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Application of modal flexibility-based deflections for damage diagnosis of a steel frame structure

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Abstract

In this paper a modal flexibility-based approach for damage diagnosis is presented and discussed. Modal flexibility matrices of structural systems can be derived from vibration tests and changes in these matrices can be associated to structural damage. One of the main challenges is to apply modal flexibility-based methods on real-life civil structures, to detect damage on structures using ambient vibration data. A recent method has been formulated for damage detection, localization, and quantification of building structures; it is based on the modal flexibility-based deflections of such structures under uniform loads. The method was originally formulated for frame buildings that can be modeled as plane shear-type structures. The objective of the paper is to test this methodology on generic buildings that, in principle, cannot be easily modeled as plane shear-type structures. The method was applied to the ambient vibration data of a steel frame structure that has a monitoring system with acceleration sensors. Various damage configurations were induced to the structure by removing diagonal braces on the external surface of the frame. The results showed that the method is able to identify the stories and the directions of the frame that have been affected by the damage.

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Keywords: damage detection; modal flexibility-based deflection; steel frame structure

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1. Introduction

Identification of damage from vibration measurements of civil, mechanical and aerospace structures has been investigated over the last few decades in the field of Structural Health Monitoring (SHM) [1,2]. In the context of civil engineering, vibration-based SHM techniques can be profitably applied to structures under ambient vibrations or normal operating conditions [3]. However, identification of damage starting from the measurements of the global dynamic responses [1] of these real-life structures, especially of building structures, is still a challenging task. Damages are defined as changes that adversely affect the performance of a structural system [1]. These damages can be generated, for example, by some unexpected loading conditions that produce a reduction in the stiffness of the structure. Most vibration-based damage detection techniques extract information about the structural system from the vibration data (e.g. the modal properties) and use this information to compare the structural condition in the inspection phase with the one of the pristine structure. Moreover, more advanced techniques can be used not only for damage detection, but also for damage localization and damage quantification, which is a procedure collectively known as damage diagnosis [1].

Modal flexibility (MF)-based methods [1,2,4-7] are important tools in vibration-based damage detection (VBDD) and experimental flexibility matrices of structures can be assembled from identified natural frequencies and mode shapes. These parameters can be extracted from ambient vibration (AV) data using operational modal analysis techniques [3]. A recent method for VBDD on building structures is based on the calculation of the modal flexibility-based deflections of the structure under a Positive Shear Inspection Load (PSIL) [4-6] (for the sake of brevity, the method is indicated in this paper as PSIL method). This method has been formulated with reference mainly to structures that can be modeled as plane shear-type frame buildings, and it can be used for damage detection, localization, and quantification. According to this method, the damage-sensitive features are the interstory drifts related to structural deflections that are calculated by applying uniform loads to experimentally-derived modal flexibility matrices. As reported in [4,5], one of the main advantages of the method is that there exists an explicit relationship between damages (such as stiffness reductions) and the damage-induced deflections. In particular, one feature of the PSIL method, which plays a key role in the damage localization, is that if the inspected structures can be modeled as plane shear-type frame structures, the damage-induced interstory drifts occur only at the damaged stories and not at the undamaged stories [4,5]. The method has been verified through vibration testing on structures with a symmetric configuration (both in the pristine and in the damaged states), using uniaxial excitations in shaking table tests [4,6] or shaker tests [5]. As reported in [4,5], the PSIL method has shown better performance than damage index or mode shape curvature methods [1,2] in the damage localization on shear buildings. Advantages of the PSIL method with respect to other VBDD techniques were also shown by Bernagozzi et al. [8] using numerical simulations on a RC shear-type frame building.

The objective of the paper is to apply the Positive Shear Inspection Load method on building structures that cannot be easily modeled as plane shear-type structures. The work thus aims to test the methodology on more complex structures. An application of the methodology to similar structures was found in the work by Zhang et al. [7], where MF-based deflections were used to detect and localize damages on the benchmark structure provided by the IASC-ASCE Structural Health Monitoring Group [9,10]; in this last work, the analyses were carried out using the data of impact hammer tests performed on the structure, and experimental modal flexibility matrices related to the behavior of the structure in one direction were assembled to perform 2D analyses. Differently from the mentioned work, the present paper aims to perform the calculations on modal flexibility matrices of the whole 3D structure and that are estimated from ambient vibration tests. A simple generalization of the original method is thus proposed in this paper to address the case of 3D structures. Moreover, another difference with respect to the work of Zhang et al. [7], is that in the present work the analyses are carried out not only for the localization but also for the quantification of the damage. A steel frame structure located at the Earthquake Engineering Research Facility of the University of British Columbia (Vancouver, Canada) was tested in September 2016 and used for the damage detection analyses presented in this paper. Ambient vibration data of the structure were collected using a dynamic monitoring system and various structural configurations with imposed stiffness reductions were tested. It is worth mentioning that this structure is the same structure that was tested on August 2002 by the IASC-ASCE Structural Health Monitoring Group [9,10].

2. Damage diagnosis using modal-flexibility based deflections

The main steps of the Positive Shear Inspection Load method [4-6] are briefly summarized herein. The method is formulated for structures that can be modeled as plane shear-type frame buildings and that are tested under ambient vibrations. The method is applicable if acceleration measurements are available at all the stories of the structure. In particular, since the method has been formulated for structures that can be modeled as plane shear-type building structures, at least one measurement of horizontal accelerations is required at each story. All the measurements have to be done in the same direction of the structure, which is the direction that is considered in the analyses. Starting from the recorded vibration data the modal parameters of the structure can be determined using identification techniques, and for example in case of ambient vibrations any operational modal analysis technique can be applied [3]. Modal flexibility matrices of the structures can be assembled using the identified modal parameters

$$\boldsymbol{F_r} = \boldsymbol{\Phi_r} \, \boldsymbol{\Lambda_r^{-1}} \, \boldsymbol{\Phi_r^T} \tag{1}$$

where $\boldsymbol{\Phi_r}_{\,n\times r}$ is the mass-normalized mode shape matrix, $\boldsymbol{\Lambda_r}_{\,r\times r}$ is a matrix with the square of the natural circular frequencies ω_i^2 on the main diagonal, r is the number of the modes included in the calculation and n is the number of the stories. Information about the structural masses are required to obtain mass-normalized mode shapes. A positive shear inspection load, which is a $n\times 1$ vector $\boldsymbol{p} = \{\boldsymbol{1}\}_{n\times 1}$ with unitary values, is then used to compute the modal flexibility-based deflections $\boldsymbol{x} = \boldsymbol{F_r}\, \boldsymbol{p}$. Starting from the estimated MF-based deflections, the interstory drifts d_j are evaluated and considered as damage-sensitive features

$$d_j = \begin{cases} x_j - x_{j-1} & for\ j = 2..n \\ x_j & for\ j = 1 \end{cases} \tag{2}$$

Localization of the damaged story is performed by analyzing the changes in the interstory drifts. In particular, a statistical approach based on a z-index test for outlier analysis is adopted to deal with the uncertainties that occur when identification techniques are applied to real vibration data. This z-index for the j-th story is defined as

$$z_j = \frac{d_j^{INS} - \bar{d}_j^{BAS}}{s(d_j^{BAS})} \tag{3}$$

where $\bar{d}_j^{BAS}$ and $s(d_j^{BAS})$ are the sample mean and the sample standard deviation of the interstory drifts calculated in the baseline state, and d_j^{INS} is the interstory drift calculated in the inspection phase. Under the simplified assumption that z_j is approximated by a normal distribution, a story is labelled as damaged using Eq. (1) if $z_j \geq z^{threshold}$ [4,5]. As also discussed and suggested in [4,5], this threshold is a user choice, and a threshold $z^{threshold} = 3$ has been selected in the present work. If a story is labelled as damaged using the z-index test for damage localization, the damage can also be quantified by evaluating the damage severity α_s [5,6]. This parameter is a relative index ($0 \leq \alpha_s < 1$) that quantifies the portion of the story stiffness that is lost due to the damage. The damage severity α_s for the j-th story is expressed as

$$\alpha_{s,j} = \frac{d_j^{INS} - \bar{d}_j^{BAS}}{d_j^{INS}} \tag{4}$$

where $a_{s,j}$ is theoretically equal to zero if the story is not damaged, while it is equal to one if the story is completely damaged [5].

In this paper a generalization of the PSIL method is considered to deal with 3D structures, instead of plane ones. The main assumptions and steps related to the investigated approach are described in the following. The approach is valid for simple rectangular “box type” 3D buildings [3], under the assumption that each floor has a rigid-body in-plane behavior. For these structures only the two horizontal displacements and the torsional rotation of the mode shapes of the building are usually estimated when these structures are subjected to ambient vibration tests, while the vertical modal displacements are usually neglected [3]. According to the original formulation of the PSIL method, having acceleration measurements available at all the stories is an assumption that has to be made also in the generalized formulation. Under the assumption of having floors with a rigid-body in-plane behavior, at least three measurements of horizontal accelerations (in different directions and locations) at each floor are required to apply the investigated method. In this way, the dynamic behavior of the structure can be captured by estimating mode shape vectors that are characterized by horizontal components in two directions and rotational components.

Starting from the identified modal parameters of the 3D structure (i.e. natural frequencies and mode shapes), experimentally-derived modal flexibility matrices $\boldsymbol{F_r}$ of the 3n-DOF structures can be assembled using Eq. (1). Then inspection loads $\boldsymbol{p_x}$ and $\boldsymbol{p_y}$ can be applied along the principal directions

$$\boldsymbol{p_x} = \begin{pmatrix} \{\boldsymbol{1}\} \\ \{\boldsymbol{0}\} \\ \{\boldsymbol{0}\} \end{pmatrix}_{3nx1} \quad ; \quad \boldsymbol{p_y} = \begin{pmatrix} \{\boldsymbol{0}\} \\ \{\boldsymbol{1}\} \\ \{\boldsymbol{0}\} \end{pmatrix}_{3nx1} \tag{5}$$

to compute the modal flexibility-based deflections $\boldsymbol{x_x} = \boldsymbol{F_r}\,\boldsymbol{p_x}$ and $\boldsymbol{x_y} = \boldsymbol{F_r}\,\boldsymbol{p_y}$. Subsequently, the interstory drifts $\boldsymbol{d_x}$ and $\boldsymbol{d_y}$ in the two directions of the structure can be calculated by applying Eq. (2). At the end, the procedure related to the original PSIL method is applied in the two prevalent directions of the structure to localize and quantity the damage using Eqs. (3) and (4), respectively.

3. Description of the ambient vibration tests

Ambient vibration tests were conducted in September 2016 on a one-third scale steel structure (Fig. 1a), which is a four-story two-bay by two-bay frame with an interstory height equal to 0.9 m and a bay width equal to 1.25 m. The members of the frame are hot rolled grade 300W steel, and the columns and the beams are double T sections (B100x9 and S75x11, respectively). The principal directions of the structure can be defined according to the orientation of the column sections (Fig. 1b): the X axis is aligned to the weak direction (West-East) of the frame and the Y axis is the strong direction (North-South). In each bay of the structure there are two threaded rods with a diameter equal to 12.5 mm. These wall bracing elements can be easily removed to impose stiffness reductions on the structure.

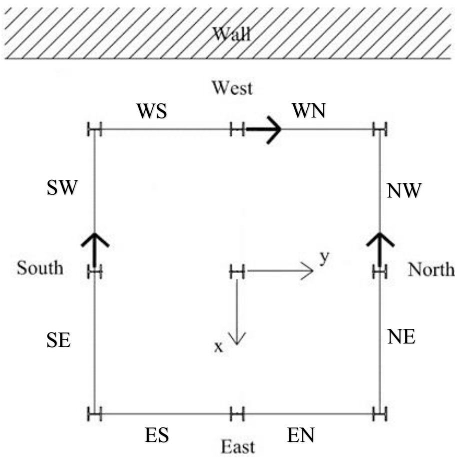

Fig. 1. Steel frame structure: (a) photo; (b) schematic plan-view and layout of the sensors at each story

Four steel plates are located at each level to create the floor masses: at the top floor the mass of each plate is equal to 342 kg and at the other floors the mass of each plate is equal to 454 kg. Plates aligned to the west-east direction were shifted towards south direction as much as possible. A dynamic monitoring system with 15 channels of acceleration sensors was used to collect the AV data. The sensors are force balance accelerometers with a full-scale range equal to ±0.5g and a sensitivity equal to 5 V/g. Three sensors were located on each story of the structure, respectively on south, west, and north sides, as indicated by the arrows in Fig. 1b. The measurements were acquired with a sampling frequency equal to 1000 Hz. Damaged configurations were induced to the structure by imposing stiffness reductions (i.e. by removing one or more threaded rods from the wall bracing system). The length of time of the measurements was approximately 3 hours for the fully braced structure (i.e. the undamaged structure) and approximately 30 minutes for each damage configuration.

The structural configurations (from C1 to C21) that were tested are reported in Table 1, where description of the braces removed in each configuration is provided using acronyms that include the following information: the story where the brace is removed (from the 1^{st} to the 4^{th}); the bay where the brace is removed (according to the orientation of the structure, Fig. 1b); the number of the braces removed (i.e. one or two rods removed). The acronyms reported in the table are thus composed as: "story – bay – no. of braces removed". The tested configurations include both single and multiple damage states. In addition, configurations with both a plan-symmetric and a plan-asymmetric distribution of the story stiffness were considered. For example, configurations C17, C18, C19 and C20 have a plan-symmetric distribution of the stiffness of each story, and they were tested consecutively and by progressively increasing the stiffness reductions imposed at the 2^{nd} story. On the contrary, other configurations are characterized by a distribution of the stiffness in the damaged level that is moderately asymmetric (e.g. configuration C8) or strongly asymmetric (e.g. configuration C2).

Table 1 – Tested structural configurations (* progressive damage test)

Configuration	Braces removed	Configuration	Braces removed
C1	none	C12	half braces removed on the west side
C2	1-SW-2; 1-SE-2	C13	half braces removed at the first story
C3	C2 + 1-NW-2; 1-NE-2	C14	3-SE-2; 3-SW-2
C4	all braces removed at the first story	C15	C14 + 2-WS-2; 2-WN-2
C5	C2 + 1-WS-2; 1-WN-2	C16	2-WS-2; 2-WN-2
C6	C2 + 1-NW-1; 1-NE-1	C17*	2-WS-1; 2-NW-1; 2-ES-1; 2-SW-1
C7	1-SE-2	C18*	C17 + 2-WN-1; 2-NE-1; 2-EN-1; 2-SE-1
C8	1-SW-1; 1-SE-1	C19*	C18 + 2-WS-1; 2-NW-1; 2-ES-1; 2-SW-1
C9	3-WS-1; 3-WN-1	C20*	C19 + 2-WN-1; 2-NE-1; 2-EN-1; 2-SE-1
C10	4 -WS-1; 4-WN-1; 2-SW-1; 2-SE-1	C21	2-SW-2; 2-SE-2; 2-WS-1; 2-WN-1; 2-NW-1;2-NE-1
C11	4 -WS-1; 4-WN-1; 2-WN-1; 2-WS-1		

4. Results: operational modal analysis and damage diagnosis

The AV measurements were decimated in the frequency range 0-50 Hz, and the data recorded for the fully braced structure (C1) were segmented into non-overlapping data segments with a length of time of 30 minutes each. Then, the operational modal analysis was applied on the AV data using the Enhanced Frequency Domain Decomposition method [3,11] implemented in ARTeMIS software [12]. The structural modes were manually identified by analyzing the plots of the singular values computed from the spectral density matrices [3,11]. Ten structural modes were identified from the data. However, in the modal validation [12] the complexity plots of the mode shapes showed that the higher modes were affected by more uncertainties than the lower ones. Thus, only the first five modes of the structure were considered for the damage diagnosis. Natural frequencies and modal damping ratios both for configuration C1 (undamaged) and for a damaged configuration (e.g. C8) are reported in Table 2.

Table 2 – Modal parameters: configuration C1 (undamaged) vs configuration C8 (damaged)

Mode no.	Type of mode shapes	Configuration C1		Configuration C8	
		Frequency f_i [Hz]	Damping ζ_i (%)	Frequency f_i [Hz]	Damping ζ_i (%)
1	1° mode - longitudinal	7.62	0.65	6.85	0.56
2	1° mode - longitudinal	8.04	0.72	7.66	0.67
3	1° mode - torsional	15.53	0.22	14.64	0.25
4	2° mode - longitudinal	21.46	0.27	20.56	0.26
5	2° mode - longitudinal	22.05	0.23	21.71	0.24

The mass matrix of a $3n$-DOF lumped-mass model of the structure was used to normalize the identified mode shapes, and then modal flexibility matrices of the 3D structure were assembled. The modal flexibility-based deflections and interstory drifts of the structure were computed by applying the inspection loads proposed in Eq. (5) for the X and the Y directions of the structure. This procedure was repeated for each tested configuration. Damage localization and quantification were thus performed by means of the z-index test for outlier detection using Eq. (3) and by calculating the damage severity using Eq. (4). An example of damage localization is presented in Fig. 2 where configuration C8 (damaged) is compared with configuration C1 (undamaged). In configuration C8 two rods were removed at the first story and on the south face of the structure. In such a way, the stiffness reduction was imposed on the weak direction of the structure. As evident in Fig. 2c, the z-index test correctly localizes the imposed damage at the first story and for the X direction of the structure.

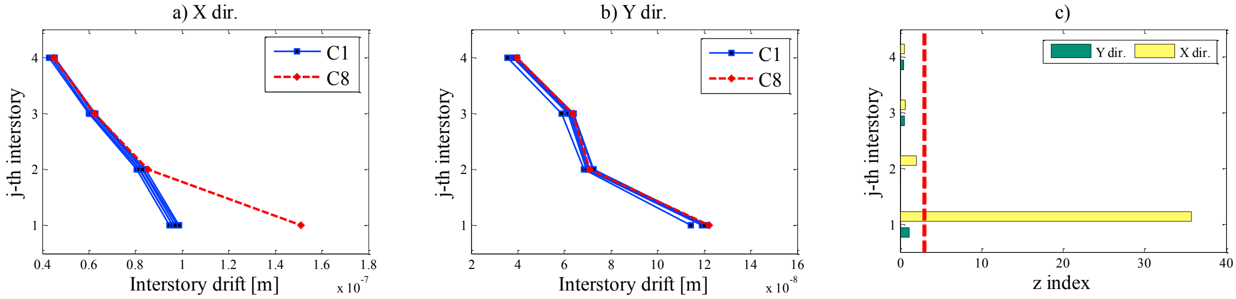

Fig. 2. Damage localization on configuration C8: (a) interstory drifts in X dir.; (b) interstory drifts in Y dir.; (c) z-index test

The results of the damage localization using the z-index are reported in Table 3 for all the tested damage configurations (from C2 to C21). In particular, the z-index values are presented in the table for each direction of the structure (i.e. X or Y direction) and for each story (from the 1st to the 4th story). The z-index values were compared with the threshold ($z^{threshold} = 3$, as defined in Section 2) to evaluate if the structure, in the considered direction and at the selected story, is damaged or not. At the end, the results of the damage localization based on these z-index tests were compared with the positions of the imposed stiffness reductions (Table 1). The number of cases that were falsely detected is reported in Table 3, where a distinction has been made between false positives and false negatives.

The total number of false positives and false negatives obtained by the algorithm is equal to 19. This number was compared to the total number of the z-index tests performed for damage localization (i.e. 160), which is equal to the number of the damaged configurations (i.e. 20) × no. of the stories (i.e. 4) × no. of the analyzed directions (i.e. 2). A success rate of 88.13 % was thus obtained in damage localization on the tested configurations.

If one considers the cases that are falsely detected, it is evident from Table 3 that most of these cases are false positives (i.e. 17 cases). In such cases, the statistical z-index test fails in the classification of the story as undamaged, and the z-index is, in general, slightly higher than the selected threshold. On the contrary, the values of the z-index that are related to the localization of a story that is effectively damaged are, in general, remarkably higher than the threshold. This is evident in Table 3, for example if the configuration C3 and the z-index values related to the X direction are considered: z_1 =140.41 is the value of the z-index that correctly localizes the damage imposed at the first story and in the x direction, while z_2 = 3.96 represents a false positive case.

False negative results in the damage localization were obtained in two cases. These two cases were obtained for configurations C11 and C12 in the localization of damages that were imposed at the fourth story of the structure in the strong or Y direction. These errors in the localization of the damage could be due to modal truncation errors that are introduced on the modal flexibility-based interstory drifts when only a limited number of modes is included in the calculation. This is the case for the present analyses, since, as already mentioned in the previous paragraphs of this section, only the first five modes of the structure were included in the calculation of the damage-sensitive features, while the higher modes affected by more uncertainties were excluded. Referring to this point, it is evident that the higher the number of modes included in the computation of the modal flexibility matrices and the MF-based deflections, the better are the estimates of these quantities with respect to the static or target values. However, it is also clear that if the higher modes are affected by significant uncertainties and are included in the analyses, then these uncertainties are also introduced on the modal flexibilities and on the deflections.

Table 3 – Damage localization using the z-index test (FP = false positive; FN = false negative)

Conf.	Dir.	z-index				FP	FN	Conf.	Dir.	z-index				FP	FN
		z_4	z_3	z_2	z_1					z_4	z_3	z_2	z_1		
C2	x	0.90	0.15	2.36	58.66	0	0	C12	x	-2.11	-2.33	-1.87	-3.36	0	0
	y	-2.59	-3.42	-3.33	-0.74	0	0		y	-1.80	5.95	10.32	8.20	0	1
C3	x	-0.21	-2.69	3.96	140.41	1	0	C13	x	-0.11	-0.94	0.82	38.56	0	0
	y	-0.89	-1.14	-0.94	-0.49	0	0		y	2.01	2.56	1.20	25.42	0	0
C4	x	-3.14	-6.42	1.42	136.04	0	0	C14	x	3.88	37.54	2.84	2.72	1	0
	y	-4.96	-4.48	-0.71	81.69	0	0		y	3.98	-0.02	2.83	3.32	2	0
C5	x	0.57	1.36	1.86	64.81	0	0	C15	x	2.95	35.79	2.21	1.02	0	0
	y	-7.70	-5.79	-7.31	41.80	0	0		y	-5.19	-5.73	32.03	-7.47	0	0
C6	x	0.70	0.08	3.15	85.61	1	0	C16	x	1.72	1.27	2.05	1.60	0	0
	y	-0.10	-0.82	-0.38	1.39	0	0		y	-6.70	-3.37	30.86	-6.55	0	0
C7	x	0.13	0.00	0.78	13.12	0	0	C17	x	3.36	3.58	13.06	5.12	3	0
	y	0.56	0.09	-0.43	0.90	0	0		y	2.00	2.79	6.31	2.52	0	0
C8	x	0.29	0.39	1.19	20.81	0	0	C18	x	1.41	1.98	32.58	1.87	0	0
	y	0.47	0.52	0.08	1.08	0	0		y	0.09	2.87	16.30	2.95	0	0
C9	x	1.51	1.38	1.23	1.37	0	0	C19	x	-0.15	1.56	57.18	0.02	0	0
	y	-0.25	7.16	-0.58	-1.19	0	0		y	-0.38	3.68	28.45	3.71	2	0
C10	x	0.81	1.27	17.11	0.77	0	0	C20	x	-0.88	3.68	128.21	-0.02	1	0
	y	5.58	2.60	0.52	0.79	0	0		y	-2.27	4.31	47.95	4.20	2	0
C11	x	1.86	1.58	1.78	2.08	0	0	C21	x	2.45	5.05	81.34	4.68	2	0
	y	0.98	-0.36	12.81	-5.40	0	1		y	2.30	5.24	9.77	4.49	2	0

Damage quantification was then carried out for each story that is labelled as damaged by the z-index test. At first, the progressive damage test (i.e. configurations C17, C18, C19 and C20) was analyzed. As evident in Fig. 3a, b (for the X and the Y directions, respectively), the higher the number of the braces removed, the higher the interstory drifts at the 2nd level, which is the story where the braces were removed. In addition, the damage severity α_s evaluated for these four configurations clearly increases, as shown in Fig. 3c. Results for all the configurations are reported in Fig. 4a and b, where the damage severity is plotted against the number of the braces removed in each story for the X and the Y directions, respectively. In this figure, blue points are related to configurations with a plan-symmetric distribution of the stiffness of all the stories (including the damaged levels). On the contrary, red points are related to configurations with a plan-asymmetric distribution of the stiffness at the damaged story. Referring to the former (i.e. blue points), a clear proportional trend is present between the damage severity α_s and the number of braces removed. Referring to the latter (i.e. red points related to plan-asymmetric configurations), it is evident that the damage severity is slightly overestimated, as the red points are, in general, located above the blue points that refer to cases with the same number of braces removed in a symmetric configuration.

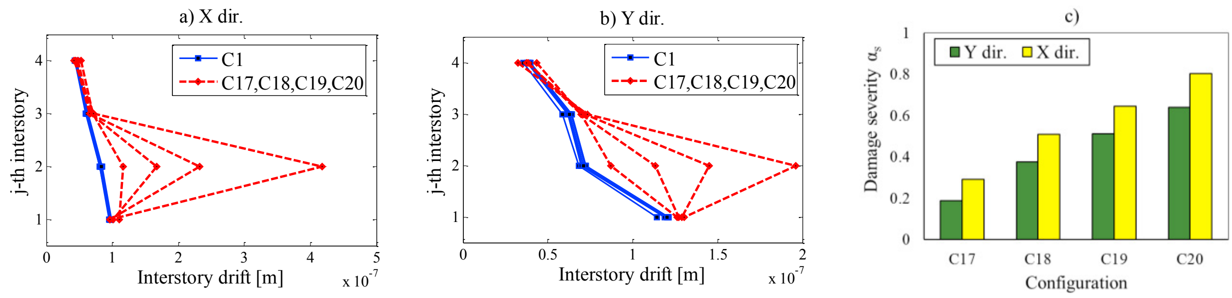

Fig. 3. Progressive damage test (symmetric configurations): (a) drifts X direction; (b) drifts Y direction; (c) damage quantification

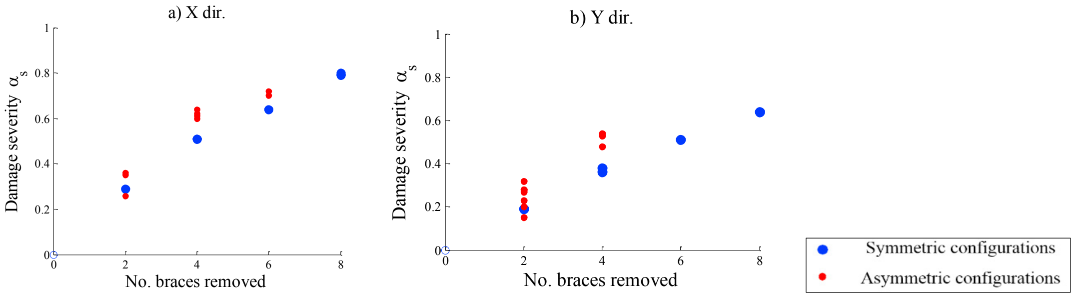

Fig. 4. Damage quantification (results plotted for all the tested configurations): (a) X direction; (b) Y direction

5. Conclusions

The Positive Shear Inspection Load (PSIL) method for damage diagnosis has been applied to a steel frame structure tested under ambient vibrations and considering various structural configurations with imposed stiffness reductions. A generalization of the PSIL method, which was originally formulated for plane shear-type structures, has been considered to deal with a 3D structure that is fully instrumented with acceleration sensors. The results of the generalized methodology showed that the damages can be localized by identifying the stories and the directions where the stiffness reductions were applied. By evaluating the performance of the method for all the tests performed, a high success rate in damage localization was obtained. Reasonable estimations of the damage severity were also obtained, especially for the damage configurations with a plan-symmetric distribution of the stiffness at the damaged story. Further investigations are required and are currently ongoing at the time of writing, to correct the overestimations that were obtained in the damage quantification for the plan-asymmetric damage configurations.

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