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Structural safety assessment criteria for dismantling operations of unique structures. San Mames Roof Arch Experience

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ABSTRACT

Dismantling is a fundamental phase of the life cycle on transport infrastructures and buildings in terms of sustainability and environmental impact but also in terms of structural safety. The requirements of the dismantling operation of a structure are linked to the complexity of the structure, and it is necessary to monitor the evolution of its structural behavior to avoid unexpected and demanding conditions and facilitate it reuse in the future. The authors present (1) an optimal methodology for the approach to the dismantling project of a structure, (2) a new global structural safety indicator for real time assessment, as well as (3) its application in the dismantling of the San Mames arch roof. The application of the vibrating chord technique in order to obtain the existing stresses in the lower tie rod of the arch of the San Mames roof arch and the monitoring of the evolution of the stresses in this tie rod during the operation of lifting and dismantling of the roof arch is presented. As a result, the paper contributes to reducing the lack of shared experience in the sector, as it is one of the few in the literature on the dismantling of large structural elements.

1. Introduction

In the context of life cycle analysis (LCA) for sustainability and environmental impact assessment, the concept of dismantling is crucial to understanding the full life cycle of infrastructure such as transport systems and buildings. Dismantling or deconstruction is the phase associated with the end of the structure's useful life and main points regarding its significance in the life LCA are:

- Resource Efficiency: Dismantling involves the removal of the structure and the potential recovery of materials and components.
- Waste Management: Proper dismantling practices can help minimize waste generation. Recycling and reusing materials from the deconstruction process reduce the amount of construction and demolition waste sent to landfills, thereby mitigating the environmental impact associated with waste disposal.
- Energy Consumption: Dismantling activities, especially if done manually or with less efficient methods, can consume energy. Sustainable dismantling practices aim to minimize energy use during the process. Additionally, the energy embedded in materials recovered during dismantling can be considered in the overall energy balance of a structure's life cycle. Steel components and structures can

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- Environmental Impact of Demolition Techniques: Different dismantling techniques have varying environmental impacts.
- Carbon Footprint: Dismantling contributes to the overall carbon footprint of a structure's life cycle. Sustainable practices, such as using low-impact dismantling methods and prioritizing material reuse, can help reduce the embodied carbon associated with the end-of-life phase.
- Policy and Regulation Compliance: Some regions have regulations and policies in place that govern the disposal and recycling of construction and demolition waste. Understanding and complying with these regulations are essential for sustainable dismantling practices.

In conclusion, dismantling practices contribute to resource efficiency, waste reduction, and overall environmental sustainability throughout the life cycle of structures.

In this regard, the European Union (EU) is asking to speed up the process for circular building and Transport Infrastructure (TI) (carbon-neutral construction, maintenance, operation and decommissioning) to ensure alignment and harmonization of protocols, norms and standards, while boosting knowledge generation and exchange of most advanced innovations at EU scale [1]. Furthermore, the building and TI sectors are asking for a new way of doing business, jumping from traditional circular product development strategies to "product-as-a-service" circular concepts and business model alignment, which must coexist with a high govern-driven sectoral structure. It is well known that building and TI has a high environmental impact due to its material use, waste production and CO2 emissions (during construction and operation). In particular, "Europe must move towards a 100 % renewable transportation system for climate, energy and sustainability reasons in 2050 and 50 % in 2030" [2]. It is essential that these impacts are reduced to achieve the European sustainability goals. However, building and TIs also have huge potential for resource generation. On one hand, much of the waste currently generated in TI interventions can be reused and recycled to create new construction materials and products. Today, in order to increase the sustainability of the construction industry by effectively managing the reuse of valuable components and the recycling of materials without limiting energy consumption as a second material process, there is the "Material and Component Bank" [3].

While some sectors such as onshore-offshore energy [4] have the decommissioning phase well internalised at the structural component level, other sectors such as construction are still in an incipient state and are still phasing the dismantling as an experimental and numerical study [5]. There are many structural typologies that use cable elements to ensure the overall static balance of the structure. Among these structures, one can highlight the large cable-stayed and hanging bridges, arch bridges with lower and intermediate decks, and arch-type or cable-stayed roof structures. To ensure the correct operation of these structures, it is essential to analyze the existence and evolution of possible damage to the cables in service through the historical record of their conditions and behavior. In this context, the most important parameter to determine or evaluate is the tension in the cables. This parameter has been recognized as a useful indicator of the safety of suspension structural elements [6]. Several devices have been developed to measure tension in cables, such as load cells, fiber optic Bragg grating sensors [7] or elasto-magnetic tension sensors [8–11]. These sensors can accurately determine the tension in the cable, and connected to a structural monitoring system allow to create a historical record of the cable tensions and provide remote access to this data in real time. The vibrating chord technique has become an economical and

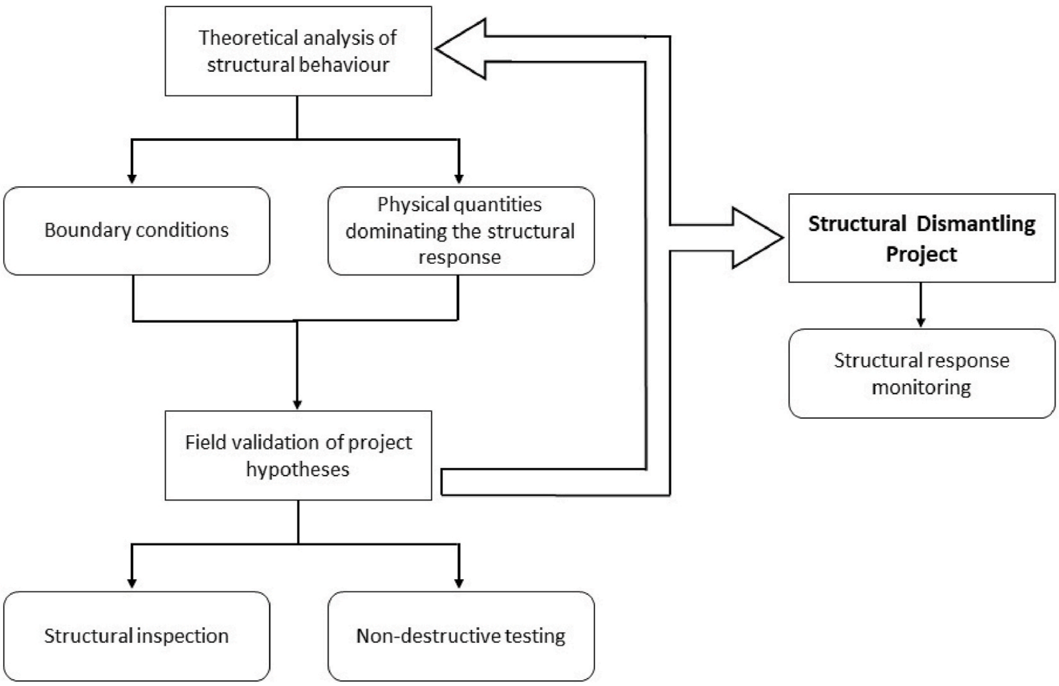

Fig. 1. Structural dismantling hybrid metamodeling approach process flowchart.

precise method to obtain the tension in the structural elements that work mainly with axial force. This technique is based on the relationship between the tension of the cable and its vibration frequency, which can be identified from the recording of the accelerations experienced by the cable under free vibrations [12–14]. Spectral decomposition techniques [15–17] allow determination of the tension in the cables in real time by identifying the vibration frequencies related to their main modes in free vibrations [18–20].

In this research work, the authors propose a (1) novel and optimised methodology that facilitates the correct design, conception and planning of infrastructure decommissioning operations. This methodology allows the definition of (2) the "Performance Indicators" (PI) associated with each of the phases of the structural dismantling project, as well as the evaluation of the "Global Structural Safety Indicator" (GSI), an indicator that allows the evolution of structural safety to be monitored during the course of the structural dismantling operations through the weighting of the different PI associated with the project.

2. Dismantling unique structures: risks and intervention actions

Paradoxically, decommissioning has been considered as a construction project in itself [21–23], requiring a design and execution phase. Nowadays, however, the particularities of this type of project are evident if material resources are to be valued effectively and efficiently [24,25]. The approach and design of the dismantling of structures is a delicate operation in which the starting assumptions of the structural design project and the reality of in situ structural behaviour in a robust variable context must converge (see Fig. 1). Design for Deconstruction (DfD) is a clear example of the need for a comprehensive approach to reduce the environmental impact of infrastructure. DfD has become a very important process to promote the reuse of entire load-bearing components of structures. The main concerns of DfD in the construction industry focus on how to assess the demountability of components, such as the dimension and stress state of components, the cost of the product and the reusability levels of components keeping them at their highest level of utility [3]. At the moment, there is still a lack of guidance for designers in specifying recycled components, as well as detailed procedures for component reuse: (1) Lack of sufficient laws and policy strategies [26]; (2) Lack of information and guidelines on the implications of certification of recovered components and recycled materials [27]; (3) Need to improve the design method for DfD, especially ensuring the structural safety of joints between elements [28]; (4) Improve the policy of CDW disposal and landfill, such as increasing the cost of disposal [29]; (5) Develop more appropriate smart deconstruction and demolition technologies; (6) Improve dismantling and material separation procedures in deconstruction; (7) Lack of effective quantitative evaluation methods of CDW to ensure the quality of recycled materials and complete components [30]; (8) Reduce the whole life cost of design and construction of structures with DfD [31]; (9) Define the remaining lifetime of reused components; (10) Better understand the reuse of structural elements, such as their residual capacity [32].

The first phase of the decommissioning project should be the analysis of the overall structural behaviour of the element, in this context it is important to clearly identify: (1) boundary conditions of the structural element; (2) identification of the fundamental physical quantities that dominate the structural response of the element. Once this phase has been completed, it is possible to propose a theoretical structural starting model, although before proposing the definitive dismantling project it is necessary to contrast the starting hypotheses with the reality on the ground. The field validation should comprise, as a minimum, the structural inspection of the element: (1) identification of the actual boundary conditions of the structural element, it is possible that due to the degradation of the supporting devices the boundary conditions have changed, and the structural system of the element has changed drastically; (2) analysis of possible pathologies affecting the physical quantities defining the overall structural behaviour of the element. The authors propose to add a field test campaign to experimentally characterise the actual global structural behaviour of the element and, together with the structural inspection campaign, to calibrate and tune the structural model with the reality in the field in a hybrid meta-modelling approach. The complexity of the structure under study will be an important conditioning factor in the decommissioning project, and it is in complex structures that DfD is of most interest. Dynamic load tests have become an optimal methodology in the experimental analysis of structures, allowing the early detection of damage or pathologies from the variation of their frequencies and vibration modes [33–35]. Experimental modal analysis makes it possible to obtain the dynamic characteristics of structures in places that are difficult to access without the need for auxiliary support elements such as inspection trucks, working platforms at different heights or cutting or demolition of elements [36–38]. Once the preliminary test campaign has been completed and the results have been compared with the starting assumptions of the theoretical structural model, the approach and design of the structural disassembly operation can be addressed. The monitoring of structures is an essential tool for the current trend towards recirculation of resources: 1) it makes it possible to anticipate pathologies incompatible with the functionality of the structure; 2) it reduces repair operations, with the consequent saving of resources and reduction of the CO2 footprint associated with them; 3) it makes it possible to plan and optimise structural adaptation operations; 4) it increases the useful life of the structures. In the case of structural dismantling works, the monitoring of structural behaviour increases the safety of the works, reducing the associated risks, such as total or partial collapse of the structure, damage to people or neighbouring structures, etc. As a measure to mitigate the risks assumed in any structural dismantling operation, it is advisable to set up a project to monitor the operation. This project would include monitoring the evolution of the fundamental physical quantities that define the structural response of the element during the disassembly operation, such as: (1) accelerations; (2) displacements; (3) rotations; (4) deformations; (5) stresses; (6) temperature. The methodology proposed by the authors for the optimal design of structural dismantling works includes the following stages (see Fig. 1): 1) theoretical study of the structural behaviour of the infrastructure; 2) empirical validation of the theoretical project hypotheses; 3) theoretical-empirical analysis of the structural behaviour of the infrastructure: (a) in the event of finding significant differences between the actual behaviour of the structure and the starting hypotheses, the need to adapt the structural model to reality would arise; (b) if, on the contrary, the actual and theoretical behaviour of the structure converge, the design and conception of the decommissioning project would be in a position to be addressed.

3. San Mames dismantling procedure

Given the need to build a new soccer stadium to expand the capacity of the old "San Mames", it was decided to demolish the latter, and occupy part of the land it occupied to build the new San Mames soccer stadium. One of the important milestones of the demolition project of the old "San Mames" football stadium consisted in the dismantling of the roof structure of its main stands. This structure consisted of a metallic upper arch from which the weight of the roof was suspended by 36 vertical cables. The arch rested on two reinforced concrete corbel-type structural elements, which supported the vertical component of the arch thrust, resulting from the arch's own weight, the suspension elements and the roof elements. The horizontal component of the arch thrust is compensated by the axial force of a lower metallic tie rod. The arch-type structural element had a length of 115 m and a height of 15 m (Fig. 2). The upper arch consisted of two metal arch-type elements with a cross-section of 460 mm wide and 1750 mm deep, braced together by eighteen San Andres crosses. The lower tie rod consisted of two metal elements with a cross-section of 190 mm wide and 400 mm deep, braced together by cross beams.

The dismantling of the roof structure included the following phases (a) demolition of the main grandstand roof; (b) demolition of the bracing beam between the roof structure and the main grandstand structure; (c) lifting of the roof arch by means of the synchronised operation of 4 heavy cranes; (d) displacement of the roof arch to the level of the old San Mames playing field; (e) cutting of the lower tie rod and release of the horizontal component of the arch thrust; (f) cutting of the roof arch for transport and subsequent assembly at the Lezama sports facilities. Given the dimensions of the roof structure, the simultaneous and synchronised use of 4 heavy cranes was necessary to correctly lift the two arch-type structural elements that make up the roof arch. Two of the cranes lift the arches by pulling on their kidneys, and the other two lift them by pulling on the supports. The weight of the structural assembly that makes up the arches of the roof of the old San Mames at the time of lifting was 190 tonnes, to be distributed among the 4 cranes that carry out the lifting. Each crane lifts the two arches at the corresponding point by means of a rocker (see Fig. 3), which allows the force exerted on the arches to have only a vertical component.

During the lifting operation, it is important to ensure the simultaneous operation of the four cranes in lifting the arch. It was decided to control the tensile force exerted by the cranes at each lifting point, guaranteeing a structural behaviour of the roof arch similar to the one it had when resting on the reinforced concrete corbels, keeping the lower tie rods working in axial force. Given the slenderness of the tie rods, if they start to work in compression due to incorrect execution of the operation, lateral instability of the tie rods and buckling of these structural elements would occur. The dimensions of the arch of the roof of the old San Mames stadium and the complexity of the lifting and dismantling process make it necessary to carry out a structural monitoring project, in which the following phases are distinguished: a) determination of the axial force in the lower tie rod before the arch is lifted; b) determination of the increase in the axial force suffered by the lower tie rod during the operation of lifting the arch; c) monitoring of the reduction in the axial force in the lower tie rod during the cutting operation.

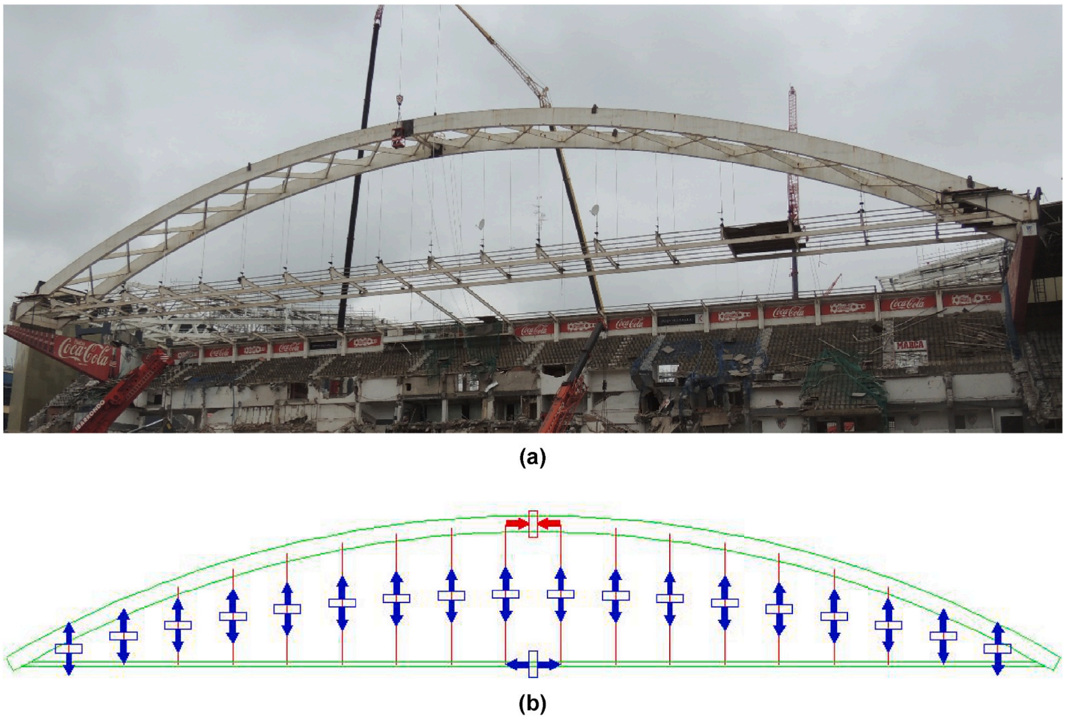

Fig. 2. Roof structure of the main grandstand of the old San Mames football stadium: (a) general view of the roof structure during work prior to dismantling; (b) structural diagram of the roof structure.

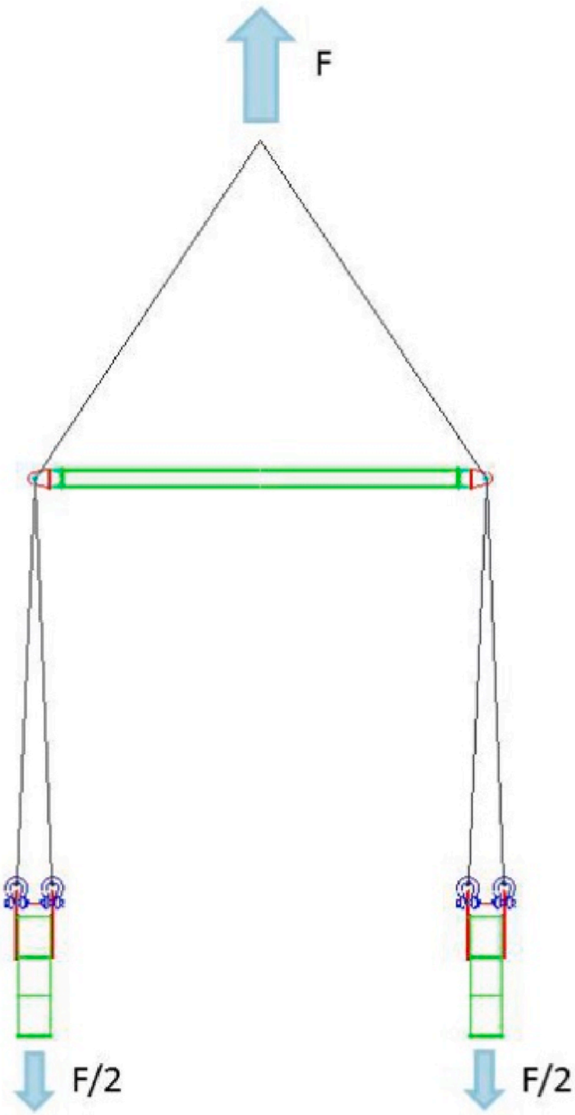

Fig. 3. Structural diagram of rockers used for the simultaneous elevation the arches of the roof of the old San Mames.

4. Structural monitoring system for the dismantling of the San Mames roof arch

In order to empirically characterise the structural behaviour of the roof structure, two groups of sensors were installed in the lower tie rod: (a) a piezoelectric accelerometer model "Metra KS-48C" in charge of characterising the acceleration experienced by the central section of the lower tie rod; (b) four bidirectional strain gauge units model "Tokyo Sokki FCA-3-11-1L" in charge of characterising the axial deformation experienced in the central section of the lower tie rod. Two bi-directional strain gauges are installed in the centre section of each lower tie rod, one on the lower face and one on the upper face (Fig. 4). The strain gauges are connected to each other by means of an electronic Wheatstone electronic full bridge assembly [39–41] (Fig. 5). This electronic assembly makes it possible to compensate for the local effects associated with the thermal variations experienced by the structural section during the course of the structural monitoring of the operation and the strain associated with the longitudinal bending of the lower tie rod [42,43]. The acquisition, recording and monitoring of the information provided by the sensors is carried out through a Structural Monitoring System (SMS) composed of the following elements: (a) a Modular Central Data Acquisition and Processing Unit (MCDA&PU) model "NI-C-DAQ-9188" with the capacity to simultaneously manage the signal from up to eight Data Acquisition Units (DAU); (b) an Acceleration DAU model "NI 9234″ that facilitates analog signal processing from an accelerometer; (c) an extensometry DAU model "NI-9237" that facilitates analog signal processing from strain gages; (d) a workstation responsible for communicating with MCDA&PU and recording and viewing data provided by sensors through a Data Acquisition and Monitoring Program designed and programmed by authors (Fig. 6).

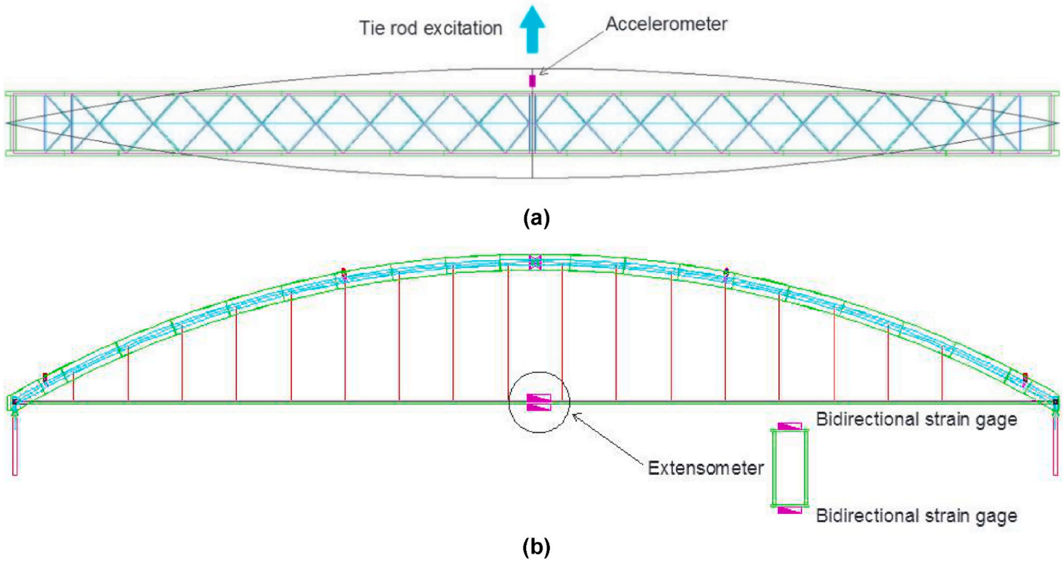

Fig. 4. Instrumentation of the roof structure: (a) plan view, installation of the piezoelectric accelerometer; (b) elevation view, installation of the extensometers.

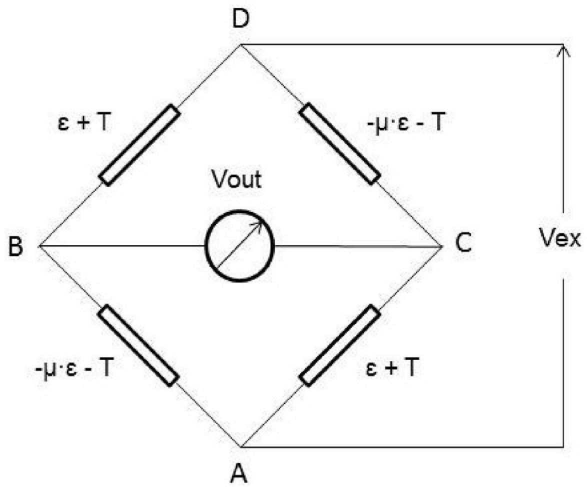

Fig. 5. Wheatstone full bridge electronic assembly.

5. Structural safety performance indicators during San Mames dismantling

Prior to the start of the dismantling operations it is necessary to define what will be the performance indicators (PI) during the dismantling of the structure [22,23]. Once defined, it will be necessary to assign the associated weights to each of the PI so that the overall structural condition indicator can be weighted. The authors propose the application of the formulation indicated in eq. (1) to obtain the PI associated with each structural phenomenon analysed in the structural dismantling project. The PI obtained shall be a positive integer with a maximum value of 100. Each PI shall have an associated operation threshold value, where if the value of the PI is less than the operation threshold value the structural dismantling operation shall be suspended. In the particular case of the dismantling of the roof arch of the old San Mames, the PI's used were the following: (a) Axial force existing in the lower tie rod of the roof arch. This indicator serves to check the initial hypotheses adopted in the structural model. (b) Pulling force of each of the lifting cranes. This indicator helps to ensure the structural safety of the operation. (c) Variation of the axial force on the lower tie rod of the roof arch. This indicator helps to ensure axial tension in the bottom tie rod.

$$PI_i = 100 - \frac{|V_r - V_t|}{V_t} \cdot 100 \tag{1}$$

Where: PIi = performance indicator associated with structural phenomenon "i"; Vr = real value during the structural dismantling

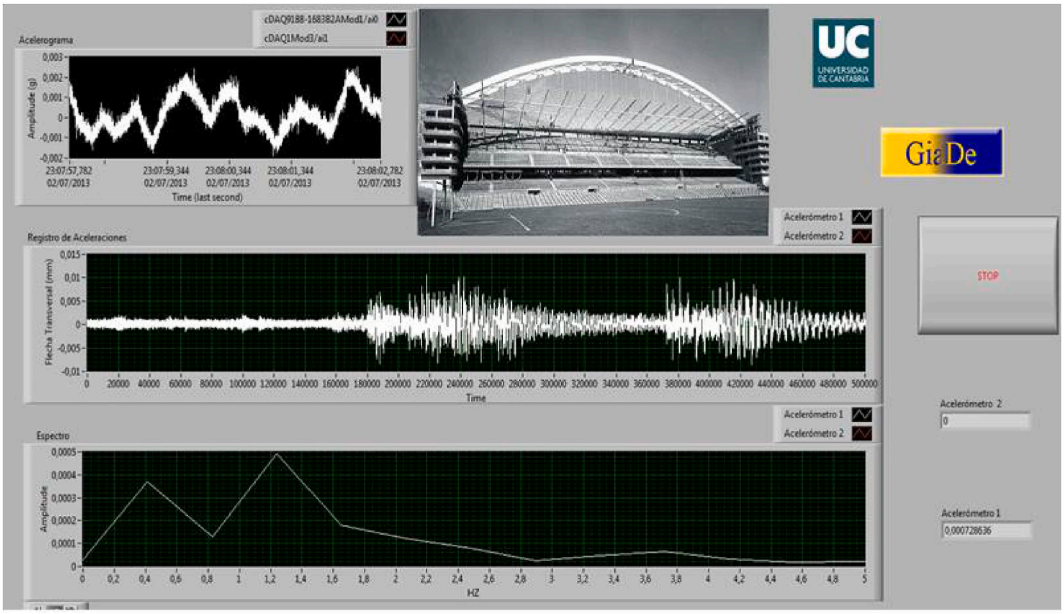

Fig. 6. Real-time visualization during the structural monitoring of the dismantling of the roof structure.

operation; Vt = Theoretical value indicated in the structural dismantling project.

If a more comprehensive or sustainable assessment of the whole structure based on SHM and/or visual inspection is required, a value-based approach would easily be allowed. In this sense, TECNALIA has developed a tool following the Integrated Value Model for Sustainability Evaluation or MIVES, a multi-criteria methodology for decision-making that evaluates each of the alternatives that can solve a defined generic problem through an index value. MIVES has been developed by Tecnalia, the University of the Basque Country, the Polytechnic University of Catalonia and the University of La Coruña [44,45]. This methodology is included within the

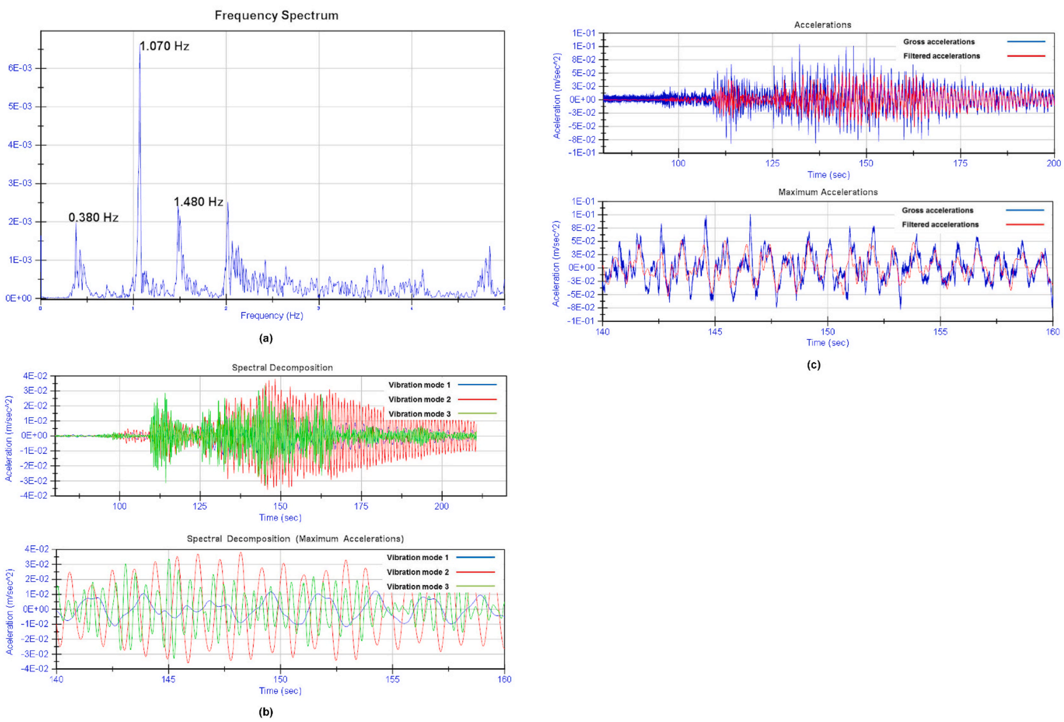

Fig. 7. Vibrating Chord test data analysis results: (a) frequency spectrum; (b) spectral decomposition; (c) filtered accelerations, associated with the first three modes of vibration.

multi-attribute utility theory, because to get the index value of each alternative, a weighted sum of the valuations of the considered criteria is done assuming that there is certainty. In other words, the preferences of the decision-maker, with respect to the proposed indicators, are known. MIVES has already been used in number of applications for the sustainability assessment of construction elements and projects, such as the sustainable design of concrete structures of the Spanish Structural Concrete Code [46] and Instruction of Structural Steel [47].

5.1. Characterization of the axial force in the lower tie rod using the vibrating chord technique

A structure vibrates according to its infinite modes of vibration. Of all of them, those corresponding to the lowest vibration frequencies are those related to the most flexible vibration modes, which will govern the dynamic behavior of the structural element. In the record of accelerations obtained during the free vibration of a cable, together with the accelerations due to the fundamental frequencies of vibration of the element under study, there are values corresponding to phenomena not related to its free vibration, such as electromagnetic noise and frequency of the electrical signal, or related to stiff modes, corresponding to very high vibration frequencies. To facilitate the analysis of the dynamic behavior of the cable, it is advisable to filter the acceleration log obtained in situ and select only those accelerations related to the lowest vibration frequencies. The procedure be followed in the dynamic structural analysis of cables was be the following: (1) Fourier analysis of the cable acceleration data series (Fig. 7); (2) identification of the fundamental vibration frequencies of the cable [48–50]; (3) spectral decomposition of the acceleration records according to the fundamental vibration modes of the cable (Fig. 7) [20,51]; (4) reconstruction of the accelerogram using the sum of the records of the filtered accelerations corresponding to the fundamental modes of vibration (Fig. 7).

The vibrating chord technique [52–54] applied to structural cables consists of a method by which it is possible to determine the tension experienced by these structural elements from the identification of their natural frequencies of vibration [55–57]. The application of this technique is based on the resolution of the differential equation eq. (2) [58–60]. The solution to the differential equation eq. (2), which makes it possible to obtain the axial force experienced in the structural tie rods from the value of their vibration frequency, is expressed in the equation eq. (3). The bending stiffness "EI" in structural cables is usually negligible with respect to their axial stiffness. This fact makes the second and third addends of the equation eq. (3) insignificant with respect to the first, which results in the equation eq. (4), which relates the axial tension of the cable with its mass and vibration frequency.

$$EI \cdot \frac{\partial^4 \vartheta(x,t)}{\partial x^4} - T \cdot \frac{\partial^2 \vartheta(x,t)}{\partial x^2} + m \cdot \frac{\partial^2 \vartheta(x,t)}{\partial t^2} = 0 \tag{2}$$

$$f = \frac{n}{2 \cdot L} \sqrt{\frac{T}{m}} \cdot \left[1 + 2 \cdot \sqrt{\frac{EI}{T \cdot L^2}} + \left(4 + \frac{n^2 \cdot \pi^2}{2} \right) \cdot \frac{EI}{T \cdot L^2} \right] \tag{3}$$

$$f = \frac{n}{2 \cdot L} \cdot \sqrt{\frac{T}{m}} \tag{4}$$

Where: EI = bending stiffness of the tie rod; ϑ(x,t) = transverse displacement of the tie rod's differential element in the position "x" of its directrix (see Fig. 8) and at the instant of time "t"; T = axial force in the tie rod; m = mass per linear metre of tie rod; x = position of the tie rod's differential element analysed; t = time variable; n = vibration mode number; f = value of the vibration frequency corresponding to mode; L = vibrating tie rod length.

Prior to the start of the dismantling operations of the "San Mames" roof arch, the vibrating chord technique was used to obtain the PI associated with the axial force existing in the lower stay. The lower tie rod of the roof arch was excited in the transverse direction of the arch (see Fig. 4), the tie rod behaving in this direction as a 6.6 m Vierendeel beam with a non-negligible bending stiffness with respect to its axial stiffness, so it is necessary to consider the three summands of equation eq. (3). In this particular case, the two addends linked to the bending stiffness of the tie represent a weight of 27 % in the formulation that relates the tie's vibration frequency with its axial force. Using the vibrating chord technique, the vibration frequency associated with the first mode of vibration of the lower tie rod is obtained, with a value of 0.380 Hz (see Fig. 7), which corresponds to a force in the set of the two tie rods of 1659.0 KN, or a force of 829.5 KN in each of the tie rods. The theoretical structural model (see Fig. 9) used for the design and definition of the dismantling operation of the roof arch was developed with the structural calculation application Midas Civil [62], and shows a force of

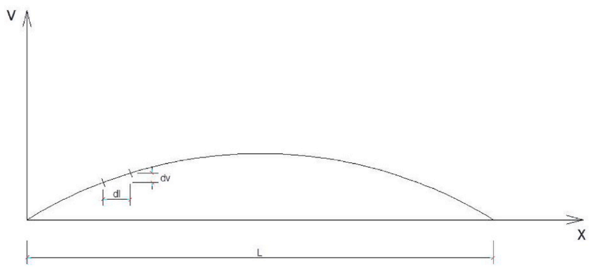

Fig. 8. Diagram of the statement of the differential equation of the vibrating wire technique [61].

877 KN in each of the lower tie rods of the arch, which would correspond to a vibration frequency of these element structures in the excitation direction of 0.386 Hz. Comparing these values with those obtained in the field test, it can be determined that the structural behavior of the roof arch is similar to that determined in the theoretical structural model and therefore that the hypotheses considered in the calculation model are correct (Table 1).

For this phase of the structural dismantling project, an operational threshold value of 90 % was defined. Since this phase of the project is a verification of the initial assumptions made in the demolition project, the permitted deviation from the theoretical values is only 10 %. In the case of a deviation higher than the allowed deviation, the engineer responsible for the demolition project must justify this deviation and adapt the demolition project to the reality of the site. Once the field values have been analysed and compared with the theoretical values indicated in the structural dismantling project, the PI associated with this phase can be obtained. The weighting factor assigned in the dismantling project for this PI was 10 %.

$$PI_{Axial\ Force} = 100 - \frac{|1659\ KN - 1754\ KN|}{1754\ KN} \cdot 100 = 95 \nless 90$$

5.2. Characterization of the pulling force on each lifting crane

The pulling force exerted by each lifting crane was provided by the crane operator. The operation manager monitored the lifting operation, so that if any of the crane operators registered a pulling force exceeding that corresponding to the operating threshold, the operation was momentarily stopped until stabilisation. Once the value of the pulling force was stabilised and balanced in the 4 cranes, the synchronised lifting operation of the roof arch was continued. The operating threshold defined for this phase was 80 %, so that the pulling force value recorded by the crane operators should be between 384 and 576 KN. The maximum pull force recorded by the crane operators was 550 KN, while the lowest value recorded was 430 KN. The PI associated with this phase will be the lowest of the values obtained below, and the weighting factor assigned in the dismantling project for this PI was 30 %.

$$PI_{Pulling\ Force} = 100 - \frac{|550\ KN - 480\ KN|}{480\ KN} \cdot 100 = 85 \nless 80$$

$$PI_{Pulling\ Force} = 100 - \frac{|430\ KN - 480\ KN|}{480\ KN} \cdot 100 = 90 \nless 80$$

5.3. Characterization of the axial force variation in the lower tie-rod of the roof arch

5.3.1. Structural monitoring of the roof arch lifting operation

In the project of dismantling the roof arch of the main grandstand of the old “San Mames”, the elevation of the arch is carried out in two phases: (a) cranes pulling anchored in the kidneys of the arch with 480 KN of pull in each crane; b) cranes pulling anchored in the arch abutments with 480 KN of pull on each crane, keeping the load on the cranes anchored in the arch kidneys. During the roof arch lifting operation, it was important to monitor the strain value provided by the extensometers installed in the lower arch tie rod. The arrangement of 2 units of bidirectional strain gauge in each tie rod (see Fig. 4) has the purpose of eliminating the strain associated with the longitudinal bending of the tie rod in the measurement [40–42]. In this way, the strain registered by the extensometers is only linked to the axial force in the tie rod (see eq. (5)).

$$\varepsilon = \frac{2 \cdot N}{E \cdot \Omega \cdot 2} + \frac{m_f \cdot \left(\frac{h}{2} - \frac{h}{2}\right)}{E \cdot I \cdot 2} = \frac{N}{E \cdot \Omega} \tag{5}$$

Where: N = axial force in the tie rod; E = modulus of elasticity of the material composing the tie rod; Ω = effective cross section of the tie rod; mf = bending moment existing in the tie rod section; h = tie rod depth; I = principal moment of inertia of the tie rod cross section.

In the first phase of lifting the arch, the lifting force in the cranes anchored to the arch kidneys is 480 KN, 240 KN in each structural

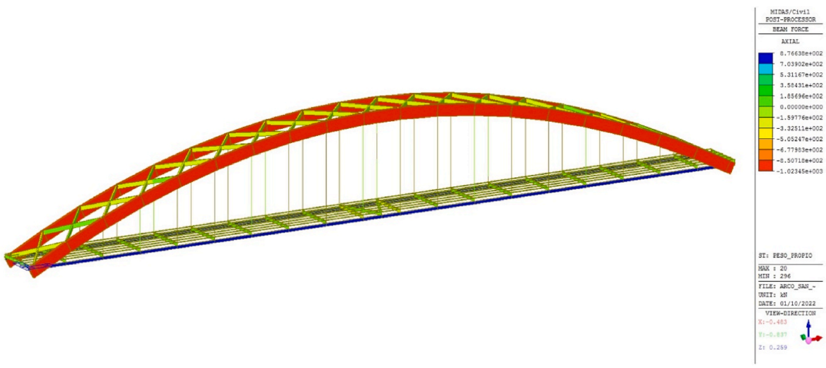

Fig. 9. Theoretical model used in the structural calculation of the San Mames roof arch dismantling operation.

Table 1
Theoretical/empirical analysis of obtaining the axial force existing in the lower tie rod of the San Mames roof arch.

Empirical Value (KN)	Theoretical Value (KN)	EV/TV (%)
1.659	1.754	95 %

element. Applying and maintaining this lifting force, and according to the hypothesis considered in the theoretical calculation model, the Axial Force on the lower tie rods of the arch should be reduced by 565 KN, maintaining an axial force of 312 KN on each of the two lower tie rods of the arch. The extensometers installed in these structural elements registered a reduction in axial force of 513 KN, maintaining an average axial force of 317 KN in each of these structural elements (see Fig. 10). In the second phase of lifting the roof arch, the lifting force of the cranes anchored to the arch abutments is 480 KN, 240 KN at the abutment of each arch-type structural element, maintaining the lifting force on the cranes anchored in the arch kidneys at 480 KN. According to the project hypothesis, the axial force in the lower tie rods during this phase is reduced by 21 KN, leaving each of the lower tie rods of the arch with a force of 291 KN. In this phase, the extensometers registered a variation of the axial force of 26 KN in the lower tie rods, maintaining each of these tie rods with an average axial force of 291 KN (see Table 2).

An operational threshold value of 80 % was defined for this phase. The PI associated with this phase was 98. During the definition of the project for the dismantling of the roof arch, the axial force on the tie rod was considered as the most important characteristic value for its correct structural performance. As long as the lower arch tie-rod remains under axial tensile force, it is an indication of the correct behaviour of the roof arch. Therefore, the weighting defined in the dismantling project for this PI was 60 %.

$$PI_{Variation\ Axial\ Force} = 100 - \frac{|634\ KN - 624\ KN|}{624\ KN} \cdot 100 = 98 \not< 80$$

5.3.2. Structural monitoring of the lower tie rod cut operation and arch disassembly

Once the lifting, transferring and provisional support operation of the roof arch had been completed, the dismantling of the arch was carried out. In this operation, the arch was reduced to segments that could be safely transported to its new location at the Lezama sports facilities. The first phase of dismantling the arch consists of cutting the lower tie rod that supported the horizontal reaction of the arch thrust. The extensometers installed in the lower tie rod of the arch allowed to monitor the cutting operation of the tie rod with the consequent release of axial force in this structural element (see Fig. 11). During this phase, the arch is still partially suspended by the cranes, but most of its weight rests on supports installed on the ground. Therefore, the weight assigned to this dismantling phase is 0 %, on the understanding that there is no risk derived from the manoeuvre. Fig. 12 shows a comparison between the empirical and theoretical values of the axial force in the lower tie rod of the Arch during the different phases of the dismantling process of the San Mames roof arch.

6. New global structural safety indicator for dismantling operations

The authors propose the development of a Global Structural Safety Indicator (GSSI) to help ensure the performance of the decommissioning operation under optimum safety conditions. It is proposed to calculate the GSSI by applying the formulation given in eq. (6). The GSSI is a living indicator, which evolves over time during the course of the structural decommissioning operation. In relatively large decommissioning operations, it is recommended to monitor in real time the evolution of the GSSI over time. The GSSI of the decommissioning operation shall correspond to the lowest GSSI obtained during the course of the operation. The GSSI obtained will be a positive integer with a maximum value of 100. Table 3 identifies the operational ranges associated with the different GSSI thresholds and the actions derived from each operational range.

$$GSSI = \frac{\sum PI_i \cdot W_i}{\sum W_i} \tag{6}$$

Where: Pi = weight associated with structural phenomenon “i".

6.1. Discussion

The authors have used the “San Mamés" arch roof dismantling project as a field test of the methodology proposed for the optimisation of this type of operation, making it possible to monitor the evolution of the safety factor during the different phases of the structural dismantling project (Fig. 13). Applying the formulation set out in eq. (6), the GSSI associated with each phase is obtained, it being possible to determine in real time and apply the actions derived from the operating threshold corresponding to the GSSI associated with the phase of the decommissioning project under study (Table 4).

7. Summary and conclusions

Although this topic is crucial there is a lack of shared experience in the sector regarding the dismantling of large structural elements. In essence, this paper suggests a novel approach to enhance the sustainability of the construction industry by efficiently handling the decommissioning phase under safety conditions for repurposing new structures. The significance of preliminary efforts preceding the dismantling of a structure is underscored in this study. The authors propose the development of a series of PIs associated with the different phases of the structural dismantling project to be included in material and component banks [3]. These PIs are

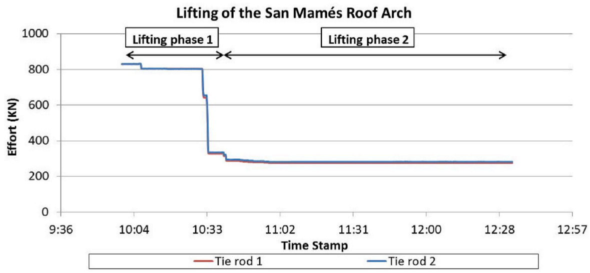

Fig. 10. Structural monitoring of the lifting operation of the San Mames roof arch.

Table 2
Theoretical/empirical analysis of the evolution of the axial force in the lower tie rod of the roof arch during the lifting operation.

	Empirical Value (KN)	Theoretical Value (KN)	EV/TV (%)
Lifting phase 1	634	624	102 %
Lifting phase 2	582	582	100 %

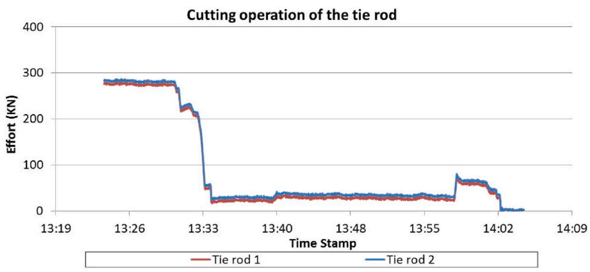

Fig. 11. Structural monitoring of the cutting operation of the lower tie rod of the San Mames roof arch.

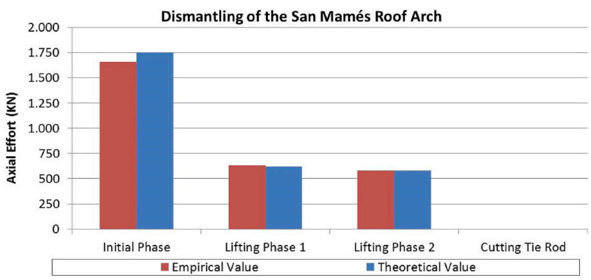

Fig. 12. Theoretical/empirical analysis of the evolution of the tension in the lower tie of the roof arch during the different phases of the dismantling operation.

Table 3
Operating ranges associated with the GSSI.

GSSI	Operating Thresholds	Derived action
90–100	Optimum	Continuation of the dismantling operation.
80–90	Acceptable	Decreasing the speed of the dismantling operation
<80	Not Acceptable	Suspension of the dismantling operation: • Revision of the starting assumptions of the structural calculation model. • Redefinition of the dismantling project. • Review of the definition of the PI_i.

indicators of structural safety during the dismantling operation. A formulation, eq. (1), is proposed for obtaining the different indicators, the result of which is a positive integer. The GSSI is obtained as a result of the weighting of the different PI's defined in the structural dismantling project. The different operational thresholds associated with the different GSSI ranges and the actions derived at each operational threshold are defined. This study presents the findings from the pre-dismantling phase of the San Mames roof arch.

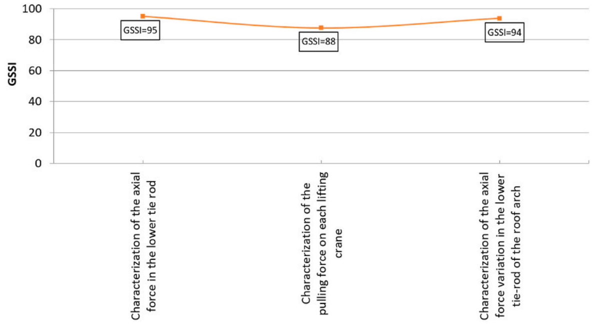

Fig. 13. Monitoring of the evolution of the GSSI associated with each of the phases of the "San Mames" roof arch dismantling project.

Table 4
Obtaining the actions derived from the GSSI associated with each phase of the "San Mames" roof arch dismantling project.

Decommissioning project phase	PI	GSSI	Derived action
Characterization of the axial force in the lower tie rod	95	95	Continuation of the dismantling operation
Characterization of the pulling force on each lifting crane	85	88	Decreasing the speed of the dismantling operation
Characterization of the axial force variation in the lower tie-rod of the roof arch	98	94	Continuation of the dismantling operation

The study validates the theoretical calculation model employed in the project for the dismantling of the San Mames roof arch. Through the application of the vibrating chord technique, the axial force in the lower tie rod of the roof arch is determined successfully demonstrating, on the one hand, the advantages of this technique: (a) its installation is possible at any stage of the project; (b) it makes it possible to record the absolute value of the tension in the cable regardless of the project stage at which the sensor is installed. On the other hand, this technique has the disadvantage that it generates a large volume of data, making it necessary to resort to spectral decomposition techniques to obtain the tension in the cable. The authors discuss the usefulness of structural monitoring in structural dismantling projects. The results of the structural monitoring of the lower tie rod of the San Mames roof arch during its lifting and dismantling operation are presented. The characterisation of the axial force in the tie rod was carried out by installing unidirectional extensometers. This monitoring made it possible to control the variation of the axial force in the tie rod and served as an early warning of a possible drastic reduction in the tensile force of the tie rod due to an incorrect execution of the lifting operation. The main advantages of this technique are the following: (a) it is a technique that involves a low economic investment; (b) installation is possible at any stage of the project. However, this technique has the following disadvantages: (a) it is a not very robust solution, very sensitive to shocks and weathering; (b) in the case of installation on tie rods in service, it provides the stress increments in the structural element, but it is not possible to obtain the absolute value of the stress in the tie rod; (c) the accuracy in the measurement of the stress in the tie rods is highly influenced by the correct on-site installation of the strain gauges.

The discussion of the results obtained from the application of the methodology proposed during the project for the dismantling of the "San Mamés" roof arch has allowed it to be validated. This methodology has been conceived as a tool to facilitate the correct performance of infrastructure dismantling operations under optimum safety conditions. This research work aims to lay the foundations for future lines of research oriented towards the following objectives: 1) development of design guidelines focused on the DfD method; 2) development of new smart dismantling technologies; 3) development of new circular construction strategies.

CRediT authorship contribution statement

Alvaro Gaute-Alonso: Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **David Garcia-Sanchez:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Resources, Visualization, Writing – original draft, Writing – review & editing. **Alan O'Connor:** Validation, Visualization, Writing – review & editing.

Declaration of Competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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