantities and likely values have been allotted. The building is on slightly sloping ground and there is no chance of a landslide. There are several wide access roads to the building and other buildings in the area are set well back.

Table 1. Intermediate parameter scores

Parameter	Score	Weight	Intermediate parameter	Calculated score
Emergency lift	1.00	0.25	Ease of evacuation	0.40
Number of people	0.80	0.15		
Safe refuge	0.00	0.25		
Travelling distances	0.20	0.15		
Wide corridors	0.00	0.20		
Architectural features	0.70	0.35	Non-structural	0.68
Building contents	0.80	0.35		
Building utilities	0.50	0.30		
Height irregularity	0.15	0.30	Regularity	0.15
Plan irregularity	0.25	0.40		
Pounding possibility	0.00	0.30		
Building height	0.20	0.60	Seismic hazard	0.22
Soil quality	0.25	0.40		
Design code	0.00	0.30	Structural capacity	0.14
Short columns	0.20	0.35		
Soft storey	0.20	0.35		
Maintenance	0.20	0.25	Structure's condition	0.05
Poor construction	0.00	0.45		
Previous damage	0.00	0.30		
Advice availability	0.15	0.15	Education	0.39
Awareness of advice	0.15	0.25		
Education and training	0.50	0.15		
Earthquake drills	0.50	0.20		
Vulnerable groups	0.60	0.25		
Contingency plans	0.25	0.30	Services	0.26
Government	0.25	0.15		
Local government	0.50	0.15		
Transport, geography	0.00	0.25		
Utilities	0.30	0.15		

Table 2. Determination of resilience

Intermediate parameter	Score	Weight	Intermediate parameter	Score	Weight	Resilience
Ease of evacuation	0.40	0.20	Construction vulnerability	0.30	0.50	0.31
Non-structural	0.68	0.20				
Regularity	0.15	0.15				
Seismic hazard	0.22	0.15				
Structural capacity	0.14	0.15				
Structure's condition	0.05	0.15				
Education	0.39	0.60	People and State behaviour	0.32	0.50	
Services	0.26	0.40				

The weighting factors of tables 1 and 2 have been determined by the authors. It must be noted that this is only an illustrative exercise as no attempt has been made to gather all available documentation and data and relevant authorities have not been contacted and questioned regarding their readiness for a catastrophic earthquake event. Therefore, some of the scores of table 1 are pure conjecture.

From the results of table 1, it can be seen that by far the non-structural parameter causes the most concern. This is mainly because the heavy furniture and fittings on the upper level are not bolted down and printed matter is not restrained. It would be an easy matter to do this. Elsewhere, installing emergency lifts would reduce the ease of evacuation parameter and this should be seriously considered. From table 2, it can be seen that the final resilience value is relatively low.

DISCUSSION

This paper has attempted to build on existing RVSPs that assess vulnerability to develop a screening procedure to assess resilience. In the worked example above, it can be clearly seen where efforts should be concentrated in order to improve resilience. Remembering that 1 represents very bad and 0 represents very good, figure 4 presents a suggested resilience scale.

Figure 4. Suggested resilience scale

The final score for the building in question was 0.31, which from figure 4 indicates borderline good to moderate. This represents a rather encouraging resilience result considering that resilience has never been considered. It has to be noted that the procedure has highlighted one or two areas where, if improvements were made, the resilience could be easily improved.

As noted above, this new procedure is in its infancy and this paper is intended to provoke discussion and debate. With reference to figure 2 above, it may be that there are other parameters that contribute to resilience and it may be found that some of the parameters are not important.

CONCLUSIONS

This paper has attempted to build on and move on from rapid visual screening procedures that merely assess seismic risk. The concept of resilience has been described. A new rapid visual screening procedure to assess urban resilience has been introduced. Factors that affect urban resilience were found to be the environmental performance during the disaster, how people behave during and after the disaster and the readiness of plans and resources in order to speed recovery after the disaster. It has been shown that vulnerable groups in society must be considered, as such groups suffer the most during a disaster and, if the built infrastructure was designed to account for vulnerable groups, everybody would benefit. The intention of this paper was to introduce concepts beyond conventional rapid visual screening procedures that have to be taken into consideration in order to encourage a society to be resilient to earthquake disaster and to stimulate discussion and debate concerning urban resilience. A worked example on an existing building has been performed to demonstrate the new procedure and a fairly good resilience result was found. Having said this, the procedure still highlighted areas where the resilience could be easily improved. It is concluded that it is time to move forward from merely assessing vulnerability and concentrate on resilience. It has been demonstrated that performing a rapid visual screening procedure to assess resilience has identified the weakest links in a society's resilience to earthquake disaster and indicated areas for improvement to increase resilience.

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