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The Dialogue between Structural Interventions and Sustainability Criteria in Rating Systems for Cultural Heritage: The Experience of GBC Historic Building

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ABSTRACT

The major disruptive seismic events that have hit Italy in recent years (2009, 2012 and 2016) have started a disciplinary debate regarding the need to tighten up requirements for structural strengthening of structures in historic buildings, in order to avoid the loss of human lives and heritage. The preservation of materials resulting from an increased level of performance would positively affect structural systems, as well as the preservation of historic and cultural values and their transmission to future generations. This article explores the relationship between cultural sustainability and the structural rehabilitation of historic architectures, two key aspects contributing to the achievement of a wider sustainability goal during the restoration and renovation process of historic buildings. The contribution explores how GBC Historic Building®, the first and only rating system assessing and certifying the sustainability level of restoration, rehabilitation, and adaptation of historic constructions, addresses the topics of structural tests and monitoring, as well as reversibility and structural compatibility.

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Diagnosis of structures; historic buildings; rating system; rehabilitation; reversibility; structural compatibility structural strengthening; structural sustainability

1. Introduction

1.1. The concept of cultural sustainability

The theme of sustainability in the preservation of historic buildings (Barthel-Bouchier 2016; Rodwell 2007) and, particularly, of technological solutions used for their restoration (Fabbri 2013; Magrini and Franco 2016; Magrini, Franco, and Guerrini 2015), taking into account their structural nature (Napolano et al. 2015; Pendhari, Kant, and Desai 2008), is an already consolidated topic but still requires the acknowledgment of being in front of a complexity that presumes a positive convergence of several operators at different levels (Rodwell 2003). So far, such complexity has been approached through the specialist's reassuring point of view and through an intensive research focused, on one side, on the study of advanced materials and innovative intervention techniques (Centonze et al. 2016; Monni et al. 2016; Righetti, Borri, and Corradi 2016) and, on the other, on the related calculation models (Ferreira, Costa, and Costa 2015). These investigations have certainly contributed to the progressive overcoming of several problems encountered in some types of structural intervention that have occurred over recent years (Borri et al. 2017). Today, a further qualitative leap with an inter-disciplinary connotation is certainly desirable: providing a deep awareness of the sterility of an analytic and fragmented research, able to go deeper and deeper into the investigation of the infinitely small, while losing sight of the infinitely large, the universe, the totality (Celeste 2009).

Within a sustainability logic, it is also necessary to conceive the consolidation of historical buildings in close relationship with the testimonial legacy that it brings with it, without thereby compromising the actual and potential wealth in the context we are asked to intervene in. If "[s]ustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development [WCED] 1987, p. 41), the call to maintain the "potential" to the benefit of future generations must be read, in this case, in many inter-dependent dimensions: environmental, economic (long-term), social, and, above all, cultural. Therefore, restoration, as a "methodological moment of recognition of the work of art, in its physical dimension and in its dual aesthetic and historical polarity, in view of its transmission to the future" (tr. from Brandi 1977), becomes a sustainable "action" itself, thus measureable through tools and methods that are relevant

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to this context (Boarin, Guglielmino, and Zuppiroli 2014; Castaldo et al. 2017). In fact, the modern understanding of sustainability and restoration arises from the critical attribution of value and from the subsequent need to allow generations in the future to enjoy what has been recognized as a value and what we are benefiting from at present. For this concept, to emancipate in modern terms, the abandonment of a strictly short-term, economic-centered vision of everything a value is attributed to is needed, be it environmental, economic, social, or cultural, in favor of a broader and, above all, a longer-term vision.

During the last decades, some authors have tried to emphasize, with some insistence, how the behaviour of pre-industrial humankind can be claimed as "sustainable" because of their particular attention to raw materials and energy consumption (Salgin et al. 2017). It is often pointed out that the recovery of these behaviours could represent, today, a first step toward a sustainable approach to development (Weber 2013). In reality, it is not really possible to speak of sustainability for pre-industrial humankind, as the use of techniques allowing an actual saving of resources is not motivated by the attribution of value to the resources themselves—in other words, by the need to allow future generations to enjoy the same amount of resources (elements to which a value is recognized) that we can enjoy at present— but from their mere economic determination as a "scarce" resource. On the contrary, a modern understanding of sustainability can occur only when the sustainable action has the purpose of safeguarding the resources to which a value has been recognized, in view of their transmission to the future. In this case as well, they represent two very distant and often contrasting aims. In the past, the need for preservation of resources arose from the scarcity of the same in the present and from recognizing an economic potential in them in the short-term. Today, the preservation of resources is the result of their foreseeable scarcity in the future, although their defence in the present appears to be economically disadvantageous. Similarly, other contributions have emphasized how some construction techniques used in the past have been particularly effective in the case of earthquakes. To this regard, the case of timber frame constructions is worth mentioning (Barucci 1990; Langenbach 2007; Ruggieri 2005). To talk about sustainable construction techniques would be inappropriate in this case as well, because the real effectiveness in the event of an earthquake is not justified by the desire to preserve the built cultural heritage in view of its transmission to the future, but from the interest on the security and protection of people inhabiting it at present.

Therefore, the concept of environmental sustainability qualifies the retention or the safeguarding action in front of an existing potential (or a balance between existing potentials) to which an environmental value has been recognized. The concept of cultural sustainability qualifies the retention or the safeguarding action in front of a pre-existence (or a balance between pre-existences) to which a cultural value has been recognized. It is therefore possible to assert that the modern understanding of restoration identifies a culturally sustainable action of a material witness, to which a cultural value has been recognized.

1.2. Cultural sustainability and structural rehabilitation of built cultural heritage

After the assessment of damages caused by the last major seismic sequence of Amatrice-Visso-Norcia (2016 Central Italy earthquake), with particular reference to the tremors of August 24 and October 26, 2016, and the identification of a significant increase of events with a magnitude equal or higher than 5.0 on a national scale, in this decade, compared to the previous one (Barani et al. 2017; Rovida et al. 2016), the disciplinary conversation is rapidly moving the attention from technological solutions for seismic improvement of unreinforced masonry buildings to the effectiveness of the concept of improvement introduced by the *Guidelines for the evaluation and reduction of seismic risk on Cultural Heritage*, published in 2006 (Ministero per i Beni e le Attività Culturali 2006).

With reference to structural intervention and seismic prevention, the concept of improvement assumes an essentially alternative value to the concept of conformation to pre-defined performance thresholds. If the request to adapt a new or existing building to the society's changed needs cannot be considered unacceptable, especially when it affects physical or environmental safety concerns, the modification of an existing construction may require the consideration of instances of a different nature, such as the testimonial value recognized in the object subject to intervention as being equally relevant. The need to make this value available to future generations often clashes with the impact that the intervention could have on the building itself. In fact, the upgrading activity attempts to find alternative solutions that can lead the pre-existence to a performance improvement within physiologically acceptable limits and in accordance with its substantial characteristics (Dalla Negra 2013):

> *"Overall, so far, the works for seismic safety have not been done with good quality. Usually, these projects did not care about the edifice, that was deliberately neglected, in the myopic belief that it was inadequate from the start; developing the idea that the only possible solution was literally to overlap the pre-existence, by using constructive principles pertinent to new buildings and by adopting, at the very least, unsuitable ways of intervention. The result was catastrophic; considerable parts of the cultural heritage have been lost and cannot be recovered whatsoever. Large amount of resources has been committed often in an ineffective way"* (translated from, *Ministero per i Beni e le Attività Culturali 2006, p. III)*

The disconsolate consideration that Roberto Cecchi and Michele Calvi report in the introduction to the 2006 Guidelines arises from the experience gained in the Italian architectural culture of the 20th century (Calderini 2008) regarding interventions following the recent earthquakes of the '70s, '80s and '90s that helped to reveal the inadequacy of the technologies for structural consolidation and seismic adaptation suggested by technical regulation in the field. In many cases, interventions such as the complete replacement of slabs or timber roofs, the modification of structural behavior of masonry vaults, etc., besides being incompatible from a preservation point of view (regarding the respect for minimum intervention, material and construction compatibility, reversibility, and, above all, material authenticity), contributed to the introduction of elements of excessive rigidity within the historical structure, generally characterized by extreme diversity, creating consequences unforeseen during the design phase.

The substantial criticism of the concept of adaptation included in the national legislation, following the direct experiences and research carried out in the context of the reconstruction of the crater left in the Umbria and Marche regions in 1997, led to a development of the concept of improvement. The notion of improvement started to emerge in parallel with the approval of the Ordinance of the Presidency of Council of Ministries no. 3274/2003 (Presidenza del Consiglio dei Ministri 2003) where the legislation on buildings in the seismic area had been completely updated. In fact, soon after the seismic events, the Italian Ministry of Cultural Heritage recognized the need to modify the legislation body, and particularly some annexes, in order to favor a different approach based on the principle of minimum intervention in historical buildings. It is to be noted that it is possible to achieve such an objective only through a careful and thorough cognitive activity that investigates the intrinsic nature of the product from a formal, material, constructive, and structural point of view, to identify solutions that could increase structural efficiency, respecting the material authenticity of context in which they are implemented. This knowledge is necessary to allow the identification and enhancement of the structure's unexpressed potential and vulnerabilities that will be faced during the intervention. The improvement project can be developed by guaranteeing suitable safety conditions and by allowing suitable solutions to be informed by the actual state of the building, without compromising the existing delicate structural balance with unrelated and poorly compatible technological solutions.

As underlined by Giovanni Carbonara in the introduction to the aforementioned 2006 Guidelines, the new improvement approach allows the definition, for historic buildings, of a "reasonable equivalent security" (translated from, Ministero per i Beni e le Attività Culturali 2006, p VII), without condemning them to the destruction of their qualifying structural characteristics as implicitly mentioned by the technical regulation through the request for adaptation to new requirements. This is an approach that must necessarily be based on comprehensive and detailed analysis of historical and construction aspects, in order to highlight strengths and weaknesses and, therefore, strategies to be implemented during consolidation.

The extensive destruction caused by the earthquake in central Italy in 2016, which particularly concerned buildings of monumental character characterized by significant elements of vulnerability, some of which had been the subject of interventions of seismic improvement after the 1997 earthquake, impose, today, a careful reflection on the need to intervene in a more resolute way but always in the most absolute respect of material authenticity, working by addition and not by subtraction.

This contribution attempts to emphasize the issue of efficiency of the concept of improvement, measured in terms of sustainability, and asks whether the risk of losing everything in the future, even if remote, is acceptable and justifies the renouncement of the preservation of some elements in the present. In other words, the question of how sustainable the concept of improvement is, from a cultural point of view, is asked. In conditions of uncertainty, such as those that characterize historic buildings, the answer seems almost impossible, but it certainly opens towards an unprecedented moment of disciplinary discussion. Actually, in other circumstances, characterized by relative certainty, the question related to the terms of sustainability is not new. The equilibrium of many ecosystems over time is based on the planned extinction of many species that could otherwise lead to the extinction of others. If the maximization of the cultural potential transmitted to future generations represents the ultimate goal of our restoration action, it appears necessary to integrate the "exposed" cultural potential in a more explicit way than has been accomplished so far, in the estimation of the expected damage and, therefore, of the assessment of the improvement level to be achieved. Moreover, under conditions of uncertainty, a careful evaluation of intervention priorities, which, even in the emergency phase, considers the exposure factor, is fundamental. These are complex evaluations under conditions of uncertainty that should be faced in a mathematical way.

2. A new tool for promoting sustainable built cultural heritage preservation: GBC Historic Building®

In recent years, the cultural environment described in the previous paragraphs has had a relevant impact on the debate among academics and professionals operating within the Italian building sector. More than 30% of the existing building stock in Italy was built before the end of World War II and presents today a very poor state of conservation or needs major maintenance works (CRESME 2012). However, considering the achievement of sustainability goals, and energy efficiency among them, existing European and Italian legislation (European Parliament and Council 2010, 2012; Il Presidente della Repubblica 2007) excluded scheduled buildings from the application of any performance requirements, thus missing the opportunity for a widespread and effective strategy on the built environment. At the same time, the conversation between conservationists and those operators of the building sectors working towards the achievement of a balance between the needs of heritage preservation and long-term sustainability was not particularly open and successful. It is within this scenario that, at the beginning of 2012, the Green Building Council of Italy (GBC Italy) decided to start a conversation on this topic, by promoting a holistic approach to consider and integrate social (cultural), environmental and economic sustainability principles.

The GBC Italy is a non-profit organisation whose mission is to promote the transformation of the built environment, advocating for a greener future and a more transparent market by developing and promoting the use of tools, such as LEED® (Leadership in Energy and Environmental Design), to improve the overall quality of constructions from a whole-building perspective and over a building's life cycle. The international experience in driving the building sector towards more sustainable outcomes shows the importance of using tools capable of guiding operators and professionals effectively and pointing them in the right direction. To this regard, rating tools for the assessment and certification of the sustainability level of buildings were developed to respond to the need of defining requirements and to suggest possible approaches to the achievement of such goals, thus defining common metrics and methodologies to measure a performance in a way that is objective and understood across the market (Boarin et al. 2014a). Environmental categories included in the most relevant and internationally recognised rating tools, such as LEED®, BREEAM® and DGNB® (but many other are present all over the world), concern topics such as sustainability of sites, efficient management of resources, optimization of energy and environmental performances, comfort in the indoor environment, use of sustainable materials and implementation of effective management models. These are recurrent topics in the life cycle of a building, from its design to the construction phase and, afterward, its operation and maintenance, and can be described through scientifically sound, objective and transparent criteria. Although the use of sustainability rating tools has become a rather common practice widely accepted by the market for the design and construction of new buildings and the retrofit of existing recent ones, their application to historic buildings has always been discouraged because of the unsuitability of the level of performance sought and for the absence of preservation-related considerations. The definition of criteria, universally recognized, to assess the sustainability of interventions on historic buildings, can become a useful means to measure and, therefore, compare, the impact of such actions, thus promoting a shift towards a culture of transparency throughout all process phases and for the building sector. It is in this context that the GBC Italy decided to take action and to lead, starting from the beginning of 2012, the development of the first third-party certification scheme for orienting and assessing restoration, rehabilitation and adaptation processes on historic buildings, namely GBC Historic Building® (GBC HB) (Green Building Council Italia 2014), in order to support and award those projects targeting sustainability goals in the preservation and renovation process.

At the time, the GBC Italy was already promoting the use of a sustainability rating system that was applicable to existing buildings as well, i.e., Green Building Nuove Costruzioni e Ristrutturazioni (LEED NC 2009 Italia®) (Green Building Council Italia 2011), the adaptation for the Italian market of LEED® Building Design and Construction: New Construction (v3) (LEED® BD + C) (U.S. Green Building Council 2009). However, this existing tool did not include any specific requirements addressing historical and cultural values in the renovation process and was barely used for historic buildings because considered inadequate for their valorization. However, the clear structure, the transparent approach to metrics and performance and the language of LEED NC 2009 Italia® and, more in general, of LEED® BD+ C, were already accepted and used across the construction sector in Italy and those aspects were considered very important to start a positive transformation in the cultural heritage field as well. Therefore, the GBC Italy decided to gather a pool of experts in the green building practice and in the restoration field (more than 70 experts in total) to develop the new GBC HB system, by activating the Technical Advisory Group 'Historic Building' (TAG HB). Similarly to the already existing TAG that developed LEED NC 2009 Italia®, the TAG HB was constituted by representatives from Italian universities and professionals representing the excellence of the Italian building industry, working alongside the technical and certification team of the Italian Association and led by a leadership group that, besides a Chair and a Deputy Chair, involved a scientific advisor in the restoration field and a representative from the Italian Ministry of Cultural Heritage as well, all contributing on a voluntary basis.

The first task of the leadership group was to produce a guideline for the TAG HB where the new protocol's field of application, the main objectives (including the new topics related to the field of restoration to be integrated), the method and phases of the development process were defined, as well as the consultation process with the wider community (Green Building Council Italia 2012). The guideline also included projects' minimum program requirements, i.e. minimum characteristics in order to be eligible for certification under GBC HB. To this regard and similarly to what happens with all existing LEED® and GBC protocols, all aspects regarding the aesthetic/architectural dimension of design are not assessed by the new protocol, nor the tool aims at judging whether the building under evaluation is worth being considered as cultural heritage or worth being preserved. In the latter case particularly, this judgment is the responsibility of relevant competent agencies such as the Italian Ministry of Cultural Heritage.

The TAG HB started its activity with the assessment of LEED NC 2009 Italia® through a gap analysis investigation which involved real case studies to understand the level of applicability of the existing tools to the cultural heritage sector (Boarin 2016). This activity was completed with an assessment of LEED® Building Design and Construction: New Construction (v4), which was later released by the US GBC in 2013 (USGBC 2013). This research led to the decision of proceeding with a re-structure of the certification scheme and the addition of a brand-new credit category, namely "Historic Value" (HV), aimed at collecting all the objectives related to the fulfillment of preservation principles within the building process, with particular attention to the acknowledgment of historic values as sustainability criteria. The new rating system structure and contents means that its applicability is broadened to the building stock constructed before the end of World War II, at the beginning of the post-war reconstruction activity and the rise of the industrialization of the building process in Europe. Being "[...] material testimony having the force of civilization" (Franceschini 1967), this part of the stock is mostly characterized by a pre-industrial building process (in terms of phases, tasks and operators), pre-industrial materials and construction techniques (spontaneous and local) and technical elements mostly made through pre-industrial processes. It is important to note that such definition embraces not only monumental buildings, usually scheduled under cultural heritage lists and subject to verification and approval of renovation intentions by relevant agencies, but widespread traditional buildings as well, usually not scheduled, thus offering a wide range of opportunities for their retrofit. GBC HB is therefore used for designing, assessing and certifying major renovations of historic buildings, whenever the activity involves significant elements of HVAC systems and the renewal or functional reorganization of interior spaces (Boarin 2016).

2.1. Structure of the new rating system

GBC HB follows the same structure of the already existing tools within the LEED® "family" of rating systems, with the addition of the brand-new category 'Historic Value' (HV), as mentioned in the previous paragraph. A set of prerequisites, i.e. mandatory requirements, and credits, i.e. voluntary actions awarded with points, are present in each category, following the typical structure of LEED® protocols. Credit categories of GBC HB are distributed as follows.

- Historic Value (HV) (20 points available): this category looks at the implementation of preservation principles at the different stages of the restoration process, while improving the overall building performances;
- Sustainable Sites (SS) (13 points available): the category awards strategies allowing for the regeneration of damaged areas, minimizing retrofit and building impacts, and promoting alternative transportation;

- Water Efficiency (WE) (8 points available): this encourages a smarter use of water and its preservation, considering indoor, outdoor, and specialized uses, as well as promoting water metering;
- Energy and Atmosphere (EA) (29 points available): this approaches energy performance improvement from a holistic perspective, considering energy efficiency as a protection tool;
- Materials and Resources (MR) (14 points available): this minimizes impacts associated with the extraction, processing, transport, maintenance and disposal of materials, as well as the embodied energy;
- Indoor Environmental Quality (EQ) (16 points available): this aims to achieve high standards of indoor air quality and thermal comfort for occupants;
- Innovation (ID) (6 points available): this rewards design solutions that are distinguished by the characteristics of innovation and high environment performance within the restoration-related process;
- Regional Priority (RP) (4 points available): this encourages design teams to focus on environmental characteristics that are unique and specific to the region in which the building is located.

All prerequisites and credits are organized in sections which provide the user with a clear structure and set of information on: (1) intents; (2) requirements; (3) benefits and issues to consider; (4) related credits; (5) summary of referenced standards; (6) implementation process; (7) timeline and team; (8) calculations; (9) documentation guidance; (10) examples; (11) exemplary performance; (12) regional variations; (13) resources; and (14) definitions. All these sections have been entirely revised and integrated to address sustainability issues in historic buildings' renovation and preservation, defining the new reference guide. Besides the reference guide, all certification forms have been revised and adapted for each of the existing credit categories, and new ones for the credit category HV developed. Among these, a brand-new form for understanding and collecting qualitative and quantitative evidence of the building's historic value has been developed, namely the 'Historic Building Identity Card' (HBIC). The use of the HBIC is required at multiple stages of the process:

- at the beginning, before the design activity starts, to verify whether the building is eligible for certification (i.e., when pre-industrial materials and technical elements represent more than 50% of the existing building fabric);
- during the design phase to establish the project's goals and to orient the activity towards the achievement of the targeted credits and related points, mainly in case the credit has multiple thresholds of performance with a different amount of points associated to them; and
- during the development of the required documentation for the submission for certification, in order to demonstrate compliance with credit requirements.

The sum of points gained through the fulfilment of requirements within the achieved credits (a total of 100 points is available across the credit categories VS, SS, GA, EA, MR and EQ, and a maximum of 10 points is available across ID and RP) will define the final score, which corresponds to the certification level, i.e. (i) "Certified", from 40–49 points; (ii) "Silver", from 50–59 points; (iii) "Gold", from 60–79 points; and (iv) "Platinum", from 80–110 points. The certification process is entirely managed by the GBC Italy which covers both the role of standard setter, i.e. they define the process steps and technical contents, and of certification body. External Accredited Verification Bodies help the GBC Italy with design and construction verifications (including site visits). After construction is completed and all inspections have had positive outcomes, the certification can be awarded.

As all LEED® protocols can achieve a maximum of 110 points across the 7 credit categories, the addition of VS generated the need of re-thinking the weighting allocation for each category and this was done based on the results of the gap analysis. All aspects of the historic building that could be evaluated through existing credits in LEED NC 2009 Italia®, even in case of their partial applicability, were integrated through additions or modifications to the credit itself, in order to preserve the existing structure and language as much as possible. Credits that were considered non-applicable to the cultural heritage context were deleted and their points allocated to the area VS (9 points). The remaining points allocated to VS are derived from a proportional reduction of points across all areas SS, GA, EA, MR and EQ, excluding ID and RP as these two areas have typically 10 points in all LEED® protocols (what changes are the credits in the other categories and the distribution of points per credit) (Boarin 2016). The comparison between the allocation of points and distribution of weightings in the reference tool and in GBC HB is shown in Table 1.

Table 1. Comparison between LEED NC 2009 Italia® and GBC HB in terms of allocation of points and distribution of weightings for each credit category.

	LEED NC 2009 Italia®		GBC HB	
Topic	Points per topic	Topic Weightings [%]	Points per topic	Topic Weightings [%]
Historic Value (HV)	-	-	20	18.2
Sustainable Sites (SS)	26	23.6	13	11.8
Water Efficiency (WE)	10	9.1	8	7.3
Energy and Atmosphere (EA)	35	31.8	29	26.4
Materials and Resources (MR)	14	12.7	14	12.7
Indoor Environmental Quality (EQ)	15	13.6	16	14.5
Innovation (ID)	6	5.5	6	5.5
Regional Priority (RP)	4	3.6	4	3.6
Total	**110**	**100%**	**110**	**100%**

Table 2. Summary of credits within the Historic Value category in GBC HB. In the column for Regional Variations: (c) continental area; (m) mountain area; (s) seaside area.

Prerequisite/Credit	Points allocated	Exemplary performance	Regional variations
Prerequisite 1 – Preliminary analysis	Mandatory	Not eligible	Not eligible
Credit 1.1 – Advanced analysis: energy audit	1–3 points	Not eligible	Eligible (c)
Credit 1.2 – Advanced analysis: diagnostic tests on materials and deterioration	2 points	Not eligible	Not eligible
Credit 1.3 – Advanced analysis: diagnostic tests on structures and structural monitoring	2–3 points	Not eligible	Not eligible
Credit 2 – Project reversibility	1–2 points	Eligible	Eligible (m)
Credit 3.1 – Compatibility of the new use and open community	1–2 points	Eligible	Eligible (m)
Credit 3.2 – Chemical and physical compatibility of mortars	1–2 points	Not eligible	Not eligible
Credit 3.3 – Structural compatibility	2 points	Not eligible	Not eligible
Credit 4 – Sustainable construction site	1 point	Eligible	Not eligible
Credit 5 – Scheduled maintenance plan	2 points	Not eligible	Eligible (s,c)
Credit 6 – Specialist in preservation of buildings and sites	1 point	Not eligible	Not eligible

2.2. The new credit category Historic Value (HV)

The credit category Historic Value is the main innovation of GBC HB, as all prerequisites and credits are brand new (Table 2). This topic focuses on the different stages of the preservation process, i.e. (Boarin, Guglielmino, and Zuppiroli 2014):

- the preliminary investigation phase, asking for a direct study of the building along with a background history research, followed by the degradation analysis (with an interpretation of their causes);
- the project phase, when the building's critical issues are defined and the intervention proposal is developed according to performances and requirements to be achieved and any restoration-related issues; and
- the construction phase, which is the most sensitive stage as almost every operation is irreversible and because the building might reveal new features as soon as the initial demolition and materials removal begin.

Within the context of the new tool and the new credit category, this article focuses on those structural aspects involved in a restoration and retrofit process of historic buildings. As mentioned in the introduction, structural aspects are considered part of the wide sustainability framework and contributing to its attainment. Therefore, this contribution introduces the background, development process and validation method for the following credits:

- Credit 1.3 – *Advanced analysis: diagnostic tests on structures and structural monitoring*, a credit that awards a range of preliminary tests to investigate the building's structural behavior and the structural monitoring after the intervention is complete;
- Credit 2 – *Project reversibility*, a credit that awards the reversibility nature of interventions, including structures;
- Credit 3.3 – *Structural compatibility*, a credit that awards the level of compatibility of structural interventions with the existing building.

Structural interventions considered in this research and in the rating tool are concerned both with the strengthening of existing structures (such as structural repairs due to deteriorations, loads increase, standard compliance, etc.) and with brand new structures introduced by the project (such as staircases, elevators, mezzanine floors, etc.).

The above-mentioned credits are analysed in depth in the following sections, introducing intents, requirements and reference standards, and discussing case studies and examples.

3. Credit HV 1.3 – Advanced analysis: diagnostic tests on structures and structural monitoring

The importance of knowledge in cases of restoration is unanimously recognized. The sector of structural restoration is subject to this logic as well and it actually represents a field of exemplary application, given the structures of a building are not always exposed and fully visible, and a deep investigation becomes therefore necessary for the achievement of effective knowledge. Generally, the diagnosis process is articulated into the following phases:

- geometric survey;
- matrix of structural modifications representing the evolution over time;
- identification of static and resistance mechanisms (global or local, vertical or horizontal actions);
- identification of nature and mechanical properties of structural materials; and
- identification of structural degradation phenomena and failure mechanisms.

Quantitatively, the allocation of points within the credit is related to the level of detail of the investigations, measured through the level of knowledge acquired on structures. The credit analyses and encourages two synergistic aspects of the investigation, i.e.:

- Part 1: Diagnostic investigations on structures (1 or 2 points);
- Part 2: Structural monitoring (1 point).

These two parts, both to be fulfilled, differ by the information they provide or the level of knowledge they allow to be reached, as well as by the phases of the survey they impact: in Part 1, investigations are immediate and produce results just after the investigation occurs, while, in Part 2, the investigation process lasts over time (before the project is implemented) and produces its results only after it is finished (which may even take years). Investigation required to complete Part 1 and Part 2 can be conducted at the same time.

3.1. Part 1: Diagnostic investigation on structures

This category includes all geometric surveys (general and detailed), surveys on materials, collections of useful documents, and *in situ* surveys that, in general, must be conducted before any intervention. The articulation of the credit (except in the case of timber structures) reflects the structure of the Italian legislation for existing buildings (Il Ministro delle Infrastrutture di concerto con il Ministro dell'Interno e con il Capo del Dipartimento della Protezione Civile 2008 and subsequent modifications). In fact, these regulations distinguished the levels of detail by construction type (masonry, steel, reinforced concrete and timber) and, for each case, they set increasing levels of investigations. Of the three levels of knowledge included in the Italian legislation, Credit HV 1.3 assigns zero points to the lower level (named LC1 by the Italian legislation), 1 point to the intermediate level (LC2) and 2 points to the highest level of knowledge (LC3) (Table 3). Surveys on timber structures do not concern buildings built entirely with this material, but they are concerned with cases where the use of such material is limited to parts of the structures, such as floors and roofs.

3.1.1. Example: structural surveys

This credit section includes a wide range of investigative activities. The right mix of investigations changes case by case, but it is generally based on well-known methodologies for each type of material.

In the case of masonry structures, the use of IR thermography provides qualitative information that, constitute a first step for an accurate mapping of walls, to be further supported by the removal of the plaster layer in some areas (if possible). In a second step, endoscopic equipment, sound tomography, or ground penetrating radar (GPR) may be useful. These tests are followed, generally, by additional tests, such as single- and double-flat jacks, chemical analyses on mortars and bricks, sclerometric or penetrometric tests on mortars, and crush tests on bricks or blocks. Of these tests, the diagonal compression test is the most destructive. In the case of reinforced concrete and steel structures, direct rupture tests on samples are performed (concrete compression and steel traction). In order to extend the results of the direct tests, other indirect tests are also important, such as the SON-REB tests, the pull-out tests, the Windsor probe on the concrete, the hardness tests (Leeb) or spectrometric analysis on the bars of steel. Tools such as pachometers are also very useful for determining the structural sections of reinforced concrete. For steel structures, in addition to the previous tests, it is possible to perform destructive laboratory tests on rivets and bolts.

In the case of timber structures, the main non-destructive tests are the ultrasonic testing, dynamic penetration (ex. Pilodyn), tests of resistance to the screw extraction and tests of resistance to perforation (Resistograph).

3.2. Part 2: Structural monitoring

Monitoring may be considered a particular type of experience, or investigation, on load-bearing structures. Many

Table 3. Summary of knowledge levels divided by building material type for the purposes of Credit HV 1.3, Part 1.

Level of knowledge (NTC 2008)	Surveys on building elements	Surveys on construction details	Tests on materials	Points awarded
MASONRY STRUCTURES				
LC1	• Surveys on brickworks, vaults, floors, stairs. • Measure of applied loads. • Identification of foundations typologies and possible failures.	*Limited tests*: • Surveys and sampling on all wall types, analyzing methods of connection between elements and supports of floors on walls; • Search for structural and non-structural elements with a potential high vulnerability. Samplings can be extended according to the types of masonry structures and floors.	*Limited investigations* obtained from visual examination and typological classifications. Samplings should be performed to understand masonry connections and their monolithic behaviour.	No points awarded
LC2		*Extensive and exhaustive tests*: tests as those included in the limited tests, but systematically extended to the entire building.	*Extended investigations*: same as limited investigations, but systematically extended to the entire building. At least three tests in situ for each identified type of wall are required (such as flat jacks tests, mortar analysis, stone and/or brickworks characterization).	1 point
LC3			*Exhaustive investigations*: same as extended investigations, but with the addition of experimental tests on the undisturbed samples taken in situ, useful to determine mechanical characteristics of specific masonries. Diagonal compression tests or compression/shear tests on panels are included.	2 points
REINFORCED CONCRETE (RC) AND STEEL (S) STRUCTURES				
LC1	In case original construction drawings are available: spot check on the correspondence between original drawings and the actual state-of-the-art. In case original construction drawings are not available: a new survey should be carried out.	• Simulation of quantity and distribution of steel bars and connections based on legislation in force at the time of construction. • Verification of quantity and distribution of steel bars and connections on 15% of structural elements.	Typical values for the construction practice at the time of construction and tests. • For RC: 1 sample of concrete every 300 m^2 of floor and 1 sample of bars each floor. • For S: 1 steel sample each of the building and 1 sample of bolt or nail each floor.	No points awarded
LC2		Incomplete construction drawings with in situ verification of quantity and distribution of bars and connections on 15% of structural elements. Alternatively: verification of quantity and distribution of bars and connections on 35% of structural elements.	From original design specifications or from original test certificates and tests. • For RC: 1 sample of concrete every 300 m^2 of floor and 1 sample of bars each floor. • For S: 1 steel sample each of the building and 1 sample of bolt or nail each floor. Tests: • For RC: 2 samples of concrete every 300 m^2 of floor and 2 samples of bars each floor; • For S: 2 steel samples each of the building and 2 samples of bolt or nail each floor.	1 point
LC3		Complete construction drawings with verification of quantity and distribution of bars and connections on 15% of structural elements.	From original design specifications or from original test certificates and tests. • For RC: 1 sample of concrete every 300 m^2 of floor and 1 sample of bars each floor. • For S: 1 steel sample each of the building and 1 sample of bolt or nail each floor.	2 points

(Continued)

Table 3. (Continued).

Level of knowledge (NTC 2008)	Surveys on building elements	Surveys on construction details	Tests on materials	Points awarded
		Alternatively: verification of quantity and distribution of bars and connections on 50% of structural elements.	Tests: • For RC: 3 samples of concrete every 300 m^2 of floor and 3 samples of bars each floor. • For S: 3 steel samples each of the building and 3 samples of bolt or nail each floor.	

TIMBER STRUCTURES

Level of knowledge	Surveys on building elements	Investigations	Classification according to resistance (*)	Extension of the investigation	Points awarded
Adequate	• Size and shape of the element. • Geometric features. • Morphological and growth features. • Position and type of defects. • Deteriorations. • Position and size of critical areas. • Other influential characteristics.	• Timber humidity. • Biohazard classification (**). • Timber species.	Based on (alternatives): • visual assessment of timber element; • non-destructive measurement of one • or more physical-mechanical features; • appropriate combinations of the previous ones.	At least 50% of primary structural elements and at least 30% of secondary structural elements (***).	1 point
Accurate				At least 100% of primary structural elements and at least 50% of secondary structural elements.	2 points

(*) According to the following standards:
UNI 11,119:2004 – Beni culturali - Manufatti lignei - Strutture portanti degli edifici - Ispezione in situ per la diagnosi degli elementi in opera;
EN 1912:2012 – Structural Timber - Strength classes - Assignment of visual grades and species.
(**) According to the following standards:
EN 335:2013 – Durability of wood and wood-based products – Use classes: definitions, application to solid wood and wood-based products.
(***) Maximum standard deviation of mechanical parameters < 20% compared to arithmetic average; maximum section reduction < 10% on each side.

parameters of the structures can be monitored: cracks, out-of-plane, stress, settlements, displacements, temperature, humidity, etc. Current technology offers the opportunity to implement multi-parameter monitoring systems with high data collection capacity and real-time processing of data. Part 2 of Credit HV 1.3 encourages the use of such procedures when they have the effect of reducing, containing and optimizing the retrofitting of existing structures. Sometimes the information obtained from an effective monitoring can also advise the designer to postpone consolidation or to use a more targeted approach that includes limited and non-extensive interventions. Existing literature supports this approach (Luechinger and Fischer 2015; UNI - Technical Commission [Structural Engineering] 2016), confirming the usefulness of monitoring campaigns, especially in cases of failures. In particular, guidelines provided by the Italian Ministry of Cultural Heritage (Ministero per i Beni e le Attività Culturali 2010) underline that monitoring campaigns are useful both in terms of preservation (through the concept of maintaining the efficiency of structures) and in the perspective of seismic safety (through the relationship with the concept of life cycle).

The structural monitoring allowed by GBC HB can only concern the design period subject to certification and any monitoring initiated and concluded outside the design and certification period are not included. Credit HV 1.3 awards structural monitoring that meets the following requirements:

- monitoring of structures that are worthy of preservation;
- monitoring that allows the preservation of the original structural use (except for small restorations); and
- monitoring representing the only or the best solution to guarantee the preservation of a structure, preventing its removal or replacement.

The third requirement is very selective in the case of its strict application. However, the concept is open to interpretation: a reinforcement that incorporates different or new structures into an existing building can in fact represent a form of exclusion. In this sense, a monitoring that prevents unnecessary reinforcements is preferred. In fact, the purpose of a credit is to encourage non-conventional diagnosis activities that are more accurate than those normally carried out in current practices and which produce concrete effects for restoration purposes.

In order to demonstrate the achievement of this credit, the rating system requires a detailed report on the monitoring design and planning and on the campaign results. Precise limits, as below, are defined, based on the economic impact of the benefits from the monitoring, so as to consider beneficial monitoring only.

In order to achieve one point for Part 2 the following must be verified:

$$C_1/C_0 > 5\%, \tag{1}$$

where:

- C_1 is the cost of the replacement or major reinforcement of structures that, thanks to monitoring, can be kept or only minimally reinforced. The calculation of the works referred to in C_1 will be carried out through a project simulation; and
- C_0 is the cost of the structural works involved in the restoration activity (excluding works concerning parts that are not worthy of preservation, for example additions of buildings, technological systems, new stairwells or lifts).

All costs will be estimated according to official price lists.

As there are no references in literature that could be taken as a model for (1), this equation was introduced by the TAG HB, translating it into 'LEED® language' (the rating tool uses objective and measurable criteria such as m^2, m^3, kg, kW/h, FTE, costs, etc. to assess performance). The suggested threshold considered a fair compromise between monitoring costs and subsequent related benefits. It is clear from (1) that monitoring is encouraged and awarded if the related savings have a relevant impact on the total cost of structural works only (in cases where there is a very large amount of structural works it is possible that the economic impact of benefits from the monitoring become irrelevant). This shows that economic weight, alone, is not necessarily a reliable measure of the importance of restoration choices.

GBC HB requires at least one point to be obtained in Part 1 of HV 1.3 in order to receive one point in Part 2.

3.2.1. Example: structural monitoring

As a consequence of several instability events, a monitoring campaign was implemented in the church of San Martino in Cinisello Balsamo, Italy. The original core of the church dates back to the 13th century, although the building underwent significant changes in the 17th and 19th centuries. Over the past years, important failures have occurred, with the presence of widespread cracks in the church structures, affecting both the walls of the main façade and some decorated barrel vaults that cover the naves. The area affected by the breakdown is that of the naves (one central and two lateral), including the façade. Perforation lesions on the brickworks vaults are major and parallel to the curvature. Some cracks showing fast and visible progression convinced the client to pursue a monitoring campaign to understand the causes and the possible evolution over time. Such monitoring ensures an effective and objective alarm system, should sudden failures occur.

The diagnosis campaign was based on a multi-channel monitoring system, managed by a control unit, connected to the sensors via wire and then connected to the processing station via radio. Sensors controlling lesions on the vaults were positioned on their extrados in the crawl space. In total, 9 sensors (with ± 5 mm measuring range) on the cracks (4 on the cracks in the most damaged vaults in the central nave and 5 on the walls of the façade) and 1 temperature sensor were positioned (Figure 1). Data were collected with a one-minute range and checked against defined alarm thresholds. Every hour the cumulative data were transmitted and saved (average, maximum, minimum, and standard deviation). The monitoring process lasted 18 months (from 3/1/2013 to 9/30/2014) at a cost of approximately EUR 12,000.

The measurements were cleaned from the contribution of temperature variations (daily and seasonal), thus obtaining the value of failure. Cracks on the façade appeared to be active and in progression, with cause of the instability being the low tension of the ties of the central nave vaults. Also, lesions on the vaults were highlighted in progression, with a more composite movement which suggested the presence of torque deriving from the asymmetry of the floor plan design. In the case of vaults, an appropriate review of tie-rods' tension and the suture of lesions on the extrados was required.

The monitoring campaign allowed a limit to be placed on consolidation works on the cracks, thus reducing the overall intervention costs. A simulation scenario showed that EUR 63,800 would have been spent on the consolidation of cracks (FRP stitching of all damaged vaults, massive seaming and tying interventions on the façade). Instead, it was possible to limit costs by reducing the interventions on the vaults only for lesions judged to be progressive and focusing on the replacement of the vaults' tie rods. The intervention for the façade are completed with the re-sewing of lesions. The cost of the works in this second scenario is EUR 22,500. Structural works amount to a total of EUR 232,500 (including the rebuilding of the roof and other structural works). Therefore:

- C_1 = EUR 63,800 - EUR 22,500 = EUR 41,300; and
- C_0 = EUR 232,500.

The C_1/C_0 ration is therefore equal to 17.7%, which is higher than 5%. The cost of monitoring is not included in the numerical verification. Furthermore, the case study meets the requirements of Credit 1.3 Part 2 regarding this intent, requirements and use of monitoring. The credit is therefore achieved and one point can be assigned for Part 2, provided that at least one point is also achieved in Part 1 of the credit.

4. Credit HV 2 – Project reversibility

International charters for the preservation and restoration of buildings and monuments (Gurrieri 1992; International Council of Monuments and Sites, ICOMOS 1964; Ministero della Pubblica Istruzione 1972) remark on the high value attributed to the principles of reversibility and distinguishability. According to the aforementioned theories, any intervention on a historic building (whether a modification, a consolidation, an addition, or a substitution), even of a structural nature, must be reversible and "at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence" (International Council of Monuments and Sites 1964, p. 3). As distinguishability involves aesthetic and subjective judgments, it is a difficult principle to assess within the scope of a metrics-based rating tool such as GBC HB. Therefore, any verification related to such a principle was excluded from the tool and left to the judgment of appropriate built cultural heritage assessors. In contrast, reversibility is a much more objective parameter to evaluate and, as such, was included in GBC HB. If new structures are to be integrated within the existing building, in the specific case of load-bearing structures, the use of dry-assembled technologies is recommended, taking advantage of connections that allow the disassembling of the integrated structures at any time. New building elements should not be hidden and no decorative elements of historical value (excluding furniture) should overlap on them. New elements must be independent, unaltered as much as possible, even by the original decorative features. Alterations must be easily removable, with limited inconvenience and costs. This approach will likely ensure the addition is distinguishable as well, thus making the intervention to respect the authenticity of the building. Additionally, since new structural elements may interfere with original structures, connection points between existing and new supports should be executed in places of minimum value, while ensuring alterations of the historical support are minimal.

Reversibility has therefore been included in the new protocol (Credit 2) and a process of ascertaining whether and how much the reversibility requirement has been achieved in the project has been developed. It should be noted that Credit 2 includes non-structural works as well, also accounting for finishes (such as false ceilings, internal partitions and insulation, and protection works), although structural items are the

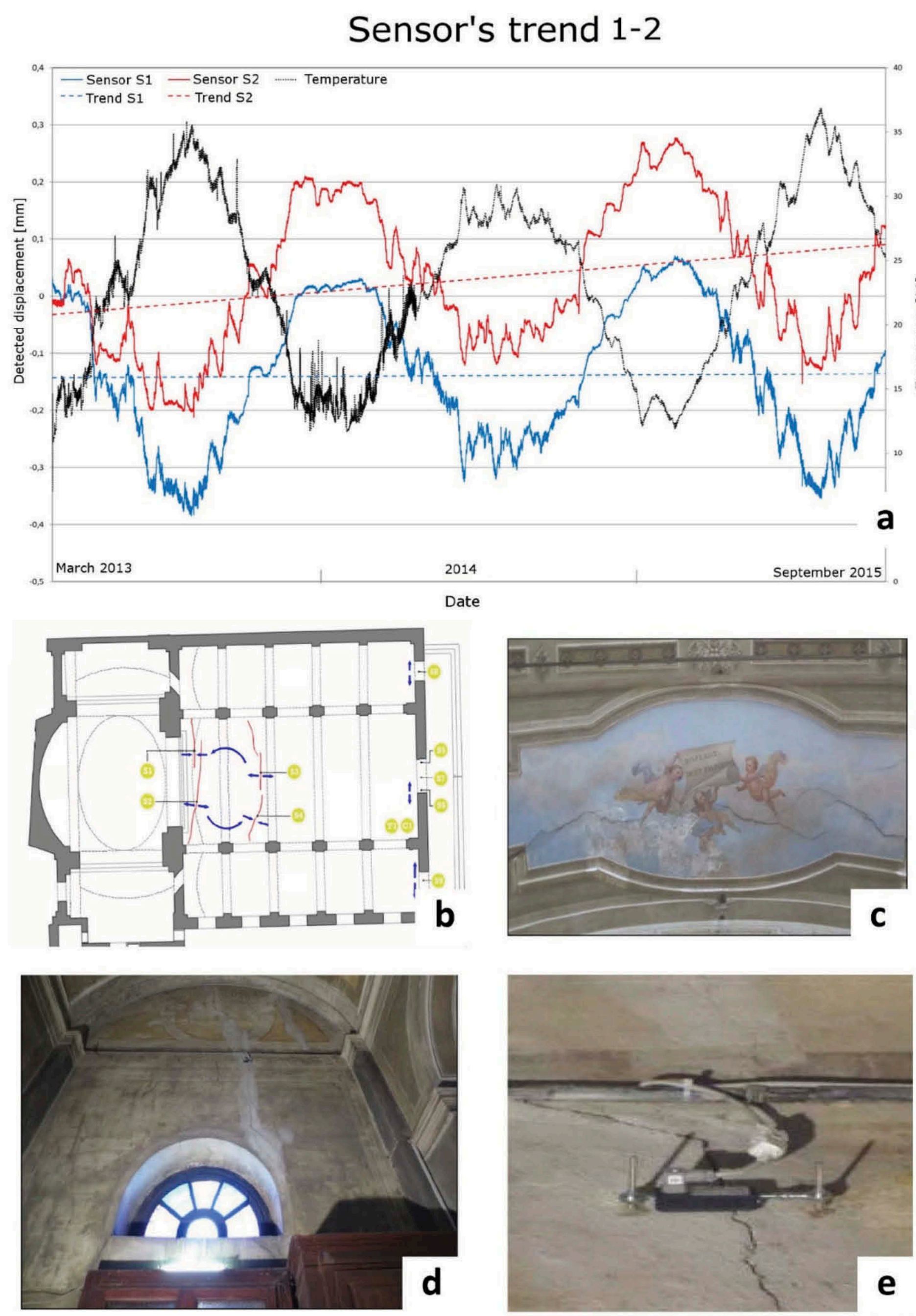

Figure 1. Monitoring campaign of the Sanctuary of San Martino in Cinisello Balsamo, Italy (Courtesy of Tecnoindagini S.r.l.). (a) Trend of sensor #1 and #2 and temperature from March 2013 to September 2015. It is possible to read a progression of the cracks under monitoring; (b) floor plan of the church with principal cracks projected from the soffit; (c) passing crack on a decoration; and (d–e) widespread cracks in the main façade and related sensor.

predominant ones. To this regard, for structural works as well, a checklist has been prepared to define whether an intervention is reversible, which is true when all the following points are verified (among structures, interventions on foundations have been excluded since they obviously cannot be reversible, nor less distinguishable):

- the verification of reversibility must be appropriate and/or necessary, which helps avoid evaluation on parts of the building with a low or very minor historic value (such as recent additions);
- the alteration must be demonstrably technically removable in the future (for example, by using steel supports, cross-laminated timber structures, or a steel tie-rod/chain);

- the technological solution suggested must be recognized as best-practice in the panorama of the techniques available at the time of the project (for example, it is preferable to inject mortars whose chemical compatibility is proven for a specific masonry, compared to the use of cement-based mortars).

Once the criteria above are verified from a qualitative point of view, a quantitative assessment based on costs (a common criteria for LEED® and GBC tools) is required. The credit is therefore based on the economic value of works considered as reversible, compared to the total of the overall structural intervention, thus defining a percentage α which estimates the level of reversibility of the same structural works and according to which points are allocated. Therefore, the percentage ratio α of works considered reversible is calculated as follows:

$$\alpha = P_{tot}/(P_{tot}+N_{tot}), \tag{2}$$

where:

- $P_{tot} = \Sigma P_i$, i.e., the cost of interventions considered reversible;
- $N_{tot} = \Sigma N_i$, i.e., the cost of interventions considered non-reversible.

Points are allocated according to the following ranges:

- if $50\% \leq \alpha < 70\%$, one point is awarded; and
- if $\alpha \geq 70\%$, two points are awarded.

Similarly to VS credit 1.3, there is no reference in the literature that could be taken as a model for (2). The defined thresholds are intended to make the project balancing out preservation benefits with related costs.

4.1. Example: assessment of reversibility on the total of structural works

The case study is a school complex placed in a former convent and female educational institute of ancient foundation (8th century for the most antique core), located in the southern limits of the territory of the City of Florence, Italy.

The credit analysis starts from the study of the project and in particular, of the quantity survey related to structural works (excluding, as already mentioned, foundation works). All structural works are considered and assessed against the preliminary criteria mentioned above. A careful grouping of works related to the same intervention category is recommended (for example, considering an opening in a masonry wall, both demolition and execution of the new frame or architrave are to be grouped together). Table 4 shows an example of assessed items for the verification of compliance with requirements of HV Credit 2. At the end of the examination of the individual points the results are collected, dividing those with positive eligibility results $P_{tot} = \Sigma P_i$ (sum of costs for reversible and distinguishable interventions) from $N_{tot} = \Sigma N_i$ (sum of costs for non-reversible or non-distinguishable interventions). Considering the case study, values are as follows:

- $P_{tot} = \Sigma P_i$ = EUR 350,000; and
- $N_{tot} = \Sigma N_i$ = EUR 275,000.

Therefore, according to (2), α is then equal to 56% and one point is awarded to the case study.

5. Credit HV 3.3 – Structural compatibility

Credit HV 3.3 focuses on performance aspects of structures involved in the restoration project. The credit aims at encouraging structural interventions that, at the same time, are respectful of the original structures and play a relevant role in improving the global

Table 4. Analysis of the estimated costs for the assessment of reversibility of total works.

#	Structural work category	Cost	Relevant context	Verification 1 (distinguishability)	Verification 2 (technical reversibility)	Verification 3 (best-practice)	Final result
n-1	…omitted…	…	…	…	…	…	…
n	Supply and installation of framed structure in cold-formed steel for the lift running way connected to floors by mechanical tiles directly applied to a masonry structure.	EUR 30,000	APPLICABLE: inside the oldest part of the building.	POSITIVE: the structure is visible, covered in crystal on the side of the floors. Distinguishable by all users.	POSITIVE: the structure is fully bolted and removable (and steel is recyclable).	POSITIVE: the bolted cold-formed steel solution reduces the weight of the structure and minimizes construction and removal works.	POSITIVE P_i = EUR 30,000
n + 1	Consolidation of wooden floor by laying metal beams on the slab extrados, included in the casting of the supporting slab. (see figure X)	EUR 30,000	APPLICABLE: inside the oldest part of the building.	NEGATIVE: hidden addition underneath floor tiles.	NEGATIVE: can be dismantled by demolishing the slab and removing floor tiles only.	N/A	NEGATIVE N_{i+1} = EUR 30,000
n + 2	…omitted…	…	…	…	…	…	…

performance of structures. The credit promotes an optimized approach to structural restoration in order to avoid possible opposite effects from occurring (i.e., excess of interventions producing a building that highly differs from the original, or excess of prudence not bringing any advantages in the consolidation process, especially from a seismic point of view).

The credit uses both economic (incidence of structural interventions against the total costs of works) and structural criteria (parameters that depend on the extent of the interventions) to define minimum thresholds of structural effectiveness. Some other parameters of structural nature are also included to ensure structural interventions do not introduce excessive perturbations across the overall structural framework.

The underpinned theme in Credit HV 3.3 is the performance of the building in response to seismic actions. The credit is divided into two alternative cases referring to two out of the three cases envisaged by the Italian Technical Regulations for Constructions (Il Ministro delle Infrastrutture di concerto con il Ministro dell'Interno e con il Capo del Dipartimento della Protezione Civile 2008 and subsequent modifications), i.e. interventions that are classified by the increasing level of response to the seismic actions:

- Case 1: interventions aimed to improve the existing structural safety (fully meet requirements for the verification of vertical forces and a simple improvement in the response to the horizontal action of the earthquake);
- Case 2: repairs or widespread local interventions (verifications are performed on involved structures only).

Credit HV 3.3 does not include the complete structural adaptation to the project's seismic actions, considering this measure too invasive in cases of restoration of the built cultural heritage. To this regard, in cases of low seismicity of the site (which in Italy may happen in category 1 seismic zone) the adaptation coincides with Case 1 and, therefore, the compliance with static verifications in those areas is the primary and most difficult objective to achieve. The credit gives structural engineers the task of identifying the most suitable structural models to understand the behaviour of the structure studied. Once the project has been allocated to the most suitable case (1 or 2, as defined above), a series of preliminary verifications must be performed in order to proceed toward the compliance with credit requirements and related calculations.

Preliminary verification 1 concerns minimum structural costs and is applicable to both Case 1 and Case 2, but with different performance thresholds. The verification requires a minimum of interventions implemented through materials compatible with the historic building. For Case 1, it is required that new structural works amount to at least 20% of the total works; for Case 2, the amount must be at least 10% of the total cost of works.

Preliminary verification 2 concerns minimum safety levels and it is applicable to Case 1 only. Parameters used to measure the compliance with requirements are derived from the approach to limit states, particularly referring to Peak Ground Acceleration (PGA) as mentioned in the Italian Technical Regulations for Constructions (Il Ministro delle Infrastrutture di concerto con il Ministro dell'Interno e con il Capo del Dipartimento della Protezione Civile 2008 and subsequent modifications). The reference limit state is the Life-Saving Limit. The PGA acceleration that can be sustained by the building with respect to the Life-Saving Limit (PGA_{CLV}) is then measured. This value, PGA_{DLV}, considered as the building resistance value, is then compared to the corresponding demand (solicitation), conventionally defined as the value that has the probability of exceeding 10% in the reference work period (i.e., return period). Preliminary verification 2 requires the following to be verified:

$$\alpha_{post\ operam} = PGA_{CLV}/PGA_{DLV} \geq 60\%. \tag{3}$$

This value represents a minimum limit of efficacy required by the credit for strengthening intervention. The 60% threshold is a value that establishes a significant building response (even if it is not totally satisfactory). The threshold was defined taking the example from the Guidelines issued by the Emilia-Romagna Region (Il Presidente della Regione Emilia-Romagna in qualità di Commissario Delegato 2012), considered a best practice in Italy. A similar threshold is also requested by Italian regulations (Il Ministro delle Infrastrutture di concerto con il Ministro dell'Interno e con il Capo del Dipartimento della Protezione Civile 2018) for earthquake improvement measures in the case of school buildings or other strategic and community buildings. When $\alpha_{post\ operam}$ reaches 100% (= 1), the building is considered as adequate (the latest update of the Italian legislation allows to consider adequate existing buildings that have undergone changes in loads or intended use even with $\alpha_{post\ operam} \geq 80\%$). In the case of masonry buildings with very light floors (such as timber structures), $\alpha_{ante\ operam}$ values are often influenced by local mechanisms (for example, the overturning of external wall panels or corner kinematics). The resolution of such kinematic mechanisms (for example by inserting ties to the slabs with metal tie-rods), in many cases, leads to an increase in the values of α.

Preliminary verification 3 concerns the extension of structural interventions and is applicable to Case 2 only. The verification requires the structures affected by interventions with compatible materials to be at least 30% of overall structures within the project boundary.

Once preliminary verifications are completed, Case 1 and Case 2 have a different compliance path to complete in order to achieve the credit and to be awarded the two points.

For Case 1:

- the project's additional load on foundations must be < 10% than original loads;
- for each floor, any modifications to the position of the centre of rigidity introduced by the project must be < 10% of the building's dimension measured perpendicularly to the direction of the seismic action; and
- for each floor, any modifications to the position of the center of mass introduced by the project must be < 5% of the building's dimension measured perpendicularly to the direction of the seismic action.

Case 2 is divided into vertical and horizontal structures, each with its own requirements, both to be fulfilled in order to achieve the two available points. Concerning vertical structures, requirements are:

- the rigidity of the modified element (in case of vertical masonry elements) must change within a maximum range of ± 15% with respect to the pre-existing state;
- the resistance and the deformation capacity (even in the plastic field) must not decrease; in case of masonry walls, the final shear value must not decrease;
- the wall's horizontal section area, on each floor, after the local intervention, must not be reduced by more than 15%;
- generally, any solutions such as total elimination of bracing walls and the creation of new openings close the walls' intersections should not be adopted, unless an appropriate rationale is provided.

Concerning horizontal structures, requirements are:

- to maintain the same structural scheme, also in case the replacement of parts or elements is required;
- to ensure loads per m^2 on floors are not increased or, if necessary, they are < 10% of the total loads (dead loads and live loads); and
- to ensure no significant modifications occur on slabs' stiffness and finished floor levels.

From the points above, it is clear that requirements regarding vertical and horizontal structures suggest maximum limits upon interventions in terms of their invasiveness. In case of local interventions (Case 2), there is no quantitative measure of the benefits related to earthquake performance, except for the performance of each new structure newly introduced by the project. This category includes works such as:

- strengthening of floors, roofs, beams, vaults, etc. due to the slight increase of loads or in case of deterioration;
- minor changes to openings on walls, also related to variations to the floor plan distribution;
- introduction of localized elements (such as stairwells or elevators) connected to the existing structure;
- consolidation of foundations and vertical elements (pillars, columns, or walls); and
- execution of works aimed at improving connections and, in general, the efficiency of structures.

5.1. Example: seismic improvement intervention (Case 1)

The building that houses the kindergarten in Barberino di Mugello, Province of Florence, Italy, dates back to the end of 18th century, being reported in the maps of the Land Registry of the Grand Duchy of Tuscany (dated around 1820). The building has masonry structures (mainly made by irregular stones) and timber slabs, except for the ground floor above the cellars, which is built with brick vaults (Figure 2). All structures were checked during an investigation campaign that involved both the walls and the slabs, with LC1 level of knowledge (minimum knowledge level). It is understood that the building is the result of many alterations, even recent ones.

Based on tests and surveys, a seismic verification was carried out according to the Italian legislation for existing buildings. The site where the building is located is ranked as medium-high risk (seismic zone level 2) with a Peak Ground Acceleration equal to 2.16 m/s^2 (Life Saving Limit State - SLV, Return Period = 712 years). After a preliminarily static type modeling, a push-over nonlinear seismic analysis, with reference to the finite elements method, was

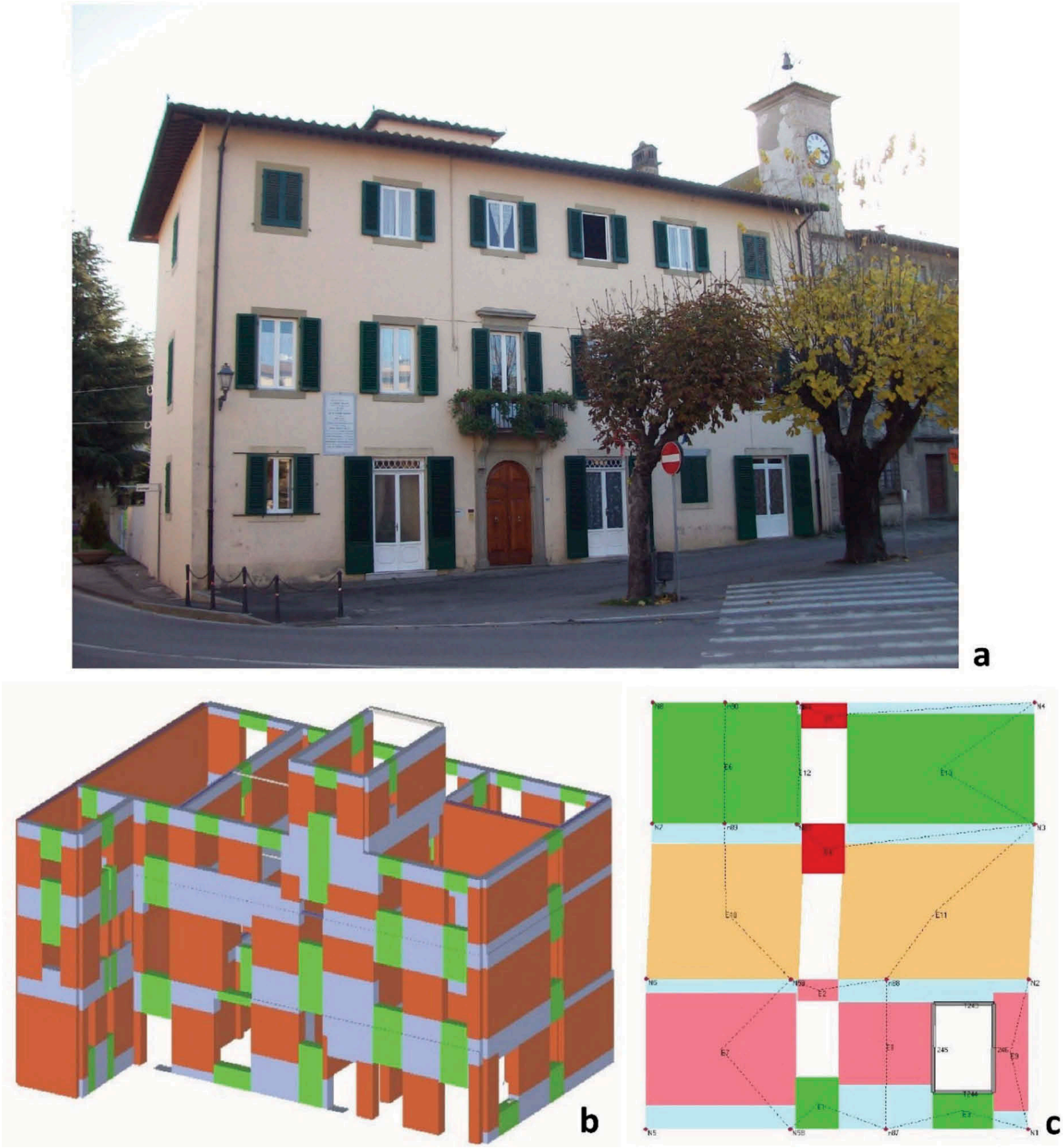

Figure 2. Example of seismic improvement intervention on a kindergarten in Barberino del Mugello, Italy. (a) Principal view of the building that dates back to the end of 18^{th} century; (b) finite elements (FE) model subjected to a push-over analysis; and (c) output from the FE model for a wall, which includes a steel frame, showing major problems related to floor bands.

carried out. Thanks to the results of the 3 tests carried out through flat jacks, the validation of the static model's result was possible. Among the values provided by the model and those measured in situ, a comforting limited gap was obtained (< 10% as average). The static analysis of vertical loads have shown limited problems on masonry panels with high slenderness and on architraves of some openings. The static-type problems on walls were solved through limited interventions (appropriately implemented according to the age and type of masonry surveyed). All slabs were checked numerically or through load tests (i.e., loaded with water tanks and checked for vertical displacement). The seismic analysis has highlighted an evident insufficiency of structures regarding the design seismic action. In particular, despite the box-shaped structural model, the reduced spans, the lack of pushing structures and the considerable thickness of brickworks, the safety factor obtained for the most problematic direction (performance VS demand) is about 0.56. The most vulnerable elements, highlighted by the modelling, are those of the small tower that rises above the roof (i.e., the dovecote), a recurring element in Tuscan rural buildings.

The building owner (a religious order) decided to execute works aimed at solving any static problems completely and, at the same time, obtaining a seismic performance improvement. Works included the consolidation of some walls, the closing of voids and cavities found in the walls (such as chimneys no longer in use) and the insertion of some metal rods (in accordance with the results of historical and material analyses conducted).

Preliminary verification 1 concerns costs, where structural works should amount to at least 20% of total works. In this case study, works carried out also included actions aimed at compliance with fire prevention regulations, universal design, as well as energy retrofit. The total value of works is EUR 397,543, while structural works are EUR 92,125. Therefore, the ratio is 23.2%, which means a positive compliance with preliminary verification 1.

Results of seismic analyses for the compliance with preliminary verification 2 are reported below:

- PGA_{DLV} (soliciting) = 2.16 m/s^2;
- condition before intervention (ante operam):
  - $PGA_{CLV(y)}$ (capacity in the y-direction, parallel to the main façade) = 1.34 m/s^2, from which $\alpha_{(y),\ ante\ operam} = PGA_{CLV(y)}/PGA_{DLV} = 0.620$; and
  - $PGA_{CLV(x)}$ (capacity in the x-direction, perpendicular to the main façade) = 1.21 m/s^2, from which $\alpha_{(x),\ ante\ operam} = PGA_{CLV(x)}/PGA_{DLV} = 0.560$.
- condition after intervention (post operam):
  - $PGA_{CLV(y)}$ (capacity in the y-direction, parallel to the main façade) = 1.318 m/s^2, from which $\alpha_{(y),\ ante\ operam} = PGA_{CLV(y)}/PGA_{DLV} = 0.610$; and
  - $PGA_{CLV(x)}$ (capacity in the x-direction, perpendicular to the main façade) = 1.60 m/s^2, from which $\alpha_{(x),\ ante\ operam} = PGA_{CLV(x)}/PGA_{DLV} = 0.741$.

Results show that the $\alpha_{post\ operam}$ value is o 0.610 and, therefore, higher than the 60% required by the credit. Results on verifications on centres of mass and stiffness are here omitted as their variation in the ante and post operam is very minor and both comply with credit's requirement. No appreciable additional loads are measured in the foundations.

All requirements are verified for this example and Credit HV 3.3, Case 1 scenario, is therefore successfully achieved and awarded with 2 points.

5.2. Example: repairs or widespread local interventions (case 2)

The case study is a former rural building (hayloft and agricultural machines storage), subject to adaptive reuse as an office building. Built in the 19th century as a service annex of an old convent, it is located in the suburb of Florence, Italy (Figure 3). The building has very simple structures, with foundations in unreinforced concrete mass poured into formworks, vertical structures in mixed stones and brickworks, an intermediate floor in mixed timber and flat bricks (almost collapsed) and a roof with a timber structure (in a poor state of conservation). It is developed over two levels on a rectangular plan of about 8 × 9 m.

The structural project concerns the preservation of the external walls, the partial demolition of a masonry wall on the ground floor (which supports the floor) and the remaking of two irremediably deteriorated floors with similar (but new) materials. The stiffness lost with the demolition of the internal panel is recovered through a metal frame. The project maintains the slab's original grid scheme. Existing pitched beams in the roof are replaced with trusses, thus eliminating the thrust of the existing inclined beams. Additionally, a crawl space underneath the ground floor and an external ditch are included to address the issue of rising damp. These last actions allow for the consolidation of foundations as well through a reinforced concrete ring beam.

The case study fulfils preliminary verifications 1 and 3 required for Case 2, as:

- the total cost of works is EUR 302,400, while structural works amounts to EUR 42,785, equal to 14% of the total, which is above the 10% required and preliminary verification 1 is therefore satisfied; and
- the intervention involves foundations, the intermediate floor and the roof, for a total volume of 71 m^3, equal to 52% of the total of 136 m^3; if foundations are not considered, then 40% of the total volume is involved in the project. In both cases, the value is > 30% required by preliminary verification 3, which is therefore satisfied.

Concerning credit requirements for Case 2 and, particularly, vertical structures:

- as steel frames are introduced to replace portions of walls, the masonry wall recovers its stiffness which is now within the maximum range of ± 15% compared to the pre-existing state;
- since the new frame has an ultimate shear which is higher than that of the eliminated wall panel, the

Figure 3. Example of widespread local interventions on a former rural building (hayloft and agricultural machines storage), subject to adaptive reuse as an office building in a suburb of Florence, Italy. (a–b) Post-operam results; (c) Roof timber structure (ante-operam); (d) activities on roof structure; and (e) metal frames recovering stiffness of demolished masonry panels.

intervention does not worsen the resistance and the deformation capacity (also in the plastic field);

- on the ground floor, the reduction of earthquake resistant walls occurs only in one direction, with a reduction of 10%, (less than the < 15% prescribed); and
- the project does not involve the elimination of any walls or any openings close to walls' intersections.

Concerning horizontal structures, the project complies with the credit's requirements for Case 2, as:

- some deteriorated structural elements are replaced in the project, but a structural scheme equal to the original is maintained;
- no additional loads relating to the building's change of use are added on floor structures; and
- the project does not change the floor stiffness and the finished floor levels.

Considerations above confirm that all the credit requirements for Case 2 are satisfied in the case study, which is therefore awarded with the 2 points available for Credit HV 3.3.

6. Discussion

Credits involving structural considerations play an important role within GBC HB and have been developed taking into account a global performance approach and impact. However, some improvements to the pilot version could be implemented according to the discussion below but always in the most absolute respect of material authenticity.

Regarding Credit HV 1.3 (Part 1: Diagnostic investigation on structures), it is possible to observe that the credit adopts a more selective and restrictive approach for timber structures compared to other structural materials (reinforced concrete or steel). In fact, the highest level of knowledge (awarded with 2 points) requires, in the case of timber structures, the direct investigation of 100% of the primary elements (such as beams) and 50% of the secondary ones. However, when structures are made by reinforced concrete or steel, the two percentages fall to 50% and 30%, respectively. The protocol's higher attention to timber material is justified by this material being more heterogeneous and perishable than other materials. However, there is a disparity between different materials, which also requires different costs for investigations (for example, when timber structures are hidden by false ceilings, their inspection is more difficult, especially if this must occur in a systematic way). Exceptions could therefore be made for cases where timber structures are hidden by other overlapping elements or materials and, at the same time, are not exposed to degradation agents (such as rain, air and soil humidity, biotic agents, UV, etc.).

Regarding Credit HV 1.3 (Part 2: Structural monitoring), the rating system does not allow monitoring campaigns that start before the design process subject to certification. This is explained by the precise time limits related to the third-party, objective and impartial certification process that can only include operations related to the site once the project has been registered for certification and, therefore, subject to site verifications and data collection. However, buildings with high historic value are often subject to long-term monitoring campaigns related to previous instability events. It would therefore be beneficial to include any previous monitoring in the credit (as a normal approach or as an exception), as it can provide valuable materials to achieve knowledge on both the building and on mechanisms of static instability. A possible approach could be to consider not the monitoring period, but rather the time of its assessment and interpretation for design purposes.

The analysis of GBC HB credits related to structural aspects carried out in previous paragraphs has highlighted the protocol's goal of pursuing performance levels that are above minimum requirements prescribed by the existing Italian legislation, thus placing the protocol at the forefront of the national scenario and beyond it. For example, to define a seismic improvement acceptable, the Italian legislation requires the improvement, even if minimum of the safety index ($\alpha_{\text{ante operam}} < \alpha_{\text{post operam}}$) (except in the case of schools or strategic buildings for civil protection purposes). Instead, as detailed in Section 5 of this article, the protocol requires a minimum level of security equal to 60% of the strengthening intervention. This threshold has been defined with the aim of providing the building with a minimum level of security, not only for short return periods, but also for the long ones. It is worth observing that $\alpha_{\text{post operam}}$ does not depend on the reinforcement works' accuracy only, but on the original capacity of the building ($PGA_{\text{CLV, ante operam}}$) and on the seismic zone (PGA_{DLV}) as well. Regarding the requirement's limit defined at 60% of the strengthening intervention, it is therefore possible to highlight some reflections, as follows:

- for the areas with low seismicity, the value of 60% (low value of PGA_{DLV}) is significantly easier to reach;
- in areas with a very low seismicity, the 60% threshold is quite easy to achieve and, in some cases, the structural strengthening cost limit (> 20%) represents the most critical threshold;
- regardless of the site seismicity, the limit value of 60% levels out the level of safety, which is the intervention objective. The principle of safeguarding human life and cultural heritage justifies a constant, transversal threshold that does not vary according to the seismic zone in which the building is located.

The approach that has informed the protocol and the definition of its objectives, which are based on the previous Italian post-earthquake legislation (developed from the 2009 seismic events in the Abruzzo region and, later, on those that occurred in the Emilia-Romagna region in 2012), appears to be perfectly in line with the current disciplinary debate, anticipating some essential elements. Even in conditions of considerable risk (high vulnerability and/or high danger), the transversal objective guarantees, in fact, a minimum safety level. In other words, risk conditions cannot be an alibi for not ensuring the protection of life and built cultural heritage.

As highlighted in introduction section of this article, the debate currently ongoing in Italy and the recent seismic events throughout the Italian peninsula, the integration of a critical and quantitative evaluation of the "exposed" cultural potential in Credit HV 3.3 might appear useful for the definition of the level of improvement to be achieved. In other words, the level of improvement could be adjusted (with a variation on the currently required 60%) according to the degree of "exposure" of cultural potential, where $\alpha_{post\ operam}$ could be > 60% in the case of high exposure and < 60% in the case of low exposure.

7. Conclusions

This article has extensively discussed the importance of considering structural rehabilitation as part of a wider sustainability framework that a historic building should aim at during a renovation process. In fact, the social component of the triple-bottom line of sustainability can be interpreted in its dimension of preservation of the building legacy, that will be available for future generations and, therefore, restoration through rehabilitation and strengthening of a structural system is part of the cultural identity of the construction. This is the approach taken by GBC Historic Building®, the first and only rating system that assesses and certifies the sustainability level of intervention on historic buildings subject to restoration, rehabilitation, and adaptation processes. The protocol focuses on the balance between historic and cultural values and sustainability issues, especially in the brand new HV credit category where structural rehabilitation is specifically and extensively addressed in its dimensions of: (1) advanced analysis through diagnostic tests on structures and structural monitoring (Credit 1.3); (2) reversibility (Credit 2); and (3) structural compatibility (Credit 3.3). These credits have a high impact (and responsibility) on the transmission of the building to the future and represent a best practice to pursue, especially in areas of high seismic-associated risk.

It is to be noted that the innovation of GBC HB does not only lie in the integration of preservation principles within a sustainability framework, but in highlighting sustainability goals within the restoration process as well. For instance, environmental factors, that are the distinctive features of sustainability rating systems such as LEED, are considered and integrated into structural rehabilitation credits that have been included in GBC HB and discussed in the present article. Indeed, the goal of environmental impacts reduction is clear in credits HV 1.3 (Advanced analysis: diagnostic tests on structures and structural monitoring) and HV 2 (Project reversibility). Credit HV 1.3 aims at achieving an advanced structural knowledge not only to have an incisive project, but to avoid redundancies and unnecessary interventions as well. In fact, an advanced knowledge on structures is the best way to avoid the use of unnecessary materials and resources in the project, with positive impacts on economic aspects as well, as a project that is tailored on the building's specific needs is more effective from the preservation perspective, as well as for the reduction of environmental impacts related to strengthening activities. At the same time, credit HV 2 awards those projects that aim at integrating reversible solutions, thus including considerations about dismantlability and disaggregatability at the end of the life cycle, which are an important part of a recycling-thinking and resource optimisation approach.

Although a conversation on how GBC HB contributes to a whole life cycle perspective falls out of the scope of this article, definitely this topic is worth mentioning as final reflection. Topics such as building and materials reuse and the optimisation of environmental impacts of building materials are not included in the topic area "Historic Value", but were integrated as new addition in the area "Materials and Resources". In particular, credit MR 4 encourages the use of products and materials for which a life cycle information is available through Environmental Product Declarations (EPD) and Life Cycle Assessment, and/or comply with a multi-attribute optimisation (which includes the use of rapidly renewable materials and FSC/PEFC certified timber as well). These credits are linked back to the HV topic area through "related credits," i.e., considering how credits across the whole rating tool are interconnected and how their synergies affect both the project and the use of other credits in different areas. This approach, which is consistent with the other rating systems of the LEED "family", help inform design and construction decisions across a wide array of sustainability goals, leading to stronger outcomes in terms of overall environmental impacts.

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