- *Technical Paper* -

CRITERIA FOR DETERMINING THE OPTIMAL SENSOR LAYOUT FOR IDENTIFYING BUILDING INELASTIC DEFORMATION MODE

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ABSTRACT

For buildings with few accelerometers, the accelerometer layout should be able to account for various possible inelastic deformation modes (i.e., total-yield or soft-story). Two criteria are proposed for evaluating the suitability of an accelerometer layout: (i) maximum recorded floor displacements should vastly differ for different deformation modes, and (ii) the maximum representative building-level displacement should be accurately estimated. The application of these criteria was demonstrated using a case study of a 12-story building with different accelerometer layouts.

Keywords: Optimal accelerometer layout, inelastic deformation mode classification, structural health monitoring, earthquake

1. INTRODUCTION

Structural health monitoring (SHM) systems are increasingly used to monitor building response during earthquakes to evaluate damage. This typically consists of an accelerometer (acceleration sensor) network that transmits data to a central server to determine changes in dynamic properties or force-displacement characteristics. For example, a building's representative capacity curve can be calculated from acceleration data following Kusunoki et al. [1], and damage can be evaluated based on building-level ductility limits (e.g., μ_1, μ_2, and μ_3 as shown in Fig. 1) such as those defined by Kusunoki [2].

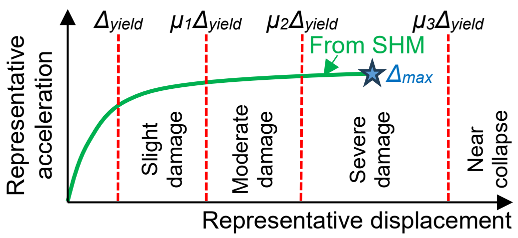

Fig. 1 Use of capacity curve to evaluate damage

In most SHM applications, accelerometers are not placed on all floors due to cost, lack of space, and difficulty in collecting data from a large accelerometer network. As such, interstory drifts cannot be easily obtained on all stories which has two implications. First, other metrics such as roof displacement need to be used to assess damage. Second, the building's inelastic deformation mode (i.e., total-yield or soft-story as shown in Fig. 2) becomes difficult to identify. This is important since there is always a possibility that the building may inelastically deform in an unexpected manner due to unforeseen defects in design or construction.

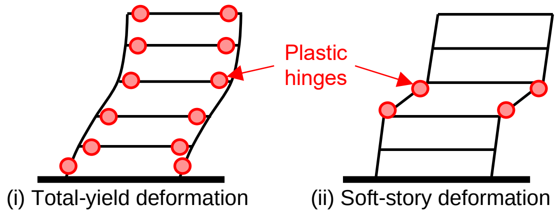

Fig. 2 Building inelastic deformation modes

Correct identification of the inelastic deformation mode is important for defining non-interstory drift-based damage limit states. For example, buildings undergoing total-yield deformation have greater building-level ductility capacity compared to those undergoing soft-story deformation. The inelastic deformation mode also affects the estimate of peak response. For example, while spline fitting can be used to estimate the response of non-monitored floors for total-yield cases [3], this cannot be used for soft-story cases due to sudden changes in the maximum displacement mode shape. Likewise, Chen and Kusunoki [4] found that using linear interpolation to estimate the response of non-monitored floors results in an underestimation of the maximum representative building-level displacement response for soft-story cases.

Another benefit of being able to identify a building's inelastic deformation mode, particularly at relatively low building-level ductility response, is to identify earthquake-prone buildings. For example, if a building was found to be susceptible to soft-story deformation, retrofitting could be performed to increase its deformation capacity and enhance life-safety.

Research has been performed by Yeow and Kusunoki [5-8] to identify features for use in training machine-learning models to classify the building's inelastic deformation mode. While they showed that an accurate classification model could be obtained using features based on plastic floor displacements (difference between floor displacements at building-level maximum

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and yield response which can be obtained from processing acceleration data) for a 6-story building with four accelerometers spaced evenly along the building's height, its accuracy may possibly be improved by using a different accelerometer layout. While past research on determining accelerometer layouts exist, they focus on structural identification rather than consideration of inelastic deformation modes (e.g., Yi et al. [9]).

In this paper, two criteria were proposed for evaluating the suitability of accelerometer layouts to account for various potential inelastic deformation modes based on maximum displacements recorded on monitored floors. These are described in Section 2.0. The criteria were then applied to three accelerometer layouts for a 12-story reinforced concrete (RC) frame building to demonstrate its application.

The scope of this research is limited to RC frame buildings as soft-story may potentially occur on upper stories, such as the 8-story Kobe City Hall building where soft-story occurred on the 6th story during the 1995 Kobe Earthquake. In contrast, soft-story failure is less likely to occur on upper stories for buildings with continuous structural walls along its height as the largest flexural demands are at its base.

2. CRITERIA FOR EVALUATING ACCELEROMETER LAYOUT

Two criteria are proposed herein for evaluating accelerometer layouts. Criteria 1 is that the adopted accelerometer layout should capture vastly different floor responses if a different inelastic deformation mode occurred to enable machine-learning models to provide more accurate classifications. Consider the example in Fig. 3 where three accelerometers are used: one on the ground, another at the roof, and the third at either location A or B. The mode-shape value at A is similar for both the total-yield and 2nd story soft-story cases, while the mode-shape value at B is much larger for the 2nd story soft-story case. Based on this, placing the accelerometer at B would be better to distinguish between the two cases compared to placing it at A.

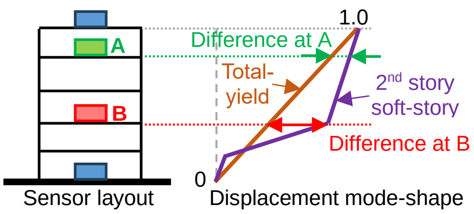

Fig. 3 Influence of accelerometer layout on distinguishing between different inelastic deformation modes

Assuming that the capacity curve approach from Fig. 1 is used to evaluate damage, Criteria 2 is that the building-level representative maximum displacement Δ_{max} calculated from Eq. 1 using accelerometer data should be near-identical to the true response.

$$\Delta_{max} = \frac{\sum m_i x_{i,max}^2}{\sum m_i x_{i,max}} \quad (1)$$

where,

m_i : i^{th} floor mass

$x_{i,max}$: i^{th} floor maximum displacement

Criteria 2 is important for soft-story cases as spline fitting cannot be used. Yeow and Kusunoki [5] noted that while it is difficult to identify the exact soft-story location if few accelerometers were used, machine-learning models could at least identify the accelerometer above and below the soft-story, and suggested that all plastic displacements incurred could be assumed to have occurred on the lowest story of the critical region. This may lead to different displacement profiles depending on the sensor layout.

Consider the case in Fig. 4 where soft-story occurred on the 4th story. If accelerometers are placed on the ground, roof and at A, and that machine-learning models correctly identified that soft-story occurred below A, then soft-story is assumed to occur on the first story for simplicity. Conversely, if the middle accelerometer is placed at B, and the machine-learning model identified that soft-story occurred above B, then soft-story is assumed to occur on the 3rd story for simplicity. Since placing the accelerometer at B results in a closer estimate of floor displacements compared to accelerometer A, it will also result in a better estimate of Δ_{max}. Therefore, it is more beneficial to place the third accelerometer at B instead of A in this scenario.

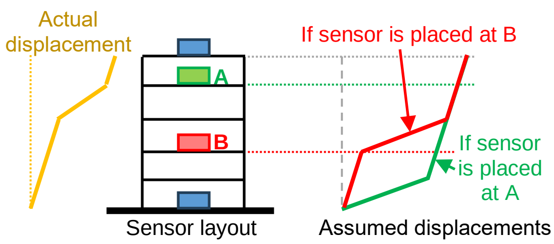

Fig. 4 Influence of accelerometer layout on assumed peak displacement response

Based on the above discussion, a good accelerometer layout should achieve a balance between obtaining vastly different displacement values for different inelastic deformation modes while also being able to estimate Δ_{max} accurately. To demonstrate the application of these criteria, a conceptual case study of a 12-story building will be considered. Details of the building and considered accelerometer layout is provided in Section 3.0.

3. CASE STUDY DETAILS

3.1 Case Study Building and Accelerometer Layout Details

To demonstrate the application of the proposed criteria, these were applied to accelerometer layouts within a 12-story building. As the building seismic response is unknown at the time of placing accelerometers, fictitious displacement profiles must be used instead.

The 12-story building is assumed to have interstory heights of 3.6 m and constant mass on all floors. Following the Japanese Building Standard Law [10], which estimates the initial fundamental period, T (in seconds), as 0.02 multiplied by the building height (in meters), T is approximately 0.86 s. Furthermore, the story lateral stiffness were either: (i) constant on all stories, or (ii) modified so that the interstory drift at yield is constant on all stories. Example elastic mode shapes of this building are shown in Fig. 5.

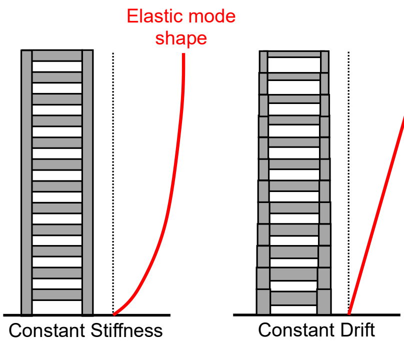

Fig. 5 Case study buildings

Five accelerometers were assumed to be placed within the building: one on the ground, one on the roof, and the remaining three distributed along the building. Three layouts were considered to demonstrate the application of the proposed criteria as shown in Fig. 6, where accelerometers were evenly distributed in A, concentrated towards the bottom in B, and concentrated towards the top in C.

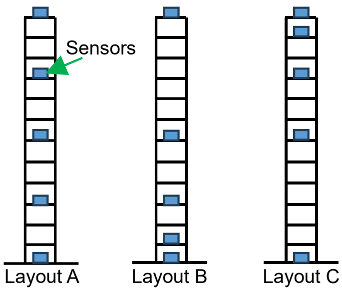

Fig. 6 Assumed accelerometer layouts

To create the fictitious displacement profiles, it was assumed that the maximum displacement is the sum of: (i) floor displacements at yield, and (ii) plastic displacements. The approach to determine the yield and plastic displacement components are described in Sections 3.2 and 3.3, respectively, while the method to obtain maximum floor displacements is described in Section 3.4.

3.2 Estimation of Yield Displacements

To estimate the floor displacement at "yield" response for the constant stiffness case, the interstory displacements were assumed to be linearly proportional to the allowable stress story shear force demands in the Japanese Building Standard Law [10]. The i^{th} story shear force demand, Q_i, was obtained following Eq. 2:

$$Q_i = C_i W_i \quad (2)$$

where,

C_i : i^{th} story lateral seismic shear coefficient
W_i : weight supported by i^{th} story

C_i can be calculated using Eq. 3:

$$C_i = Z R_t A_i C_0 \quad (3)$$

where,

Z : seismic zone factor
R_t : design spectral factor
A_i : lateral shear distribution factor
C_0 : standard shear coefficient

Out of all parameters in Eq. 3, only A_i varies along the height of the building. The calculation for A_i is shown in Eq. 4.

$$A_i = 1 + \left(\frac{1}{\sqrt{a_i}} - a_i\right)\frac{2T}{1+3T} \quad (4)$$

where,

T : elastic building period
a_i : ratio of W_i to the entire building weight

For the constant stiffness case, the interstory displacements are directly proportional to Q_i. Thus, the normalized i^{th} story drift at building-level yielding response, $\delta_{i,yield,norm}$, which equals to 1.0 on the story with the largest drift, can be calculated using Eq. 5.

$$\delta_{i,yield,norm} = \frac{Q_i}{max(Q_i)} = \frac{W_i A_i}{max(W_i A_i)} \quad (5)$$

For the constant drift case, $\delta_{i,yield,norm}$ is taken as 1.0 for all stories instead.

For both constant stiffness and drift cases, Eq. 6 can be applied to obtain the normalized floor displacement, $x_{i,yield,norm}$. Note that the value of $x_{i,yield,norm}$ on its own has no meaning since it does not explicitly consider Z, R_t and C_0. Instead, it can be thought of as the displacement mode shape when $\delta_{i,yield,norm}$=1.0. This is suitable for the purpose of this study since the displacement mode shape alone may be representative of the deformation mode without needing to know the amplitude of response. The resulting $x_{i,yield,norm}$ for the two different stiffness variations are shown in Fig. 7.

$$x_{i,yield,norm} = \sum_1^i \delta_{i,yield,norm} \quad (6)$$

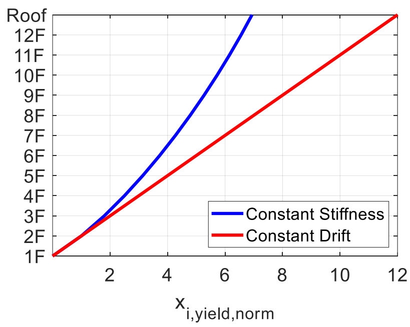

Fig. 7 Normalized yield displacement profiles

It should be noted that there are cases where the building may have a story that is more flexible than others, such as for buildings with Pilotis which are commonly used where shopfronts are present on the ground floor. Such cases are outside the scope of this study but will be considered in future studies.

3.3 Estimation of Plastic Displacements

To estimate the plastic displacement for total-yield cases, it was assumed that the normalized plastic drift, $\delta_{i,plastic,norm,}$, matches either of the $\delta_{i,yield,norm}$ profiles from Fig. 7. For cases where soft-story deformation occurs within the i^{th} story of the building, $\delta_{i,plastic,norm}$ can be obtained following Eq. 7. The normalized plastic floor displacements, $x_{i,plastic,norm}$, are then obtained from Eq. 8. The resulting $x_{i,plastic,norm}$ for the different total-yield plastic displacement modes and for soft-story occurring on the 5th story are shown in Fig. 8.

$$\delta_{i,plastic,norm} = \begin{cases} 1 & \text{at soft-story} \\ 0 & \text{at other stories} \end{cases} \tag{7}$$

$$x_{i,plastic,norm} = \textstyle\sum_1^i \delta_{i,plastic,norm} \tag{8}$$

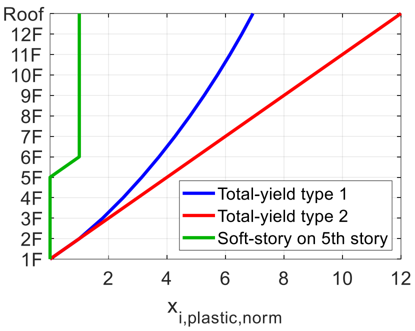

Fig. 8 Normalized plastic displacement profiles

3.4 Estimation of Maximum Displacements

The maximum normalized floor displacement is calculated following Eq. 9.

$$x_{i,max,norm} = x_{i,yield,norm} + \gamma . x_{i,plastic,norm} \tag{9}$$

where,

γ : plastic displacement amplification factor

γ will increase as the degree of building inelastic behavior increases. However, as one of the benefits of detecting inelastic deformation modes is to identify buildings which may require retrofiting, it is desirable for classification models to be able to determine the inelastic deformation mode even at low ductility response. As such, the target interstory ductility ratio was set to 2.0. Based on this, γ was set to 1.0 for the total-yield cases, and to the value of $\delta_{i,yield,norm}$ of the critical story for soft-story cases.

Following this approach, a total of 28 displacement profiles were considered. This was based on a combination of (i) two different yield deformation modes (constant stiffness and constant drift), and (ii) fourteen different inelastic deformation modes (two total-yield and twelve soft-story cases).

4. APPLICATION OF CRITERIA

4.1 Criterion 1: Difference in Accelerometer Readings

Criteria 1 is that the accelerometer layout should capture vastly different floor responses for different inelastic deformation modes. As the displacement mode shape is more indicative of the deformation mode compared to the displacement amplitude, the ratio of the j^{th} accelerometer displacement to that of roof for each inelastic deformation mode, $Ratio_{x,j}$, will be considered. $Ratio_{x,j,}$ can be calculated using Eq. 10.

$$Ratio_{x,j} = \frac{x_{j,max,norm}}{x_{roof,max,norm}} \tag{10}$$

The difference in accelerometer readings was determined by taking the square root of sum squares, *SRSS*, of all accelerometer readings between each inelastic deformation mode and that exhibiting total-yield type 1 (TY1) deformation. The *SRSS* for each inelastic deformation mode is calculated from Eq. 11.

$$SRSS = \sqrt{\textstyle\sum_{j=1}^{5}\left(Ratio_{x,j} - Ratio_{x,j,TY1}\right)^2} \tag{11}$$

The resulting *SRSS* is shown in Fig. 9, where CS and CD refers to constant stiffness and drift, respectively, TY2 is the total-yield type 2 deformation mode, SS is soft-story deformation mode, and the number after SS denotes the soft-story location. Here, the *SRSS* error trends are similar regardless of the yield displacement mode (i.e., CS or CD). Furthermore, *SRSS* for TY2 is similar regardless of layout, indicating that accelerometer layout has less influence for such cases.

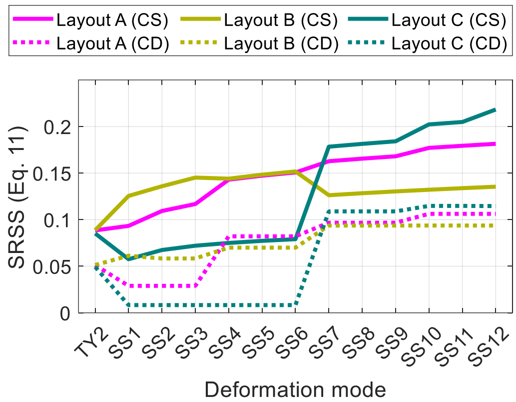

Fig. 9 *SRSS* in accelerometer readings between TY1 and other inelastic deformation modes

Considering only CS cases, the *SRSS* increases as the soft-story is located higher in the building for Layout A. Layout B had the largest *SRSS* for SS1~SS6, indicating that it is best at locating soft-story on lower stories. However, it has the lowest *SRSS* for SS7~SS12, though this value was still greater than the *SRSS* for TY2. For Layout C, *SRSS* for SS1~SS6 is similar to or lower than for TY2, though it does have the greatest *SRSS* for SS7~SS12.

4.2 Criterion 2: Error in Representative Building-Level Maximum Displacement Response

The second criterion is that the prediction error for Δ_{max} obtained from Eq.1 using accelerometer data should be small. However, the method to obtain maximum floor displacements used in the calculation differs for each inelastic deformation mode. For total-yield cases, spline fitting was performed to estimate displacements on non-monitored floors. For soft-story cases, it was assumed that soft-story occurred on the lowest story in the identified soft-story region as previously shown in Fig. 4, and that all plastic displacement incurred between the bottom and top accelerometers of the critical region is concentrated within that single story. The Δ_{max} calculated considering all floor displacements is denoted as Δ_{true}, while those estimated using accelerometer data were denoted as Δ_{sensor}. A $\Delta_{true}/\Delta_{sensor}$ ratio of 1.0 indicates high accuracy. A ratio greater than 1.0 indicates that Δ_{max} was underestimated which would lead to unconservative damage assessments, while a ratio less than 1.0 indicates a conservative assessment of damage.

The $\Delta_{true}/\Delta_{sensor}$ ratios are shown in Fig. 10. While the trends are again similar regardless of the yield displacement mode (i.e., CS or CD), the ratios are much closer to 1.0 for the CD case. This is because the yield displacements are greater for the CD case as shown in Fig. 7, which would result in the elastic component of Δ_{max} being greater for the CD case. This would imply that accelerometer layout has lesser influence for such cases considering this criterion. However, as this finding is based on an interstory ductility of 2.0, this could still be an issue for structures exhibiting greater inelastic behavior. The $\Delta_{true}/\Delta_{sensor}$ ratio was also closer to 1.0 for both TY1 and TY2, indicating that accelerometer layout is not as important for total-yield cases.

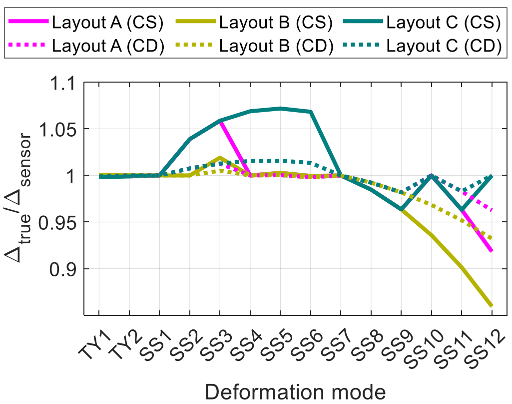

Fig. 10 Difference between actual and estimated maximum representative displacement

Layout A has a $\Delta_{true}/\Delta_{sensor}$ ratio greater than 1.0 for SS2 and SS3, but lower than 1.0 for most cases between SS8~SS12. Layout B has a ratio close to 1.0 for SS1~SS7. However, it had the lowest ratio when soft-story occurred above the 7th story. Layout C had the largest ratio for SS2~SS6. While it generally had a ratio closer to 1.0 for soft-story occurring above the 7th story compared to Layout B, the ratios were similar to that obtained from Layout A except when soft-story occurred on the top story.

5. DISCUSSION

5.1 Interpretation and Usage of Results

While two criteria for determining the optimal accelerometer layout for classifying building deformation modes were proposed, methods to utilize this information to evaluate if the accelerometer layout is suitable had not been proposed.

In some cases, the implication is obvious. For example, Layout C is the worst out of the three options considered as: (i) classification models trained using Layout C may have greater difficulty in distinguishing between TY2 and SS1~SS6 due to the small *SRSS* values for SS1~SS6 cases, and (ii) Δ_{max} was underestimated for SS2~SS6 cases. The former observation is sensible as there are large displacements in the bottom half of the building for total-yield and SS1~SS6 cases, and thus it is difficult to differentiate between these cases without adding accelerometers in that region. The latter observation was due to the assumption that soft-story occurred on the lowest story within the critical region. While this is conservative from the viewpoint of floor displacements, it is unconservative when considering the representative displacement (Eq. 4) as the $x_{i,max}$ term is present in the numerator and denominator. To address the latter, one could instead assume that soft-story occurs in a location which results in the greatest representative displacement instead of the lowest floor within the critical region, though this causes the opposite problem where the prediction becomes too conservative. Note that these two observations can also be applied to other accelerometer layouts where few accelerometers were used on the bottom half of the building.

In other cases, the findings are open to interpretation. For example, it is not easy to decide whether Layout A or B is more optimal. This is because Layout A is better at dealing with soft-story on upper stories while Layout B is better for soft-story occurring on lower stories. One could argue that Layout B should be selected as it provides a more conservative estimate of Δ_{max} based on its lower $\Delta_{true}/\Delta_{sensor}$ ratio, which results in more conservative building damage evaluations and thus ensuring life-safety. A counter argument is that Layout B is too conservative when soft-story occurs above the 7th story, which could result in safe buildings being unnecessarily classified as being damaged, resulting in buildings being unnecessarily demolished and higher socioeconomic losses. In such cases, Layout A may be preferred instead.

An additional usage of the results could be to decide how to further optimize the accelerometer layout. For example, by comparing Layouts A and C with Layout B, placing a accelerometer on the 10th story allows the accelerometer layout to better deal with soft-story occurring on the upper half of the building. As Layout B is the best at dealing with soft-story on lower stories, placing an additional accelerometer (if available) on the 10th story would indisputably make it more optimal compared to the three layouts considered. This process could then be further repeated until all available accelerometers are used, or a suitable accuracy is obtained regardless of the inelastic deformation mode.

5.2 Future Work

One extension to this study could be to develop a method to utilize information from applying the two criteria to determine an optimal accelerometer layout. This would remove subjectivity in the assessment which may lead to more widespread adoption of this methodology. One approach is to define limits, such as specifying that *SRSS* for soft-story cases, $SRSS_{SS}$, must be greater than $SRSS_{TY2}$ by a certain amount. For example, if $SRSS_{SS}$-$SRSS_{TY2} \geq 0.03$ is used as a limit for CS cases, then Layout B will be selected. Similar limits could also be applied to the $\Delta_{true}/\Delta_{sensor}$ ratio. Research into determining such limits for a wide range of scenarios (e.g., building height, mode shapes, number and layout of accelerometers, etc.) will be required.

One possible avenue of research is to train machine-learning deformation mode classifier models like those by Yeow and Kusunoki [5-8] for each possible accelerometer layout, and use the models' misclassification ratios to determine limits to favor layouts which leads to greater modelling accuracy. Others could then adopt such limits to determine an optimal accelerometer layout and train a single machine-learning model accordingly which decreases model development time while providing high accuracy.

One other limitation of this study is that simple idealized floor displacement profiles were considered. It is not clear if the proposed criteria could also work for more realistic building response, or for cases where buildings have different elastic mode shapes such as those with a flexible story. As such, data obtained from shake-table experiments or inelastic dynamic numerical simulations should also be considered to evaluate the suitability of these criteria.

6. CONCLUSIONS

In this study, two criteria were proposed to evaluate the suitability of accelerometer layouts to account for various potential inelastic deformation modes for buildings with few accelerometers. The first criterion is that the accelerometer layout should give vastly different readings for different inelastic deformation modes, which was evaluated using *SRSS* (Eq. 11). The second is that the representative maximum displacement response Δ_{max} (Eq. 1) obtained using accelerometer data should be similar to the actual building-level response. In general, it was found that:

(1) Concentrating accelerometers towards the top of buildings is the least desirable layout as: (i) it is more difficult to distinguish between total-yield deformation and soft-story occurring on lower stories, and (ii) it provides unconservative estimates of Δ_{max} when soft-story occurs on lower stories.

(2) Using smaller accelerometer spacing near the bottom of the building allows soft-story occurring on the bottom half of the building to be better considered but is worse at dealing with soft-story on upper stories. However, using such spacing does generally result in more conservative evaluation of building damage which enhances life-safety compared to cases were accelerometers were evenly distributed along the building's height.

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