Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Benefits of Using Access Panel for Post-earthquake Structural Inspection: Concept and a Case Study

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Abstract: Access panels may be placed in buildings so that structural damage can be quickly inspected and possibly repaired without damaging building non-skeletal elements (NSEs) after earthquakes. Such access panels are readily available, and can be placed near the dissipative elements of building structures for inspection. This paper describes the concept of structural access panel (SAP) and the benefit from analysis considering inspection cost and downtime. When damage inspections are required after the peak ground acceleration is greater than SLS level, the SAP can be beneficial for structural inspection when structural damage occurs at lower shaking levels than the levels causing building irreparability, or major NSE damage. A 6-storey 3-bay eccentrically braced frame structure using different levels of earthquake intensity shaking is conducted and simulated by nonlinear time history analysis, to evaluate the changes in structural inspection costs in buildings with and without SAPs. It is shown that the probability of the SAP being beneficial decreases as the shaking intensity increases, Additionally, SAPs are more beneficial in buildings with low-damage NSEs. The total savings resulting from use of SAP, considering damage and downtime, is up to 15 times the initial cost of SAP. It reveals that SAPs may be a cost-effective post-earthquake structural inspection scheme significantly accelerating and simplifying the post-earthquake structural inspection process.

Keywords: structural inspection, post-earthquake repair, access panel, loss estimation, case study

INTRODUCTION

To ensure that buildings remain functional after an earthquake, the use of seismic resilient structures has become increasingly popular [1]. These structures are generally implemented to be repairable and the damage-controlled in some designated locations [2], one of the most common type is eccentrically braced frame (EBF) structures with replaceable energy dissipation links, as shown in Fig. 1, these links need to be inspected and probably repaired after earthquakes [3]. However, there are also difficulties in using visual inspection methods in practice, because a large number of non-skeletal elements (NSE), i. e. claddings and partitions, are used in buildings. As illustrated in Fig. 2, NSEs may cover the shear links of EBF, making it challenging to inspect and also repair these dissipative components after an earthquake.

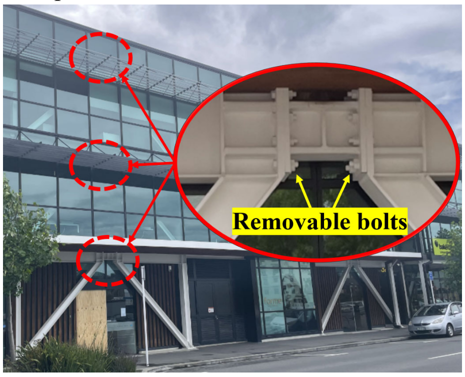


Figure 1. The structure with removable links

Figure 2. Structural elements covered by NSE

Structural health monitoring (SHM) technology can non-destructively assess the safety of structures after an earthquake [4]. However, it requires on placement of expensive devices, and use of systems for data gathering, analysis and reporting which rely on electricity and communication networks. These depend on electricity from batteries or mains systems which may not be reliable during or after an event. Furthermore, many facility owners are reluctant to have instruments placed in their structure due to a lack of trust about how any information may be used. In addition to this, generally a physical visual check by a professional engineer is also needed to confirm findings. For these reasons SHM has not been widely deployed in most structures.

At present, in order to perform a visual check for structural safety, a significant number of NSEs must be dismantled or damaged. However, this process can be costly and time-consuming. As a result, some individuals may choose to ignore structural inspections in order to save money. Nevertheless, neglecting inspections can pose a safety risk, even if there is only cosmetic damage to the fire protection coating.

It may be seen from the above discussion that there is a need for a low-cost and straight forward method for post-earthquake structural inspections. This paper seeks to address this need by seeking answers to the following questions:

i) Can a simple and reliable non-destructive approach be developed for post-earthquake construction?

ii) When is such an approach likely to be effective?

iii) Can a system be developed to quantify the benefit of the approach?

iv) For a specific case study, what is the likely benefit/cost ratio?

BENEFIT OF STRUCTURAL ACCESS PANEL

Concept

This paper proposes an innovative post-earthquake structural inspection scheme, which is using an openable access panel, termed a structural access panel (SAP), installed on NSEs to facilitate visual structural inspection and repair. This concept has been already widely used for mechanical, electrical and plumbing (MEP) maintenance in buildings, as shown in Fig. 3(a), which has low cost and good aesthetic effect for architecture. Similarly, these openable access panels can also be installed near the dissipative elements of structure, then a reliable visual inspection and repair for structures can easily be achieved without damaging any NSE, as illustrated in Fig. 3(b). Therefore, the advantages of SAP in post-earthquake structural inspection and repair work can be emerged in the aspects: 1) Effectively saving the cost of opening and repairing the access holes on NSE for structural inspection and repair; 2) Greatly reducing the downtime and improving the speed of building function recovery.

(a) *(b)*

Figure 3. Access panels used for structural maintenance: (a) Access panel for MEP, (b) Proposed structural access panel (SAP)

Conditions for generating benefits

SAPs are effective only when structural inspection is needed, which means that there may not be a need for inspection if the shaking level is very low. Additionally, structural inspection is also not required if the building has already collapsed or is determined irreparable after an earthquake, thus the shaking level will affect the benefit of SAPs significantly. Besides that, SAPs are only valuable when their related NSEs keep serviceable after events, if the NSEs are seriously damaged in events, structural components can be checked by destroying NSEs directly.

Framework of benefit evaluation

The quantified benefit estimation process is framed and shown in Fig. 4. SAP do not need to be used when the earthquake level is very low, because there is no structural inspection required. So, the seismic analysis is carried out with the PGAs exceed a certain level that structural damage may be occurred. there are three conditions that must be evaluated to determine the usefulness of SAP. These conditions include assessing the potential for building collapse, the repairability of the building, and the serviceability of each NSE that is equipped with SAP. To consider the uncertainty of earthquake, the method of generating additional correlated Engineering Demand Parameter (EDP) [5] from the calculated EDP results is adopted, and Monte Carlo simulation is used to consider the randomness of every judgement in the flow. Once these evaluations have been completed, the amount of beneficial SAP can be determined for each scenario. Finally, the benefits of SAP on costs and downtime can be quantitatively obtained.

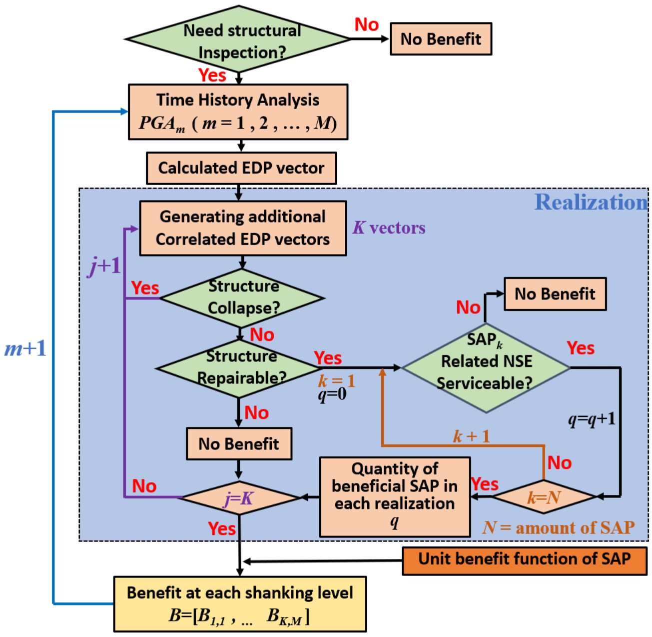


Figure 4. Flow chart for quantified benefit of SAP

In practice, the unit benefit of SAP would be discounted as the quantity increases, the benefit affected by quantity is described as Eq. (1) according to the IPW repair cost and downtime consequence function in FEMA P-58 [6]. Therefore, the unit benefit function ($UB(q)$) can be calculated as the difference in monetary cost and downtime between using SAP and not using it, and can be expressed as Eq. (2). It provides an intuitive representation of the cost (m_1/m_2) and downtime (dt_1/dt_2) for structural inspection using two methods (with/without SAP). In addition, the unit benefit of SAP should have uncertainties that can be modeled using a lognormal distribution, according to the repair cost and downtime of IPW from FEMA P-58 [6], the dispersions for the distribution of cost and downtime is 0.559 and 0.6095, respectively, where q is the amount of serviceable SAP after the event.

$$Bs(q) = \begin{cases} 1 - 0.052(q\text{-}1) & (1 \le q \le 10) \\ 0.532 & (q > 10) \end{cases} \tag{1}$$

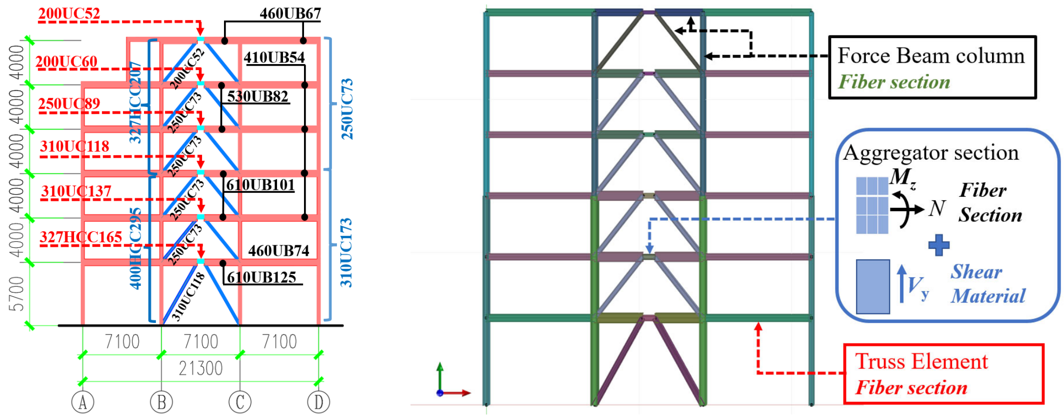
$$UB(q) = \begin{cases} (m_2 - m_1)Bs(q) & (\$) \\ (dt_2 - dt_1)Bs(q) & (\text{downtime}) \end{cases} \tag{2}$$

CASE STUDY

In this case study, a scenario loss estimation study is carried out to make an initial assessment of the benefit for structural inspection with SAPs, and the impact of the main influencing factors including shaking levels and seismic performance of NSE can be considered.

Numerical model

The case study is carried out based on a practical project [7], located in the CBD of Christchurch, New Zealand, which is a typical office building using eccentrically braced frame (EBF) structure with replaceable shear links designed in accordance with NZS 1170.5 [8]. The elevation and sections of components in the EBF are illustrated in Fig. 5(a). OpenSees model was established with the GUI software STKO [9], the structure at top-story is modified to be symmetric in the model for simplicity, as shown in Fig. 5(b). Both ends of the beams in the Bay A-B and C-D are pinned, and the bottom of columns in B and C axis are fixed and those in A and D axis are pinned. Columns, braces and middle-span beams use the force-based beam-column element with fiber section, and side-span beams use truss element. The fiber sections with shear material is used to simulate flexure and shear nonlinear behavior of shear links [10]and the shear material uses Steel02 material model with f_y and E corresponding to the yield shear force V_p and shear stiffness GA_w of the shear link [11], respectively. Steel02 material is used to simulate steel fiber and shear material, the parameters defined according to an experimentally verified simulation [12]. The seismic mass of the building was obtained using dead and live load of the building is 2.6 kPa and 0.9 kPa, respectively. The 1st modal period of the structure is 0.92s.



(a) *(b)*

Figure 5. Information of the case study structure: (a) Elevation of EBF, (b) Numerical model

Parameters used in evaluation

The maximum inter-story drift ratio (IDR) of structure under design level shaking is 2.5% according to NZ 1170.5:2004. The repairability of the building can be defined as the residual IDR of structure does not exceed 1% [6]. The serviceability limit of NSE is determined by the damage state of the interior partition wall (IPW). For conventional IPWs with fixed top and bottom, the DS2 limit can be used with a threshold of 1% IDR [6]. The seismic performance of NSE is a key factor in determining the benefits of SAP. To emphasize the advantages of using SAP in low-damage NSE, a comparison was made between the rocking IPW and the conventional IPW, which has a high deformation capacity and should not incur significant damage before the IDR reaches 3% [13].

In this case, replaceable shear links of EBF need to be checked when the earthquake level exceed SLS. It is easy to install openable SAPs on the partition walls, the initial investment of installing one SAP (size is 0.6m×0.6m) is NZ $300. The cost and downtime of the inspection is affected by labour and price in different regions, the data listed in Tab. 1 is suggested by an experienced engineer in Christchurch, New Zealand.

Table 1. Cost of the structrual inspection

NO.(i)	Situation	Mean cost m_i	Mean downtime dt_i
1	Inspection with SAP	NZ $50	0.1 day
2	Inspection without SAP	NZ $1000	1 day

Quantification of benefit

The earthquake records including 22 far-field earthquake records recommended by FEMA P-695 [14] are used as inputs for non-linear time history analysis. In this case, the building is located in Christchurch city, PGA levels of selected records are set to 0.1g (Serviceability Level State (SLS), and annual probability of exceedance (APE) is 1/50), 0.3g (Ultimate Level State (ULS), and APE is 1/500) and 0.58g (Maximum Considered Earthquake (MCE), and APE is 1/2500) to obtain EDPs of the structure by time history analysis. The workflow (shown in Fig. 4) is coded in MATLAB to evaluate the benefit of SAP. In the program, each EDP set is generated up to 10,000 vectors, the probability of SAP being beneficial on the different stories with different hosting NSE can be shown as Fig. 6.

The structural inspection is needed when the shaking is greater than SLS level, because the shear of links will exceed their yield strength, potentially resulting in cosmetic damage to their fire protection coating. It can be found that SAPs on conventional IPW located at 2nd ~ 4th Floors are less beneficial than others with shaking increasing, e.g. the probability of the SAP on 3rd Floor being beneficial is 96.5%, 75.0%, 36.5% at SLS, ULS and MCE shaking level, respectively (Fig. 6), because the benefit of SAP is closely related to the damage of IPW depending on the max. IDR of structure in earthquakes. The SAPs used in low-damage IPWs achieves greater benefit compared to conventional IPWs, particularly at higher levels of shaking. For instance, the probability of the SAP on the 3rd floor is 77.7% with low-damage IPW, which is more than twice the probability of conventional IPW, highlighting SAP are more useful for buildings with low-damage NSE.

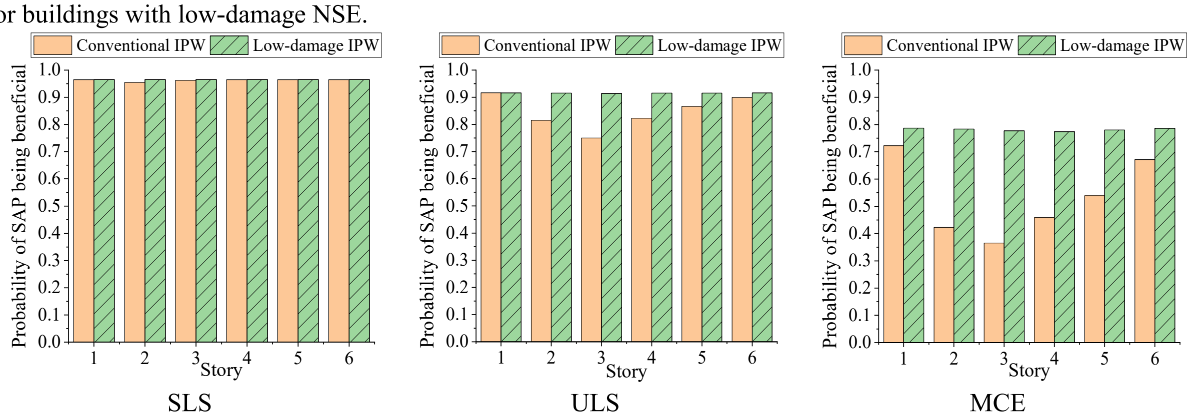
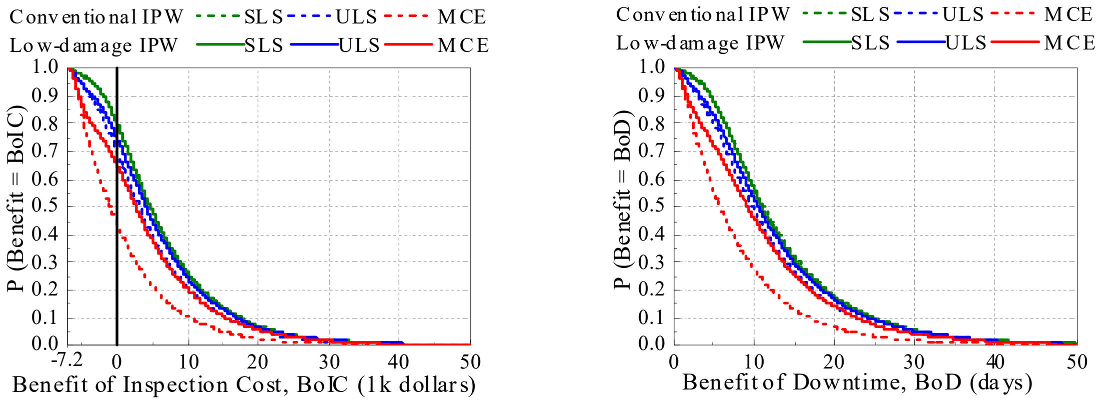


Figure 6. Probabilty of the SAP being beneficial

Assuming the benefit of SAP is equal for all 4 EBFs in this case building. Using the monetary and downtime data in Tab. 1, and the quantified benefit of each realization can be obtained. The complementary curves of the cumulative distribution functions of the benefit of inspection cost (BoIC) at different shaking levels are plotted in Fig. 7(a). Considering the initial investment of SAPs (24 SAPs cost 7.2k NZ dollars for the whole building), BoIC could be negative because SAPs are useless when the building is irreparable or the related NSE is damaged in earthquakes. When BoIC is equal to zero, indicating that the saving from inspection cost can cover the initial cost of SAP, the probability of BoIC is 80%, 70% and 44% for conventional IPW at SLS, ULS, MCE level, respectively, and it is 80%, 75% and 65% for low-damage IPW, comparing that SAP is more beneficial for inspection in more frequent events and that is more suitable for low-damage NSEs to get better benefits. While benefit of downtime (BoD) is all positive value, and the distribution of probability of BoD has the same pattern with that of BoIC.



(a) *(b)*

Figure 7. Probablistic benefit of SAP: (a) Benefit of inspection cost, (b) Benefit of downtime

The benefits are often measured by the media value, which represents the 50th percentile in the cumulative distribution function (CDF) curve. In Tab. 2, the median values of the benefits for inspection cost (BoIC) and downtime (BoD) are obtained from the CDF curves presented in Fig. 7(b). The benefit of inspection cost (BoIC) is ranged from -1k ~5k dollars, which may be considered as a small benefit cost for the entire building. On the other hand, the benefit of downtime (BoD) is distributed from 6 to 11 days, for office buildings, the loss of downtime can be conservatively evaluated by the loss of rental expenses for the building owner. According to Colliers [15], for this case building, the estimated rental loss due to downtime is approximately 9.3k NZ$/day for the total floor area of 7750 m^2. Using the media values listed in Tab. 2, the total monetary loss saving due to BoIC and BoD can be estimated to be up to 108 k NZ$ to 54 k NZ$ for SLS to MCE level, respectively, showing that the benefit can be 7.4 to 15 times the initial investment of SAP, indicating a significant return on investment, demonstrating that SAP is a cost-effective method for post-earthquake structural inspection.

Table 2. Median value of the benefit of SAP

Benefit type	**NSE type**	**Shaking level**		
		SLS	ULS	MCE
Median of BoIC (1k dollars)	Conventional IPW	4.7	3.2	**-1.0**
	Low-damage IPW	4.8	4.1	2.7
Median of BoD (days)	Conventional IPW	11.2	9.9	**5.9**
	Low-damage IPW	11.0	10.5	9.3
Total monetary saving (1k dollars)	Conventional IPW	108.9	95.3	53.9
	Low-damage IPW	107.1	101.8	89.2

CONCLUSIONS

This study describes the development and benefit assessment of a simple manual SHM method. It is found that:

(1) A low-cost and reliable post-earthquake structural inspection scheme using structural access panels (SAPs) is proposed. The SAP can permit a physical inspection of dissipative elements in structures without damaging non-skeletal elements (NSEs).

(2) The SAP is effective for post-earthquake structural safety inspection when the building has been subjected to greater than serviceable level state excitations. However, the benefit reduces at large shaking intensities when i) NSEs are significantly damaged, or ii) the building has large residual drifts, or iii) the building collapses.

(3) A probabilistic loss estimation approach is developed to evaluate the benefit of SAPs using nonlinear time history analysis and Monte Carlo simulation. It enables quantification of the cost savings resulting from the use of SAPs, considering inspection costs and downtime.

(4) A scenario-based case study was conducted on an office building, considering three shaking levels. For this study using SAPs was beneficial particularly for reducing inspection downtime. Based on the assumptions made, benefit to cost ratios for SAPs installed in buildings with conventional NSEs ranged from 7.4 for at MCE level shaking, to 15 for SLS level shaking. For low-damage NSEs the benefit to cost ratios ranged from 12.4 to 15, respectively. It demonstrates their cost-effectiveness of SAPs for post-earthquake structural inspection.

ACKNOWLEDGMENTS

The authors would like to thank the support provided by the International Laboratories on Earthquake Engineering (ILEE) China-New Zealand joint research project-ROBUST and QuakeCoRE Inter-Disciplinary Programme 1 (sub-project 2d). The QuakeCoRE paper number is 0866. Financial support from China Scholarship Council (NO. 202108610186) for the first author is greatly appreciated. In addition, thanks to ASDEA Software company for providing an academic license of STKO software to improve efficiency of modeling in OpenSees.

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