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Rapid check of presumed seismic structural behaviour of buildings using ambient vibration measurements

S. Grimaz, P. Malisan and A. Pividori

SPRINT-Lab, Polytechnic Department of Engineering and Architecture, University of Udine, Udine, Italy

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ABSTRACT One of the main strategies of disaster risk reduction policies in seismic-prone areas is to assess a building's susceptibility to critical structural behaviour, which could induce and aggravate seismic damage. Subsequently, it is important to implement structural upgrading interventions to remove or reduce such critical issues. For existing buildings, this strategy is a core aspect of vulnerability assessment methods, and it is usually inferred by analysing specific features of site and building conditions. Both vulnerability assessments and structural upgrading interventions would benefit from a rapid check aimed at verifying, through on-site measurements, if the presumed structural behaviour (before and/or after the interventions) corresponds to the actual situation. This paper presents an integrated methodology, conceived to account for the above-mentioned issues, based on the acquisition and interpretation of ambient vibrations. The paper illustrates the use of the proposed methodology in different applications, first, for a preliminary characterisation of the situations, then, as a support in the assessment and definition of actions to reduce the structural vulnerability, and finally, for *a-posteriori* effectiveness control of the upgrading interventions being implemented. To conclude, the paper provides some considerations on the strengths and limitations concerning the use of the methodology for seismic risk reduction purposes.

Key words: disaster risk reduction, ambient vibrations, seismic risk, site-building system, SDG11.

1. Introduction

The UN Global Agenda 2030 for Sustainable Development (United Nations General Assembly, 2015) and the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015) aim, among other things, to make infrastructures, cities, and human settlements safer and more resilient, highlighting the importance of adopting a pro-active and contextualised approach to disaster risk reduction (DRR).

DRR strategies rely closely on preventive actions aimed at avoiding or limiting the susceptibility of the built environment to suffer critical consequences in the case of shocks, such as in the case of an earthquake. Focusing on the physical components of the built environment, the critical consequences depend both on the severity of the event and on the intrinsic and specific characteristics of sites and constructions (physical vulnerability). Considering the complexity of the problem, especially in the seismic case, DRR evaluations and actions should consider the overall site-building system, both in the case of new constructions and existing ones.

For new constructions, and for retrofitting or upgrading existing buildings, generally, DRR is implicitly implemented by applying building codes (e.g. EN BS 1990, 2002; International Code Council, 2018) that prescribe an interdisciplinary design process, involving different disciplines and professions (ranging from geological to engineering fields). Site studies and investigations, on-site measurements, laboratory tests, computing analysis, and simulations are the tools for designing safer and more resilient new (or renewed) built environments.

For existing buildings, different methods and techniques are used to assess the actual situation of the site and the building, in order to better finalise the upgrading or improvement interventions (see e.g. Hans *et al.*, 2005; Boutin and Hans, 2009; Luechinger *et al.*, 2015; Žugić *et al.*, 2018). When DRR policies are formulated for a multitude of site-building systems, the characterisation of the physical vulnerability of buildings is usually done using rapid and cost-effective assessment methodologies based, for example, on indirect assessments such as statistical estimations, simplified models working with low-detail data, and expert-based visual inspections. Some examples of these methodologies are Level 1 of Hazus® (Federal Emergency Management Agency, 2004), Rapid Visual Screening of FEMA (Federal Emergency Management Agency, 2015), GLOSI (The World Bank, 2018), Level 1 of Grant *et al.* (2007), VISUS (Grimaz and Malisan, 2016, 2019), and SCOSSO (D'Ayala *et al.*, 2020) among others. The indirect vulnerability assessment considers structural building features such as: plan and elevation shape irregularities, structural system typology and distribution, structural disconnections (e.g. joints), and structural improvements. These assessments enable identifying the potential susceptibility of a building to critical structural behaviour; however, these evaluations being indirect, they must be considered as hypothesised or presumed and should be counter-checked by on-site measurements.

A building's structural behaviour can be measured through direct vulnerability assessment methodologies based on the acquisition and interpretation of vibration measurements. These methodologies can either impose forced vibrations to the structures (Motte *et al.*, 2015) or can analyse ambient vibrations, to identify the actual structural behaviour under elastic conditions (Krishnamurthy *et al.*, 2008; Reynders, 2012; Rainieri and Fabbrocino, 2014; Brincker and Ventura, 2015; Sadhu *et al.*, 2017). In addition, vibration measurements also allow assessing site dynamic characteristics, with varied detail (see, for example, Mucciarelli *et al.*, 2009; Mucciarelli, 2012; Malehmir *et al.*, 2016; Mahvelati *et al.*, 2018; Caielli *et al.*, 2020).

Nevertheless, it could be useful and sufficient to adopt rapid and non-invasive techniques for checking the accuracy (i.e. correspondence to reality) of specific presumed structural behaviour or checking if the goals of upgrading interventions are effectively reached.

The purpose of this paper is to illustrate an integrated methodology conceived for counter-checking rapidly and through non-invasive *in-situ* techniques the susceptibility to specific structural critical behaviour, considering the site-building system. The methodology is named 'Integrated Check of site-structure behaviour' (from now on: CheckIn), and is based on a coordinated and finalised measurement of ambient noise, both on the site and on the building. The CheckIn methodology aims either at counter-verifying the actual susceptibility of a building to the critical structural behaviour hypothesised through indirect vulnerability assessments, or to check the effectiveness of structural interventions aimed at reducing critical structural behaviour.

The CheckIn methodology is based on the concepts of 'behaviour' and 'susceptibility'. Behaviour is intended as the part of the site-building system response associated with: the specific types of the seismic site response; the different modes and shapes of deformation of the building induced by stresses (and they could be regular or irregular); and the activation of a dynamic synchronisation between site and building responses during a seismic event. Susceptibility refers to the intrinsic characteristics of a structure (or a site) that lead to a tendency to respond with a specific behaviour. Moreover, in the methodology, 'check' is intended as counter-verification, i.e. a verification of the correspondence between the actual and the previously hypothesised or esteemed behaviour.

Considering these concepts and definitions, the CheckIn methodology was specifically developed for performing a rapid check of a site-building system aimed at the identification (or exclusion) of the susceptibility to pre-codified critical behaviour that concur significantly in determining negative consequences in the case of an earthquake. The goal is not a detailed seismic characterisation of site and structure, but a pragmatic and cost-effective check, as fundamental knowledge support for the decision-making process of DRR. This perspective constitutes an innovative element with regard to the different methodologies present in the literature.

The CheckIn methodology is illustrated in section 2. First, the motivations for choosing ambient noise measurement as a source of data for the check are explained and the main critical behaviour investigated by the methodology are described. Then, the framework of the methodology is illustrated: the paper shows how the CheckIn is applied on the whole site-building system, with an emphasis on the criteria for checking the susceptibility of buildings to critical behaviour. Section 3 shows the application of CheckIn methodology in three case studies, with a brief discussion and the results. Finally, considerations on the use and limitations of the methodology for DRR purposes are summarised.

2. The CheckIn methodology

The CheckIn methodology was developed specifically as a decision-making support in the DRR process, based on a pragmatic and rapid check approach to the susceptibility of a site-building system to critical behaviour in case of an earthquake. Although in most cases it is possible to improve the situation by intervening solely on buildings, it is important to perform an integrated evaluation that considers both the interconnected sub-systems of site and building.

For the site sub-system, it is worth noting that the condition of site stability must be verified before the application of the CheckIn methodology, since site instability makes the site inadequate, or causes local induced hazards. Site instability can be identified either through desk analysis (if seismic micro-zonation has been assessed) or through specific inspections (Working Group on Seismic Microzoning, 2008). In the following, when referring to 'site', the stability condition will be implicitly assumed. In these sites, it is important to recognise the presence of conditions that concur in modifying the seismic input signal.

For the building sub-system, critical behaviour is related to structural disjunctions, the degree of rigidity of diaphragms, and the susceptibility to irregular responses in the horizontal and vertical planes. The integrated assessment of site and buildings allows investigating the critical behaviour of site-building double resonance.

Starting from these considerations, the development of the methodology was founded on three pillars: the identification of existing techniques that can be effectively used for the above-mentioned purposes; the definition of specific integrative assessment and interpretation methods; and, the definition of a framework for performing an integrated checking process of the site-building system.

The ambient noise measurement techniques were evaluated as the best candidate for developing a rapid, cost-effective, and integrated methodology for checking. This is because they are not invasive, passive, cheap, and could be applied both on the site and on the buildings (Mucciarelli *et al*., 2009). Although ambient noise techniques enable evaluating the response of sites and structures in elastic conditions, related literature (e.g. Michel *et al*., 2008, 2010) shows that the behaviour in elastic conditions can be considered good indicators of the expected behaviour during an earthquake. Therefore, the CheckIn methodology consists of the integration of an overall framework of various ambient vibration analysis techniques already used for characterising sites and buildings, combined with the original multiple application of the kinematic coupling characterisation (KCC) method (Grimaz and Malisan, 2022).

The CheckIn methodology is established on a two-phase procedure (Fig. 1). The first phase consists of formulating the hypothesis on the expected critical behaviour for the site and the building sub-systems; the second phase consists of checking the hypotheses' accuracy, through the execution and interpretation of ambient vibration measures. The results obtained by assessing the two sub-systems permit, subsequently, further evaluations on the whole site-building system.

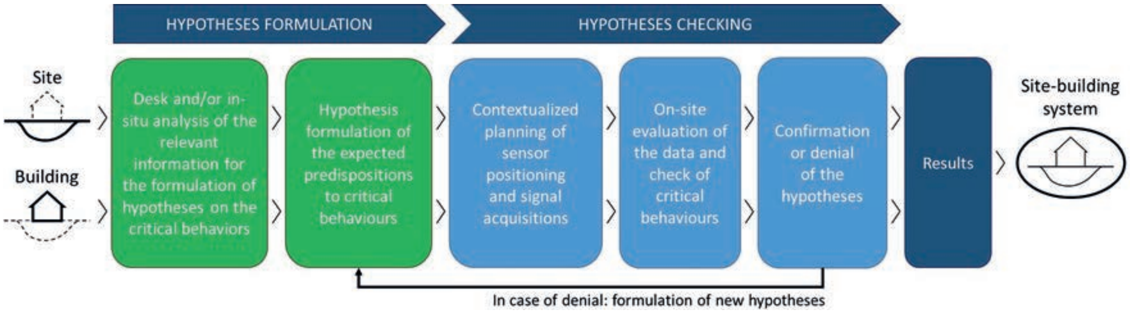


Fig. 1 - Overall framework distinguishing the two main phases of the CheckIn methodology.

The two phases are detailed in the following:

1. hypothesis formulation: this phase aims at a first estimation of the presumable critical behaviour characterising the system. This estimation is developed by rapidly analysing the essential available information both for site and building. For the (stable) site, desk-analysis information, such as topography and site stratigraphy, can be obtained from geological maps or other geophysical surveys previously developed in the site or in the surrounding areas. For example, in Italy, there are microzonation surveys that can provide relevant information (Working Group on Seismic Microzoning, 2008). For the building, experts (usually civil engineers) hypothesise the susceptibility to specific structural behaviour, either by developing an expert-based conceptual model of the building, using indirect vulnerability methodologies, or by considering the result of simulation models. This phase requires the knowledge of basic features of the building, such as building geometry (in-plane and in-elevation), structural system, structural irregularities, and the potential presence of structural retrofitting interventions. Very often these elements of information can be acquired during a rapid survey of the building before the measurement campaign. Desk analyses, both for site and building allow formulating hypotheses on the expected susceptibility to critical behaviour;
2. hypothesis checking: this phase consists of the acquisition and interpretation of the ambient vibrations in the site and in the building, and aims at confirming or denying the presence of

the presumed critical behaviour (both for site and building). Vibration signals are acquired in the pre-identified measurement points, through specific context-dependent acquisition sequences and synchronised couples of measurements. The on-site evaluation of the data allows checking the presence of the hypothesised critical behaviour. If the evaluation outcomes deny the initial hypothesis, then, a new hypothesis must be formulated and (potentially) new measurements must be performed and evaluated. The results obtained for site and building should be, successively, confronted to check the presence of critical behaviour for the whole site-building system.

The specific indicators and critical behaviour considered in the CheckIn methodology are described in the following sub-sections 2.1. and 2.2., respectively for the site and the building. Section 2.3. illustrates the integrated evaluation for the site-building system.

2.1. CheckIn applied to the site sub-system

The CheckIn application to (stable) sites aims at counter-verifying the presence of the following conditions:

- susceptibility to seismic amplification conditions, which can be linked to the presence of contrasts of impedance in the subsoil, and can potentially imply seismic ground motion variations in terms of amplification, duration, and frequency content;
- presence of velocity inversion in the subsoil, which could cause non-linear effects with large shear strain deformations in the soft layer (Fabozzi *et al*., 2021).

Moreover, the methodology allows identifying the site fundamental frequency(ies) to use in combination with the building fundamental frequency(ies), to check the presence of potential site-building resonance.

2.1.1. Check with HVSR technique

For the site, the CheckIn methodology uses the Horizontal-to-Vertical Spectral Ratios (HVSR) technique (SESAME, 2004; Sylvette *et al*., 2006; Haghshenas *et al*., 2008; Barazza *et al*., 2009) based on the measurement of ambient vibration signals. The position of the sensor on the site depends closely on the preliminary analysis of the site conditions that considers the geomorphology, the presumed impedance contrast between bedrock and shallow strata (or between strata), irregularities, and boundary effects (SESAME, 2004). As a rule, it is suggested to follow the criteria illustrated in SESAME (2004). When measurements are done in an urban environment, the signal-to-noise ratio could be very low, and it may be difficult to identify the site's fundamental frequency (Stanko *et al*., 2019). Moreover, the sensor should be not positioned close to the building, otherwise the outcomes could show the natural frequencies of the building together with those of the site. If local variations of the site characteristics are not expected, it is possible to perform site measurements also relatively far from the assessed area, however, a measurement close to the building must be acquired to confirm the validity of this hypothesis.

Ambient vibration signals are interpreted according to the well-known procedures described in the literature (SESAME, 2004; Albarello *et al*., 2011; Caielli *et al*., 2020) for the identification and interpretation of the HVSR curves. This check provides a rough assessment of the situation. A more detailed characterisation can be achieved through specific additional geophysical (and/or geological, geotechnical) analyses.

2.2. CheckIn applied to the building sub-system

The CheckIn methodology applied to the building sub-system enables checking the susceptibility of a structure to pre-codified critical behaviour (one or more). The application allows firstly to check:

- if the building is composed of one or more structural units, i.e. independent 'building blocks' that provide (potentially) different structural responses;
- the rigidity degree of building diaphragms (slabs).

After these preliminary checks, in the cases of rigid or semirigid diaphragms, the methodology allows checking, for each structural unit, the in-plane motion of a diaphragm, and the behaviour of the structure in elevation, in correspondence with the first natural frequencies of the building.

Fig. 2 illustrates the framework of the CheckIn methodology applied to buildings, and shows all the aspects that can be checked, i.e.:

- disjunctions. This check enables identifying different blocks which could have an independent structural response, and determining negative interactions in case of an earthquake [e.g. pounding effects (Fig. 2a)]. This hypothesis can derive from preliminary analysis when there is any suspicion of the presence of thermic joints, blocks abjointed, or structural cracks in the main walls. In case of doubt, this check is important to identify both the absence or presence of separation between two parts and the different structural units that make up the building on which the other checks of the methodology will be applied. If more units or blocks have been identified, each of them is checked separately;
- in-plane rigidity of diaphragms. This check allows classifying a diaphragm as: rigid, semi-rigid, non-rigid (Figs. 2b, 2c, and 2d, respectively). The slab rigidity is a fundamental aspect of earthquake-resistant structures according to modern seismic codes. Moreover, the presence of non-rigid slabs can facilitate the out-of-plane behaviour of masonry walls. The check of the rigidity of slabs is the first check applied to the measurements: if this check confirms the presence of a non-rigid slab, the CheckIn methodology ends with a warning concerning non-rigidity condition identification. In the case of a non-rigid slab, the lateral

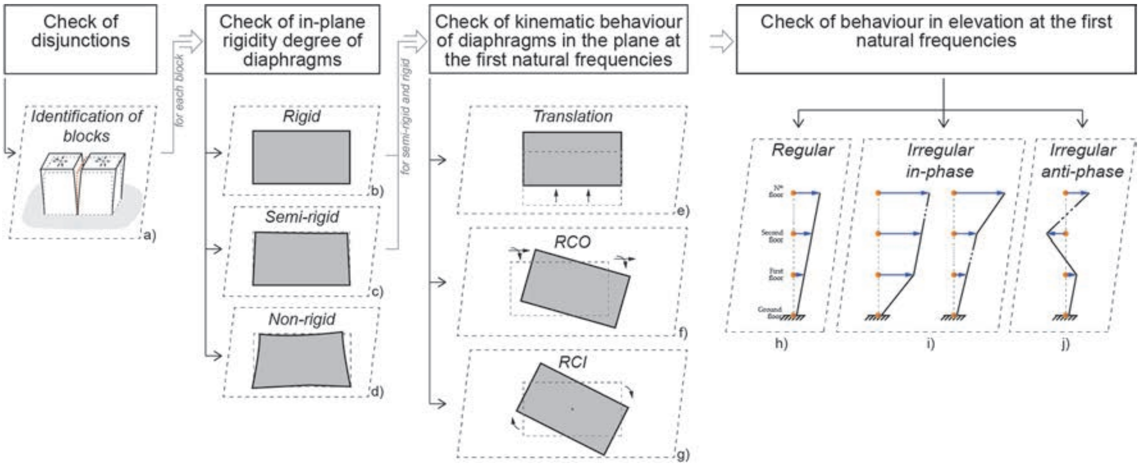


Fig. 2 - Framework of the CheckIn methodology applied to buildings: a) check of blocks disjunction: if disjunct, two blocks can move independently from each other; b to d) check of the rigidity of the diaphragm: rigid (b), semi-rigid (c), deformable diaphragms (d); e to g) kinematic behaviour of rigid diaphragms in plan: translation (e), rotation with rotation centre outside the envelope - RCO (f), rotation with rotation centre inside the envelope - RCI (g); h to j) reference behaviour in elevation: regular (h), irregular - in phase (i), irregular - antiphase (j).

load is not distributed to the load-bearing vertical structures according to their stiffness, as usually assumed by structural models used for the design. In this case, the building must be investigated by identifying the different macro-elements (see, e.g. Doglioni *et al.*, 1994). This issue is outside the scope of this paper;

- kinematic behaviour of diaphragms in the plane at the first natural frequencies. This check permits classifying the predominant motion of the diaphragm as: translation (Fig. 2e), rotation with rotation centre outside the envelope of the structure [in the following: RCO (Fig. 2f)], and rotation with rotation centre inside the envelope of the structure [in the following: RCI (Fig. 2g)]. A desirable structural behaviour during a seismic event is usually characterised mainly by translations and eventually by RCOs. Semi-rigid diaphragms, or also local structural irregularities, can lead to other types of displacement not related to rigid body kinematics: all these different kinds of behaviour are grouped as ‘other behaviour’;
- behaviour in elevation at the first natural frequencies. This check enables the classification of the behaviour in elevation of the structure as: ‘regular’ [flexional behaviour (Fig. 2h)], ‘irregular - in phase’ (Fig. 2i), and ‘irregular - antiphase’ (Fig. 2j). If one of the previous kinds of behaviour is not assigned then the check is classified as ‘other’. Measurements should be performed (and represented) in correspondence with each level, comprising the ground floor, vertically aligning the sensors (if possible).

The checks of the above-listed features are performed using the KCC method, described in section 2.2.1. Section 2.2.2. illustrates how to plan the sensor positioning for multiple applications of the KCC method. Finally, starting from the acquired measures, sections from 2.2.3. to 2.2.6. show the procedures of multiple applications of the KCC for the CheckIn checks illustrated in Fig. 2.

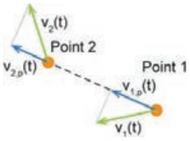
2.2.1. Method of the kinematic coupling characterisation

The KCC method aims at analysing ambient vibration signals recorded synchronously at two points of a structure. Considering these two points as virtually linked through a connection, the purpose of KCC method is to provide a procedure for characterising the type of coupling of the two points in terms of rigidity degree of the connection, and of motion typology, distinguishing between horizontal and vertical connections.

Firstly, the method characterises the rigidity degree of the connection. Within the KCC method, the rigid condition is intended as a ‘practical rigidity’, which satisfies the theoretical definition of rigidity (i.e. two points of a rigid body must have velocity vectors with equal norm and sense if projected along with the joining orientation) with a predefined tolerance. Details are described in Grimaz and Malisan (2022). The rigidity check of the connection (in the following, this check is referred to as ‘KCC-c’) is defined through three classes of coupling degree: rigid, semi-rigid, and non-rigid classes. To carry out this classification, the KCC-c method uses the synchronised measurements of velocity acquired in two points and further projected along the conjunction direction between the two points, i.e. $v_{1,p}(t)$ and $v_{2,p}(t)$. These measurements are compared at each sampling instant t, and for each instant the Type of Instantaneous Relative Motion (TIRM) is classified using the definitions in Table 1, distinguishing:

- concordant and similar: if, at a specific instant t, the two projected velocity vectors have the same sign and similar values;
- discordant: if, at a specific instant t, the two projected velocity vectors have an opposite sign;
- other: all the other cases.

Table 1 - Criteria for the definition of the types of relative motion and reference scheme of two points with velocity vectors.

Type of relative motion	Assignment criteria	Reference scheme
Concordant and similar	$\text{sign}[v_{1,p}(t)] = \text{sign}[v_{2,p}(t)]$ $\wedge$ $\lvert v_{2,p}(t) - v_{1,p}(t) \rvert \leq 0.2 \cdot \min[\lvert v_{1,p}(t) \rvert, \lvert v_{2,p}(t) \rvert]$	
Discordant	$\text{sign}[v_{1,p}(t)] \neq \text{sign}[v_{2,p}(t)]$	
Other	$\text{sign}[v_{1,p}(t)] = \text{sign}[v_{2,p}(t)]$ $\wedge$ $\lvert v_{2,p}(t) - v_{1,p}(t) \rvert > 0.2 \cdot \min[\lvert v_{1,p}(t) \rvert, \lvert v_{2,p}(t) \rvert]$	

Then, considering the distribution of the TIRM values for the analysed couple, the threshold values of Table 2 are used to assign the class of coupling degree. The values in Table 2 were defined empirically and calibrated through the study of well-known real situations (see Grimaz and Malisan, 2022, and references therein).

If the points are on the same diaphragm (horizontal connection), the KCC-h (where 'h' stands for 'horizontal') method evaluates the relative behaviour in correspondence with the main natural frequencies. This step needs the analysis of measurements in the frequency domain and it is based on the comparison of mode shape vectors. The KCC-h method studies senses and amplitudes of the projected mode shape vectors for each natural frequency to check if the connector motion refers to a translation, a rotation, or another relative motion. The method was defined and calibrated thanks to empirical data acquired in 39 buildings within the ASSESS (Grimaz *et al.*, 2016), Edifici Sentinella (Edifici Sentinella project, 2019), and Armonia (ARMONIA project, 2020) projects.

If the two points are on different floors and are almost vertically aligned (vertical connection), the KCC-v ('vertical') method can be applied to characterise the vertical behaviour for the main natural frequencies. The vertical behaviour of a couple of measurements can be either 'in phase' (with potential different amplitudes) or 'in phase opposition'.

Table 2 - Percentage thresholds for the definition of the coupling degree classes of a connection (from Grimaz and Malisan, 2022).

Ranges thresholds		**TIRM% of concordant and similar**		
		> 40%	**20-40%**	**< 20%**
TIRM% of discordant	< 5%	Rigid	Rigid	Semi-rigid
	5-15%	Rigid	Semi-rigid	Non-rigid
	> 15%	Semi-rigid	Non-rigid	Non-rigid

2.2.2. Sensor positions for multiple KCC applications

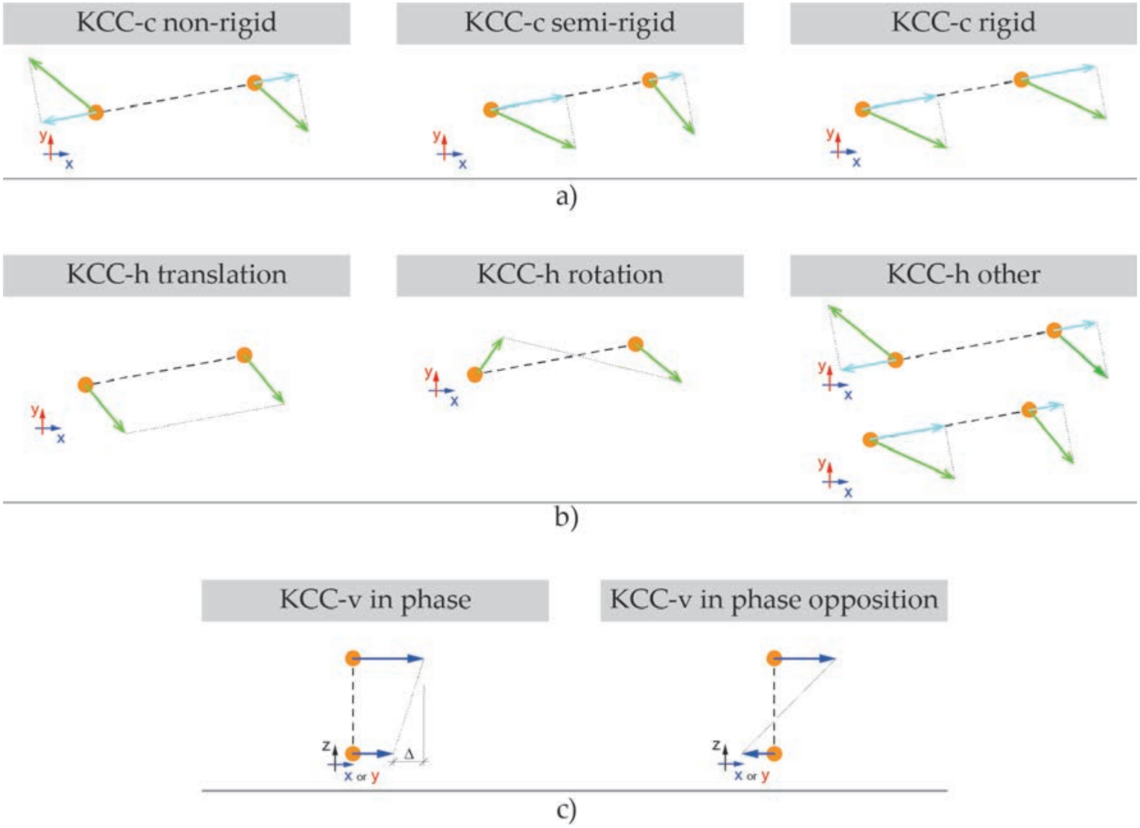
The planning of sensor positions is crucial to correctly investigate the susceptibility of the structure to the pre-codified critical behaviour. This operation is necessary to improve the efficacy of the measurement phase. The number of series of synchronised measures depends on the hypothesised conceptual model and on the complexity of the structure: every specific series is associated with one or more kinds of behaviour to be checked (or verified). One general rule is maximising the signal-to-noise ratio by placing, when possible, the sensors on the highest floor. Furthermore, sensors should be placed close to vertical structural elements to reduce the influence of the vertical motion of the diaphragm on the measure. Table 3 summarises the suggested criteria for positioning the sensors for multiple KCC analyses, starting from the hypotheses to check.

The availability of a limited number of sensors should also be considered. This sets a binding clause for the planning of the measurement campaign; a strategy to overcome this limitation is placing a sensor in a fixed place and using it as a reference to compare and scale the measurements of the other sensors [for a detailed description see Rainieri and Fabbrocino (2014)]. CheckIn methodology requires at least two three-component sensors, but it is preferable to use more to speed up the measurement phase.

Finally, another essential aspect to consider for sensors positioning is the coherence in the direction of all sensors. As a rule, it is suggested to use one of the main directions of the building plan as the orientation direction of the sensor.

Table 3 - Criteria for positioning the sensors to check the formulated hypothesis.

Hypothesis to check		**Suggested positioning of sensors to apply CheckIn methodology**
In plan	Presence of disjunctions	• At the opposite side of the disjunction • On the last highest floor to maximise the signal-to-noise ratio
	Rigid diaphragm	• Spaced on the diaphragm area • On the last highest floor to maximise the signal-to-noise ratio
	Translation kinematic behaviour RCO kinematic behaviour RCI kinematic behaviour	• One or more sensors at the plan extremities, possibly creating a diagonal between two opposite vertexes • One sensor near the hypothesised rotation centre of the diaphragm • On the last highest floor to maximise the signal-to-noise ratio
	Local behaviour due to plan shape irregularities (e.g. L, H, E, T, or elongated shapes)	• One sensor in the main structural body • One or more sensors at the extremities of the protruding elements • On the last highest floor to maximise the signal-to-noise ratio
	Irregular behaviour caused by large voids in the diaphragm	• At the opposite sides of the void
In elevation	Regular behaviour	• One sensor on each floor, near the vertical structural elements • All sensors have to be aligned in elevation
	Irregular - in phase behaviour	• If the soft storey concerns the entire floor: one sensor on each floor, near the vertical structural elements and closed to the centre of the diaphragm • If the soft storey concerns part of the plan (e.g. portico), two vertical series are suggested: one including the portico area and one on the other side • All sensors have to be aligned in elevation
	Irregular - antiphase behaviour	• One sensor on each floor, near the vertical structural elements and possibly near the centre of rigidity • All sensors have to be aligned in elevation



KCC-c non-rigid

KCC-c semi-rigid

KCC-c rigid

KCC-h translation

KCC-h rotation

KCC-h other

KCC-v in phase

KCC-v in phase opposition

Fig. 3 - Schematic representation of the KCC analyses: a) KCC-c for the rigidity of the connection; b) KCC-h for the rigid 'horizontal' motion of the connection; c) KCC-v for the 'vertical' motion of the connection.

2.2.3. Check of disjunctions

The first check of the methodology concerns the presence of the presumed disjunctions among different structural parts. This check is done by positioning one or more couples of synchronised measurements on the opposite sides of the disjunction (possibly quite close to each other). The signals are analysed using the KCC-c method: if the outcome indicates the presence of semi-rigid or non-rigid coupling between the two points, then, the two parts could be considered disjunct.

2.2.4. Check of the rigidity of horizontal diaphragms

The second check of the methodology concerns the rigidity degree of horizontal diaphragms. This check is done by analysing a series of points at the same level through the application of the KCC-c method to all the couples. Operatively, the check of rigidity requires at least one couple of synchronised measurements; more reliable results can, however, be obtained with a larger number of couples. The in-plane checks of the diaphragm rigidity are:

1. rigid diaphragm: if all the KCC-c connections between the couples of measurements are rigid;
2. non-rigid (deformable) diaphragm: if there are one or more non-rigid KCC-c connections;
3. semi-rigid diaphragm: in all other cases.

In the case of a rigid diaphragm, points should move coherently according to the motion of the entire floor, and maintain the same relative distances over time. The presence of a non-rigid (deformable) diaphragm implies that different points can move independently, requiring different evaluation approaches. Between these two situations, a semi-rigid condition can be identified, in which some in-plane deformations of the diaphragm should be considered. This happens especially in structures characterised by irregular shapes (such as L-, T-, or C-shape) or buildings with long and narrow plans or with end walls (Moon and Lee, 1994). It is useful to underline that the rigidity of a diaphragm is usually quickly assessed by identifying its structural typology. However, complex floor shapes or large voids may affect the diaphragm stiffness in its plane so that it is not possible to assume the rigid behaviour among all the points of the floor; in this case, there could be areas in which stresses during an earthquake are unexpectedly exacerbated, leading to damage increase.

2.2.5. Check of kinematic behaviour of diaphragms in plane at the first natural frequencies

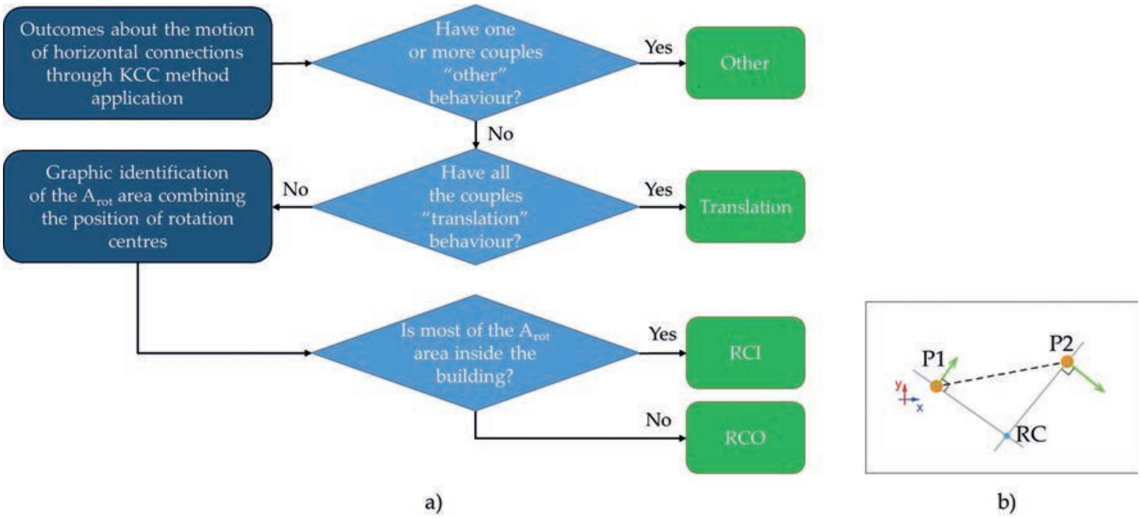
The main dynamical characteristics of a structure are analysed through the application of frequency-domain analyses of the ambient vibration signals, which permit identifying the natural frequencies and the mode shape vectors by evaluating the measurements of each series.

The application of Windowed Discrete Fourier Transform [WDFT: Sherlock (1999)], coherence analysis (Bendat and Piersol, 2013), Singular Value Decomposition [SVD: Rainieri and Fabbrocino (2014)], and frequency domain decomposition [FDD: Brincker and Ventura (2015)] methods allow obtaining:

- amplitude spectrum of the signals (calculated for the three components of the signal acquired in each point) for the identification of the natural frequencies through the peak picking (SVD can be used to improve the results in case of close natural frequencies);
- phase spectrum, to estimate if the couples of measuring points are ‘in phase’ or ‘in phase opposition’ in correspondence to the natural frequencies;
- coherence graph, to confirm the effectiveness of the evaluation. Coherence values close to unity indicate the frequency values in which the two signals are ‘in phase’, conversely, the more the coherence value is close to zero, the more the signals are ‘in phase opposition’;
- plot of the building diagram with the mode shape vectors, to show how the diaphragm behaves;
- plot of the in-plane motion of the measured points through the confidence ellipse calculated for the horizontal projection of the particle motion (Brincker and Ventura, 2015; Caselles *et al.*, 2015).

The above evaluations are summarised by the assignment of the kinematic behaviour to the horizontal diaphragm. This assignment is calculated according to the flowchart in Fig. 4a:

1. application of the KCC-h method to all the couples of measurements of the series;
2. assignment of the ‘other’ kinematic behaviour. If the KCC-h outcome of one or more couples is ‘other’, then, the kinematic behaviour of the diaphragm is ‘other’, since the rigid behaviour of the diaphragm could be not satisfied;
3. assignment of the translation kinematic behaviour. If all the KCC-h outcomes are ‘translation’, then, the translation kinematic behaviour is checked also for the entire diaphragm;



a) b)

Fig. 4 - a) Flow-chart for checking pre-codified horizontal kinematic behaviour; b) identification of the rotation centre (RC).

4. assignment of the rotation kinematic behaviours. This step is performed when the kinematic behaviour is predominantly rotational, and it is necessary to estimate the position of the rotation centre. The theoretical position of the rotation centre of the floor is defined by considering the couples that have a rotation motion, and their position of the rotation centre (as the intersection between the directions perpendicular to the motion of the points, Fig. 4b). The combination (envelope) of all these points allows identifying the area (Arot) in which the rotation centre of the diaphragm is located. If most of this area is inside the building, then, the behaviour is RCI. Otherwise, it is an RCO behaviour.

If a kinematic behaviour is assigned at a certain step, the analysis stops; otherwise, it continues with the next step.

2.2.6. Check of in elevation behaviour at the first natural frequencies

The behaviour in elevation of the structure is checked using a series of sensors located at different floors of the building and possibly vertically aligned. Fig. 5a summarises the criteria and steps for the check:

1. application of the KCC-v method to all the couples of measurements of the series;
2. assignment of 'irregular - antiphase' behaviour. If the KCC-v outcome of one or more couples is 'in phase opposition', then the kinematic behaviour of the vertical line is 'irregular - antiphase', since there exists at least one change of phase in the mode shape vectors. The couple at the lower level is excluded from this step of analysis if it considers a measurement on the ground floor;
3. the amplitude difference calculated by the KCC-v method is used to evaluate a tentative indicator of the floor rigidity. Fig. 5b illustrates a scheme for the calculation, where Δ_1 and Δ_2 represent the amplitude differences of two subsequent couples; h_1 and h_2 represent the inter-storey heights; and, $\alpha_1 = \mathrm{atan}(h_1/\Delta_1)$ and $\alpha_2 = \mathrm{atan}(h_2/\Delta_2)$.

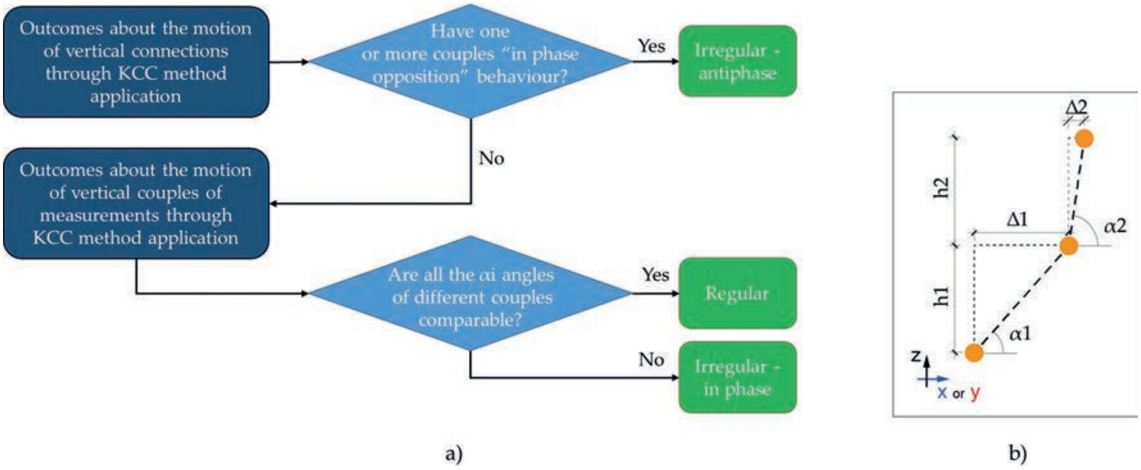


Fig. 5 - a) KCC-v flowchart for checking pre-codified vertical kinematic behaviour; b) scheme for the definition of the parameters for the KCC-v calculations.

4. assignment of 'regular' behaviour. If all the α_i angles are comparable, then, the 'regular' behaviour in elevation is checked;
5. assignment of 'irregular - in phase' behaviour in all other cases.

2.3. Integrated evaluation for site-building system

The integrated check of the site and building is useful to assess the potential presence of site-structure resonance. If the natural frequencies of the site and of the building are close to each other, it is possible to assign a warning of potential resonance for the site-building system. Moreover, resonance is also assigned when the fundamental frequency of the site is a little lower than the building's natural frequencies; in fact, in this case, if the building sustains damage after an earthquake its frequency decreases, thus leading to the potential synchronisation of frequencies between the site and the damaged structure. The assessment of the resonance of the site-building system is important for the definition of DRR strategies in case of a seismic event, since it can lead to a relevant increment of the damage if compared to situations without site-structure resonance, as has been previously widely documented (see, e.g. Lang *et al.*, 2011; Panzera *et al.*, 2018; Mayoral *et al.*, 2019).

3. Applications

In the following, the applications of the CheckIn methodology on real cases are illustrated. The ambient vibrations were acquired using four recording stations comprising a Lennartz LE 3Dlite-1s seismometer (eigenfrequency: 1 Hz, upper frequency: 100 Hz) with three orthogonal components, and a Sara SL06 seismograph connected to a GPS sensor. Stations were also connected through a wireless network, to ensure synchronisation. Signals have been acquired with a sampling frequency of 150 Hz. The minimum recording time was 10 min. for each series.

The case studies presented are characterised by buildings with a maximum of three above-ground floors and plan dimensions < 35 m, with different types of bearing structure (i.e. masonry walls, masonry walls and reinforced concrete frame and walls, reinforced concrete frame). The measurements were conducted during the ARMONIA project (ARMONIA project, 2020). The campaign measurement for each case study required between four to five hours (comprising the hypothesis formulation through desk analysis, visual inspection, measures execution, and interpretation).

The analyses regarding the first case study are presented in detail, in order to explain step-by-step the elaboration process, while in the other cases only significant results are presented and commented.

3.1. Tricesimo town hall

Tricesimo (Udine province) is a municipality located in the Friuli Venezia Giulia region, NE of Italy. The site of the Tricesimo town hall, i.e. the considered case study, is located in a Morainic Amphitheatre (Zanferrari *et al.*, 2008), and previous geological investigations refer to the presence of a stiff subsoil (deeper than 35 m, i.e. the depth of a direct geophysical prospection). The Tricesimo town hall (Fig. 6a) is located in the middle of the town, facing a small square. The town hall was built between 1914 and 1924. It has a masonry-wall load-bearing structure and has a basement, three above-ground floors, and an attic, accessible for maintenance only (Fig. 6b). A portico spanning half of the ground floor characterises the structure. At the time of the construction, the overall horizontal stiffness of the portico's columns was notably lower than the one of the walls, therefore, causing an irregular distribution of stiffness on the plan and at the

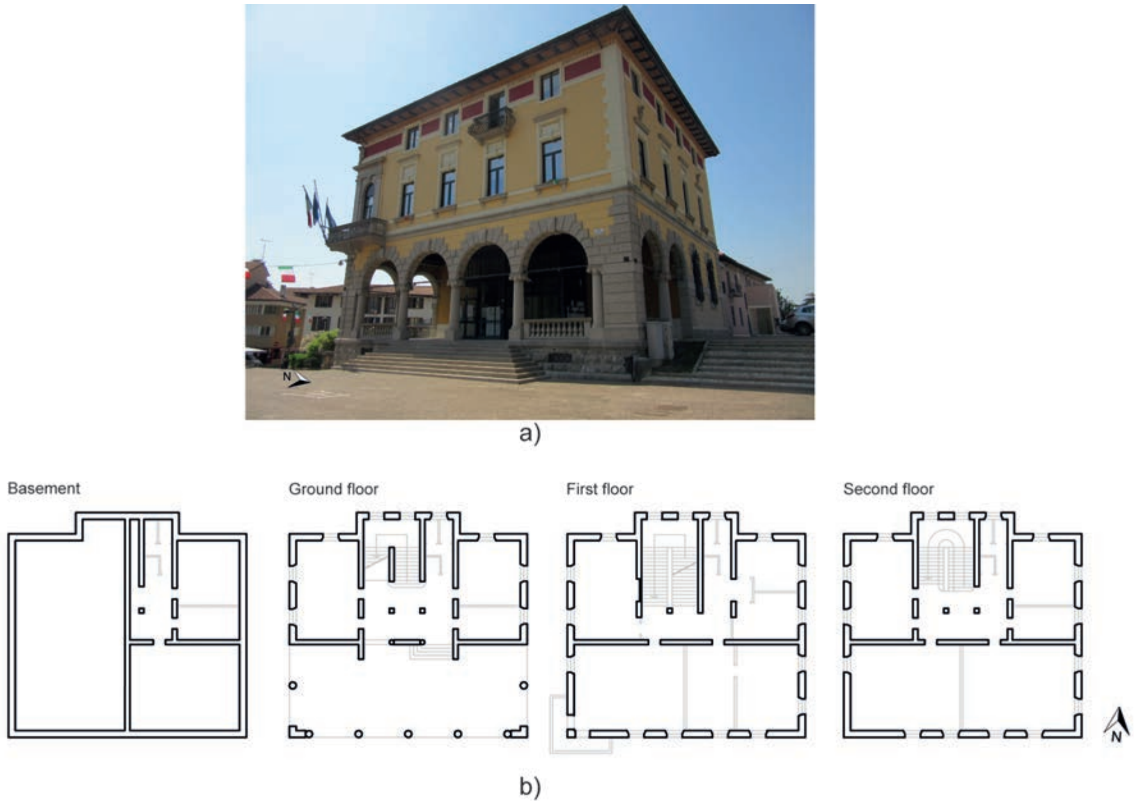


Fig. 6 - a) photo of the *façade* of Tricesimo town hall; b) plans of the building.

same time a soft storey effect at the ground floor. The 1976 Friuli (NE of Italy) earthquake [M_w = 6.4 (Slejko, 2018), with epicentre at about 10-15 km from Tricesimo (D'Amico *et al.*, 2020)] caused damage to the structure, which was consequently retrofitted in 1980-1981. Reinforced concrete frames and walls were added to improve the seismic resistance of the structure and reduce the influence of the soft storey and rotational effects of the upper floors.

Considering the above-described information, the CheckIn methodology was applied also with diagnostic purposes to verify the effectiveness of the retrofitting interventions. Specifically, the methodology aimed at checking the reduced or removed influence of the rotational effects obtained by the retrofit.

3.1.1. Hypothesis formulation

Considering the information acquired during the desk analysis and the *in-situ* preliminary survey, the susceptibility to potential amplification at low frequencies, or even no amplification (since the soil is classified as stiff), was hypothesised for the site. Moreover, since the topographic and geological conditions in the Morainic Amphitheatre could change even at small distances, the subsoil conditions were hypothesised as not 1D.

For the building, the hypothesised behaviour was: rigid slab, translation (or at least RCO) horizontal behaviour in correspondence of the first natural frequencies, and an almost regular behaviour in elevation. These assumptions were hypothesised because of the presence of structural retrofit interventions.

3.1.2. CheckIn application

Considering the formulated hypothesis, the measurements for the site were made in the square in front of the town hall (Fig. 7a). Three measurements were done in the square, to check the potential presence of local site variations. For the building, two series of contemporary and synchronised measurements were designed:

- series 1: three sensors were positioned along a diagonal on the second (and highest accessible) floor, aiming to check the slab rigidity degree and the horizontal kinematic behaviour (Fig. 7b). The analysis of this series aimed at estimating the first natural frequencies and checking the hypothesised critical behaviour. The point in the middle was expected to present low displacements with a dominant RCI behaviour, while the external points should have shown larger displacements;

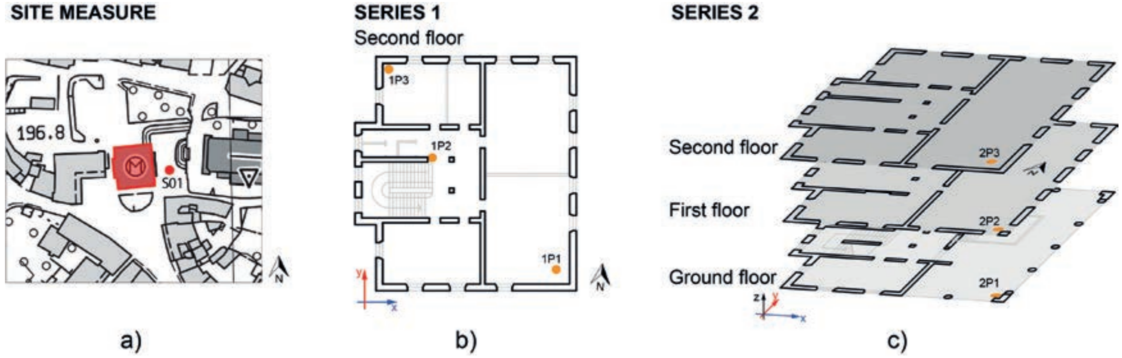


Fig. 7 - a) S01 measurement in the site; b) series 1; c) series 2 of synchronised ambient vibration measurements.

- series 2: three sensors were placed along a vertical line on three different above-ground floors, to investigate the vertical behaviour of the building and the possible influence of the portico (Fig. 7c).

A fourth sensor was placed on the ground, near the building to check both the presence of soil-building resonance and the presence of coloured signals.

Fig. 8a shows the HVSR curves calculated for the site in point S01. It can be observed that the curves do not show peaks ascribable to site amplification of ground motion, thus confirming the formulated hypothesis. Moreover, the rotational spectra of the site measurement did not reveal significant variations, suggesting that locally the 1D condition can be assumed.

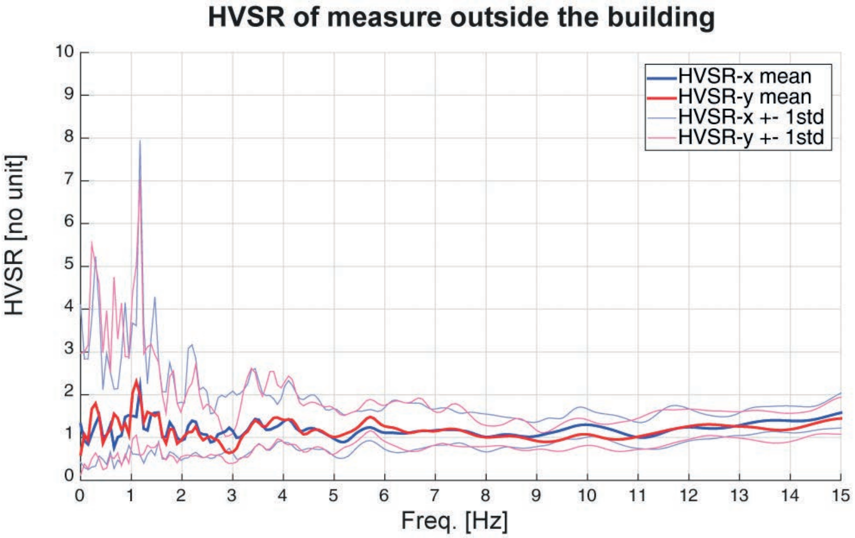


Fig. 8 - HVSR curves of the measurement performed on the site (square in front of the town hall).

For the check of the diaphragm rigidity degree, the CheckIn methodology was applied with the measurements of series 1. Fig. 9 illustrates the TIRM distributions for each couple of measurement points. These distributions confirm that all connections fulfil the rigid behaviour hypothesis, so the floor can be considered rigid.

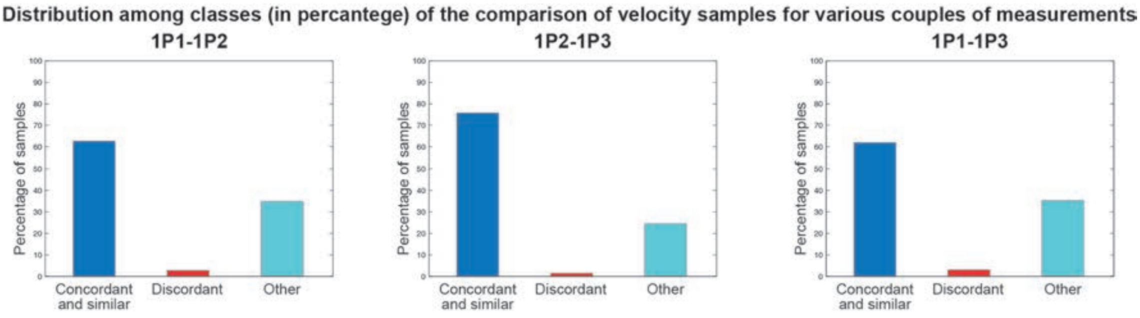


Fig. 9 - Result of KCC-c method: distribution of the TIRM values for the couples of measurement points.

The check of in-plane behaviour, using the measurements of series 1 allowed us to calculate:

- amplitude spectrum (Fig. 10). From the graph, it is possible to identify the natural frequencies of the structure (about 4.5, 4.8, and 6.0 Hz);

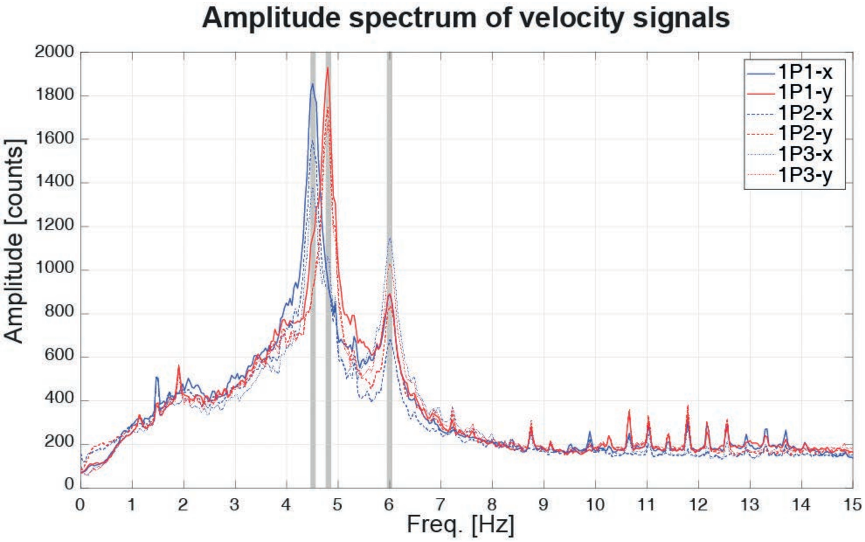


Fig. 10 - Average amplitude spectra of the points in series 1. The light grey bands highlight the identified natural frequencies.

- phase spectrum (Fig. 11). In correspondence with the identified natural frequencies, an integrated analysis considering the amplitude spectra of the different points and phase differences among them enables outlining an initial idea of the global behaviour of the structure;

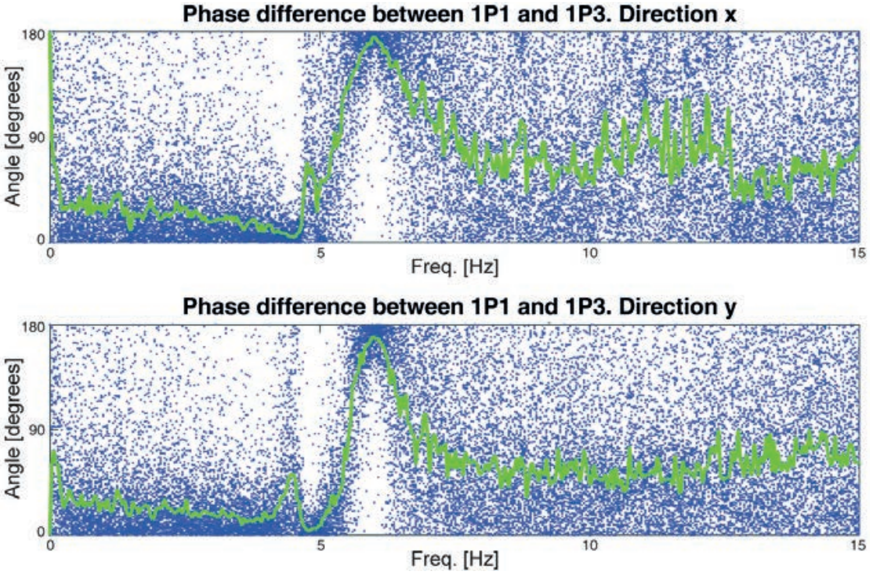


Fig. 11 - Distribution graph of the phase difference between 1P1 and 1P3 measurement points with the representation of the median value (green line).

- coherence graph (Fig. 12). The coherence values are represented for all the couples along with the three directions. In the graphs, the natural frequencies, previously identified, are indicated by grey bands. It is possible to observe that the outcomes reflect the phase difference outcomes;

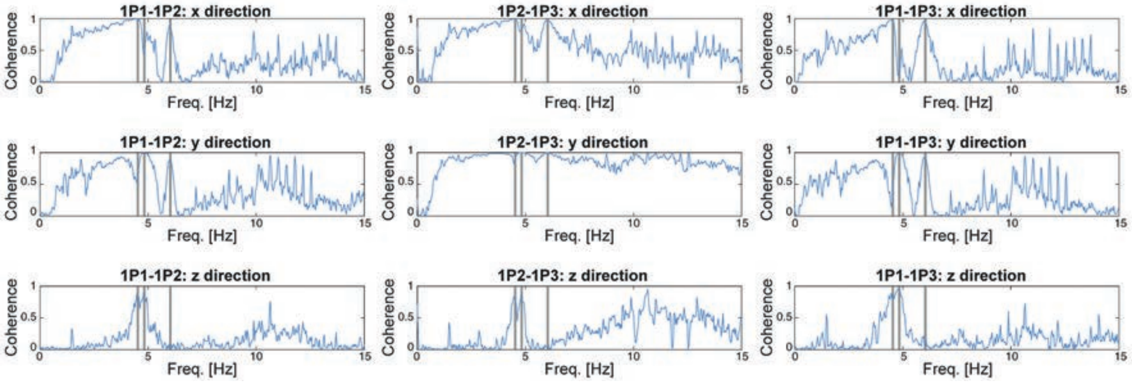


Fig. 12 - Coherence graphs for series 1. The light grey bands highlight the identified natural frequencies of the building.

- plot of the building diagram with the mode shape vectors. The representation of the calculated mode shape vectors (Fig. 13) allows an understanding of how the points move, relative to each other;

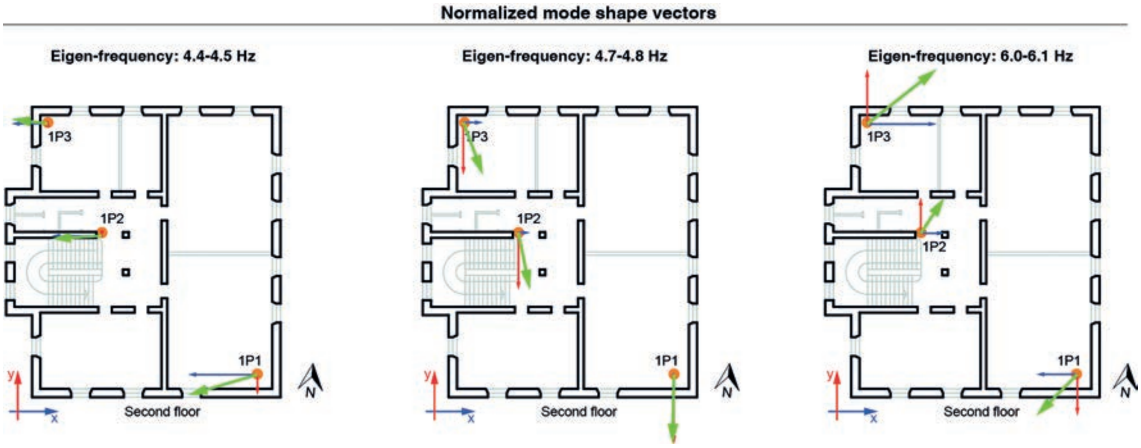


Fig. 13 - Mode shape vectors for all the measurements at the different natural frequencies.

- plot of the in-plane motion of the measured points in correspondence with each natural frequency (Fig. 14a). The displacement signal is filtered and the 2D particle motion of the filtered signal is represented together with its confidence ellipse.

The hypothesised behaviour in correspondence of each natural frequency was checked using the KCC-h method. The outcomes and the rules previously illustrated enable checking the

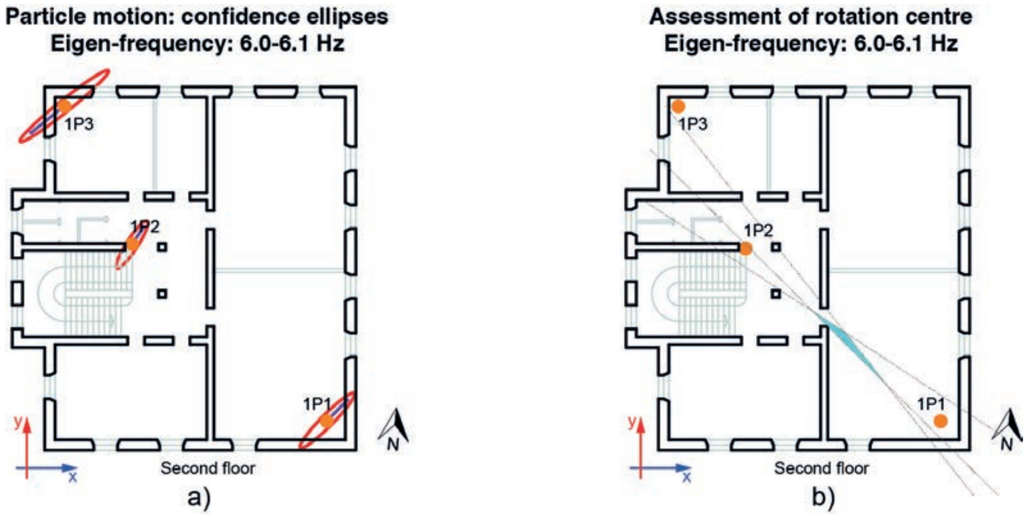


Fig. 14 - a) Confidence ellipses for the kinematic behaviour associated with the third natural frequency; b) area of the rotation centre (light-blue).

following behaviour:

- 4.4-4.5 Hz: RCO;
- 4.7-4.8 Hz: translation;
- 6.0-6.1 Hz: RCI; Fig. 14b shows the area in which the rotation centre is located.

The behaviour in elevation of the building was checked using the measurements of series 2. Fig. 15 shows the moderate influence of the portico on vertical behaviour. Relative motion between the ground and first floor is rather higher than the one evaluated between the first and second floor, and the slope difference is slightly higher than the threshold value. The application of the KCC-v and of the flowchart in Fig. 5a allows recognising this situation as an 'irregular - in phase' behaviour due to different stiffness in the height.

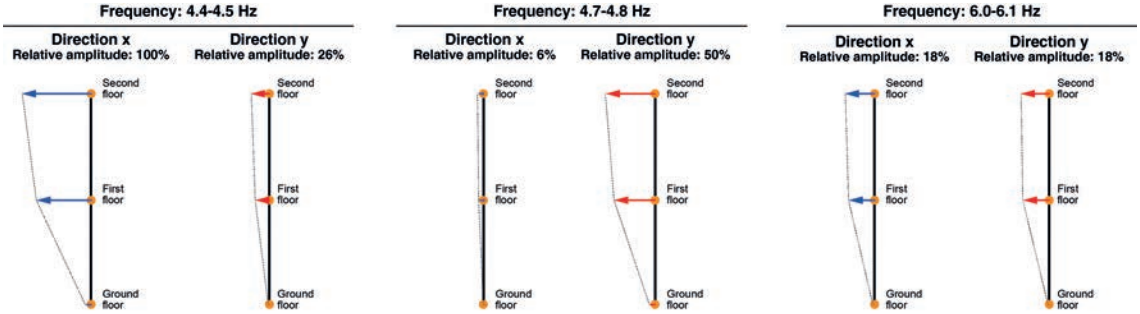


Fig. 15 - Vertical behaviour in correspondence to the normal frequencies.

For the site-building system integrated behaviour, the comparison of the HVSR graph (Fig. 8) with the amplitude spectra of the building (Fig. 10) leads to excluding the hypothesis of site-structure resonance.

3.1.3. Results

The outcomes of CheckIn methodology applied to the Tricesimo town hall show that the site-building system does not have resonance critical behaviour and further that the site should not strongly amplify the seismic ground motion. Moreover, the checks demonstrate that a torsional behaviour exists in the building response, but it should not be predominant in the overall response of the structure considering the RCO and translational behaviour associated to the first two natural frequencies. Moreover, a slight soft-storey effect is present even after the retrofitting interventions. The checks allow, therefore, to conclude that the structural retrofit intervention allowed to reduce, but not to remove, the irregular effects of the building that caused the damage during the 1976 Friuli earthquake. The CheckIn methodology in Tricesimo was applied in a short time (less than half a day), confirming its rapid applicability.

3.2. Cordenons town hall

Cordenons (Pordenone province) is a municipality in the west of Friuli Venezia Giulia Region. The geomorphological characteristics of the area indicate the presence of a deep (> 100 m) cover of Quaternary deposits, with the potential presence of silt and clay lenses. The town hall was built between the 1960s and 1970s. It is composed of two adjacent structural units and the main unit has three above-ground floors (ground, first, and second) and a basement (Fig. 16a). The structure of the building is mainly made up of a reinforced concrete frame. A singular feature is represented by a large void in the middle of the first and the second floor that could affect their horizontal rigidity.

The main objective of the application of CheckIn methodology was to investigate the influence of the voids in the first and second floors of the building, both in terms of rigidity of the diaphragm and of the in-plane behaviour of the structure. For this reason, only the results for the building are illustrated.

3.2.1. CheckIn application

Preliminary evaluations of the kinematic behaviour of the structure led to hypothesise a response dominated by RCO and RCI modes because of the presence of different structural elements and the voids on the floors. To verify this hypothesis, a series of measurements on the second floor was performed.

The check on the rigidity of the second floor indicated that virtual connections between measurement points that cross the void are semi-rigid (Fig. 16c), therefore it is possible to proceed with the check of the kinematic behaviours.

Regarding the horizontal kinematic behaviour, four natural frequencies were identified from the average amplitude spectra (Fig. 16d). Different kinds of behaviour from modal vectors (Fig. 16e) associated with those frequencies are:

- 3.8-3.9 Hz: RCI;
- 4.3-4.4 Hz: RCO;
- 5.4-5.5 Hz: RCO;
- 7.2-7.3 Hz: RCI.

The first natural frequency is associated with a torsional behaviour, which worsens the seismic response of the structure. None of the first four natural frequencies is associated with a translational behaviour.

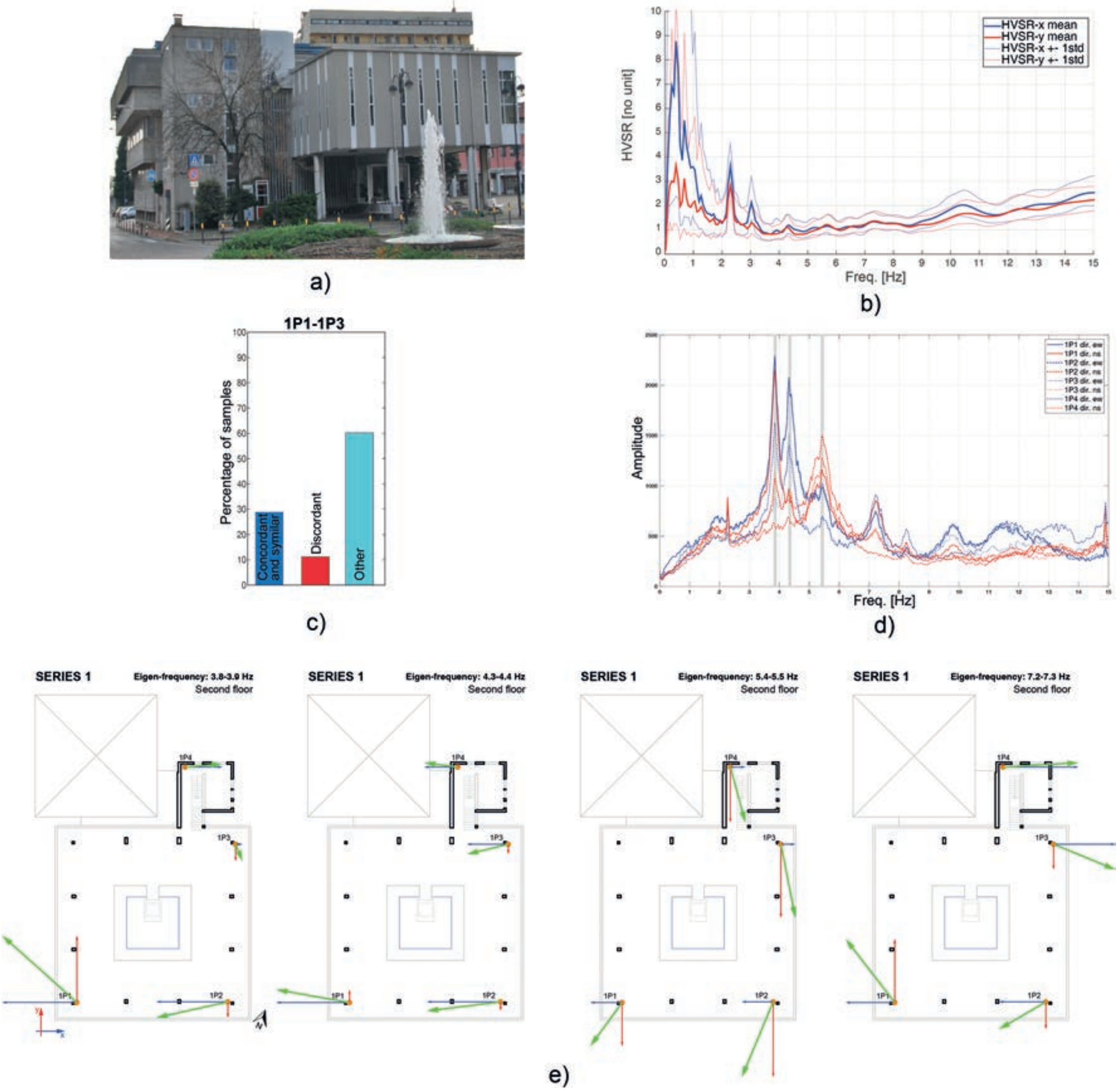


Fig. 16 - a) Photo of the *façade* of Cordenons town-hall; b) HVSR curves for the site measurements; c) percentage of samples distributed in the three rigidity classes; d) average amplitude spectra; e) normalised mode shape vectors for series 1.

The site is characterised by being at the intersection between the alluvial fan and the alluvial plain. HVSR curves (Fig. 16b) show peaks at frequencies lower than 1 Hz (the peak at about 2.3 Hz has an anthropic origin).

3.2.2. Results

The results confirm that the voids influence the rigidity of the diaphragms, which proved to be semi-rigid in their plane. The comparison of the site and building frequencies exclude the possibility of resonance for the site-building system.

3.3. Fogliano Redipuglia town hall

Fogliano Redipuglia (Gorizia province) is a town located in the SE of the Friuli Venezia Giulia region. The site is plane and is characterised as very stiff; therefore, it was supposed to have no peaks in the HVSR curve. The town hall was built between the end of the 19th and the beginning of the 20th century. The building has a masonry-wall load-bearing structure (Fig. 17a) and two above-ground floors (ground and first). The ground plan of the structure is characterised by a ‘C’ shape, denoting an irregularity in the ground plan according to the Italian technical regulations for buildings (Ministero Infrastrutture e Trasporti, 2018).

One of the hypothesised kinds of behaviour to be checked through the application of CheckIn methodology was an irregular response due to the presence of wings.

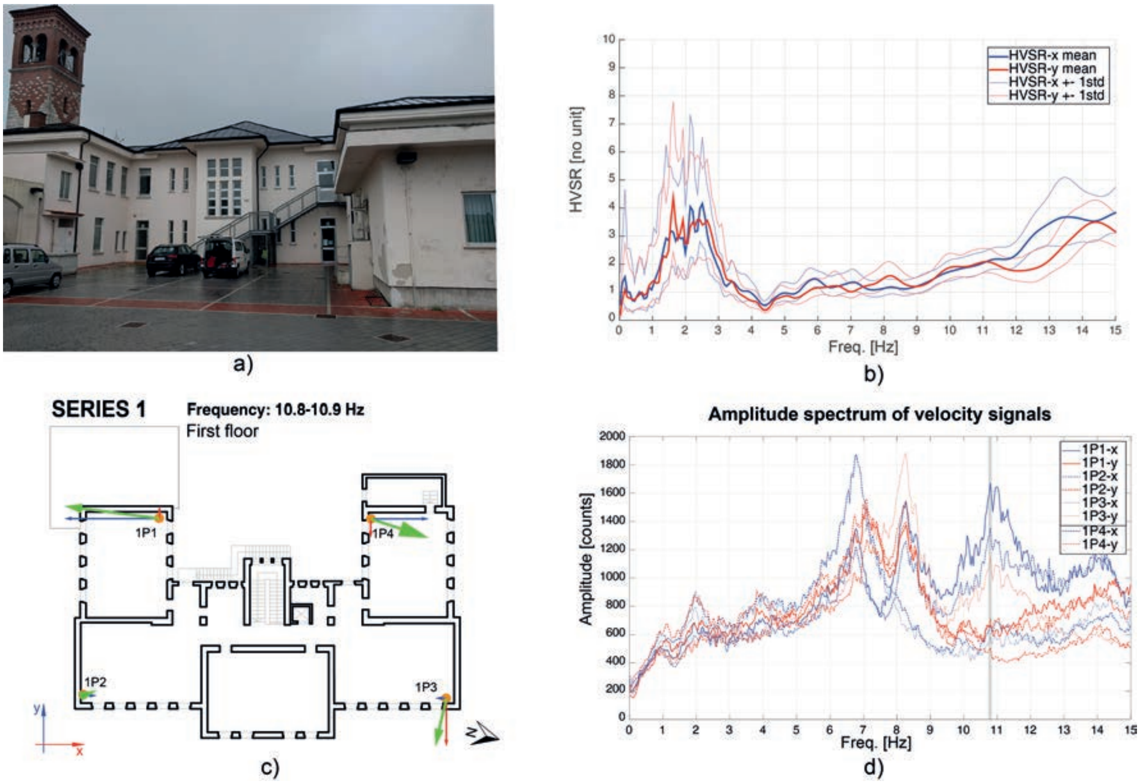


Fig. 17 - a) Photo of the *façade* of Fogliano Redipuglia town hall; b) HVSR curves for the site measurement; c) normalised mode shape vectors at 10.8 Hz, referring to the irregular behaviour of the wings; d) amplitude spectra relative to series 1.

3.3.1. CheckIn application

The ambient vibration measurements for the site revealed the presence of peaks in the range of 1.5 to 2.5 Hz, with a significant amplitude (about 3-4). This indicated the expected presence of an impedance contrast in depth. For the building, considering the presence of wings, an in-plane behaviour identified as ‘other behaviour’ was expected after preliminary hypotheses formulation. However, since the structure is quite small (only two floors), the influence of the wings should not be predominant considering the overall behaviour of the structure. Average amplitude spectra and mode shape vectors referring to the horizontal behaviour at 10.8 Hz (Figs. 17b and 17c, respectively) demonstrated that the hypothesised local behaviour associated with the wings is checked, but it is not associated with the first natural frequencies.

3.3.2. Results

The outcomes of CheckIn methodology confirm the hypothesis of the susceptibility to an irregular response due to the shape of the building. The comparison of the frequencies of the building and of the site indicates that there should be no resonance of the site-building system.

4. Conclusions

DRR management and resilience improvement aim at limiting and, if possible, avoiding critical consequences for the built environment in the case of adverse events, and in particular in the case of an earthquake. Assessing the susceptibility of a building to critical behaviour is an important issue for defining a contextualised DRR action plan. This paper illustrates the CheckIn methodology that permits to perform a rapid check of the susceptibility to critical behaviour of the site-building system, through the execution of a coordinated and finalised campaign of ambient vibration measurements in both the site and building. The outcomes of the CheckIn methodology can be considered as complementary information of a rapid visual assessment of the building vulnerability. The CheckIn methodology combines an integrated procedure of existing techniques of analysis of ambient vibration measurements (such as HVSR) and signal analysis (WDFT, SVD, coherence analysis, and FDD), with the innovative multiple application of the KCC method.

The CheckIn procedure relies on two main steps: first, the hypotheses formulation about the susceptibility to critical behaviour; second, the check of the hypotheses, through the combined interpretation of sets of ambient vibration measurements appositely designed. In particular, with the CheckIn methodology, it is possible to investigate in an integrated manner the susceptibility to worsening effects in the seismic response of the site-building system, such as:

- structural disjunctions in the building that could cause pounding effects;
- in plane rigidity degree of the slabs;
- the evaluation of the influence of irregularities (e.g. particular shapes of the floors, irregular distributions of stiffness in elevation, voids in the diaphragms);
- the potential double resonance between site and structure.

Moreover, the application of the CheckIn procedure after retrofitting permits checking the effectiveness of interventions, and verifying if the critical behaviour has been removed or reduced. The application of the methodology has been illustrated considering three case studies.

For its use from a DRR perspective, it is worth highlighting the following limitations:

- CheckIn is applicable only for stable sites. The presence of site effects such as liquefaction, near-source effects, landslides, rockfalls, etc. could introduce critical effects not considered by the CheckIn methodology;
- the evaluations are defined through the interpretation of the response in elastic conditions. Therefore, they must be considered as indicators of the susceptibility to specific critical behaviour in the case of a strong earthquake;

- the method does not consider the resistance capacity of the structure but only the behaviour. Buildings with weak structures can have worse responses even if the behaviour is regular.

Finally, it is worth underlining that the CheckIn methodology permits evaluating the susceptibility to specific critical behaviour and is not aimed at the quantitative estimation of the building response or damageability in case of an earthquake. Presented case studies show that, within the above-mentioned limitations, the methodology can provide rapid and cost-effective information to assist the decision-making process of disaster risk reduction in earthquake-prone areas, underlining how the methodology can be used to support physical vulnerability assessments and counter-verifications of the effectiveness of structural interventions.

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Corresponding author: Stefano Grimaz
SPRINT-Lab, Polytechnic Department of Engineering and Architecture, University of Udine, Italy
Via del Cotonificio 114, 33100 Udine, Italy
Phone: +39 0432 558731; e-mail: stefano.grimaz@uniud.it