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Stress Evaluation in Axially Loaded Members of Masonry Buildings and Space Structures: From Traditional Methods to Combinations with Artificial Intelligence Approaches

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Abstract: Stress state evaluation in axially loaded structural members is significant for sustaining and preserving the service life of buildings. While successful monitoring furnishes staunch information on the health, integrity, safety and serviceability of structures, maintaining the structural performance of a building with time significantly depends on assessing the occurrence. Variations in the stress in axially loaded members may occur in masonry buildings or space structures caused by different conditions and human-induced factors. In the last decades, numerous nondestructive methods have been generated to furnish practical means for identifying axial load in the tie-rods of masonry buildings and in the structural members of space structures. Significant effort has been put into dynamic-based approaches, which make use of the vibrational response of the monitored member to investigate its condition and evaluate the axial load. In particular, wide laboratory and field tests have been executed worldwide, resulting in several findings. Meanwhile, with flourishing sensing technology and computing power, Artificial Intelligence (AI) applications, such as hybrid methods, optimization techniques and deep learning algorithms, have become more practicable and widely used in vibration-based axial stress prediction, with efficiency and, frequently, with strict precision. While there have been various manuscripts published on dynamic-based axial stress evaluation, there are no works in which the passage from traditional methods to combinations with AI approaches have been illustrated. This article aims to address this gap by introducing the highlights of the traditional methods, and furnish a review of the applications of AI techniques used for nondestructive-based axial stress prediction in tie-rods and structural members. Conclusions, including further studies and field developments, have also been mentioned at the end of the article.

Keywords: artificial intelligence approach; axial load; frequency; inverse problem; masonry building; nondestructive test; space structure; stress evaluation; structural member; tie-rod

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1. Introduction

Space structures are generally used in many large frames or roof trusses, such as auditoriums, gymnasiums, etc. (Figure 1a). Nevertheless, due to the breaking of key structural members, the collapse of the space grid structure frequently occurs [1]. In 1978, the collapse of the square pyramid space truss gymnasium in Hartford City Center [2,3] due to the local buckling of structural members, impressed the American civil engineering community. Hence, nondestructive methods are required to accurately estimate the safety conditions of the members of space structures to formulate their maintenance programs [4,5]. The stress evaluation of such axially loaded members is highly sought after because it can help verify the design model and evaluate the remaining performance of the entire structure [6]. As occurred in the case of the space truss gymnasium in Hartford City Center in 1978 [2,3], a significant re-distribution of the internal axial stresses can indicate a possible collapse for buckling [7,8]. Indeed, the increment of material strengths allowed us to design space structures composed of ever more highly slender elements (Figure 1a). Conversely, metal tie-rods are important elements which can mainly be found in heritage masonry buildings (Figure 1b). Tie-rods guarantee a proper connection between walls and play a significant part in the control of horizontal thrusts caused by static loads acting on arches and vaults, or seismic-induced dynamic loads in the event of earthquake actions [9]. In particular, tie-rods have often been inserted in historical buildings during the construction phase (Figure 1b). Nevertheless, they have also been installed in buildings in subsequent phases, if it has been necessary to modify a structure (building aggregations, super elevations, etc.), increase the load, substitute elements subjected to a heavy decay, or repair a building after an earthquake [10]. Still today, the insertion of tie-rods is one of the most widespread methods utilized to reinforce historical masonry buildings in seismic-prone areas. Similarly to what has been implemented for space structures, dynamic-based techniques have been developed to provide practical means for identifying axial tensile stress in the tie-rods of masonry buildings (usually in historical ones).

(**a**) (**b**)

Figure 1. (**a**) Example of a steel space structure (Scientific-Technological Pole, University of Ferrara, Italy); (**b**) Example of ancient metal tie-rods of a masonry building.

As mentioned above, the traditional methods for axial stress evaluation in the structural members of buildings are mainly based on the vibrational response of the element itself to be investigated [11]. Yet, there could be issues which may practically impede the application of such techniques [12]. Primarily, the dimensions of these buildings are commonly relatively large, which means that common assessment can be both laborious and time consuming. Secondly, since the traditional methods also depend on human decision and data interpretation, they require highly trained and skilled labor. Nevertheless, the first successes of vibration-based axial stress evaluation methods in tie-rods and structural members have motivated researchers to develop new techniques. The final goal has been that of overcoming the problems related to the traditional methodologies by providing more feasible ways of identifying the axial stress according to the dynamics of the member itself [13]. Meanwhile, in the last decade, plenty of advancements in sensor technology and computational power have enabled the combination of Artificial Intelligence (AI) approaches, such as hybrid vibration testing methods, optimization techniques and deep learning algorithms, with generic applications in the field of Structural Health Monitoring and Assessment (SHMA).

In this article, the research works conducted worldwide on evaluating stress in the axially loaded tie-rods of masonry buildings and structural elements of space structures have specifically been illustrated. Indeed, the safety conditions of masonry buildings, space frames and roof trusses depend significantly on assessing the existing axial loads.

Variations of the axial stress in such members may occur because of different conditions and human-induced factors [14]. Scholars implemented a large number of nondestructive methods, resulting in several findings, to improve their principles and techniques along with their deployment in applications in the field of SHMA. Specifically, the methods have been analyzed from three categories concerning investigations into traditional ones, new devices and combinations with AI approaches (Figure 2). In fact, with flourishing sensing technology and computing power, hybrid methods, optimization and deep learning algorithms have become more feasible in vibration-based axial stress prediction with efficiency and, frequently, with strict precision. While there have been multiple manuscripts published on dynamic-based axial stress evaluation, there are no works in which the transition from traditional methods to combinations with AI techniques has been discussed (Figure 2). This article aims to address this gap by introducing the main highlights and furnishing a literature review. In future investigations, the development of long-term automatic dynamic-based methods, designed on a one-system-per-tie-rod or space structure basis, are particularly encouraged and, when it is feasible, in combination with advanced AI approaches.

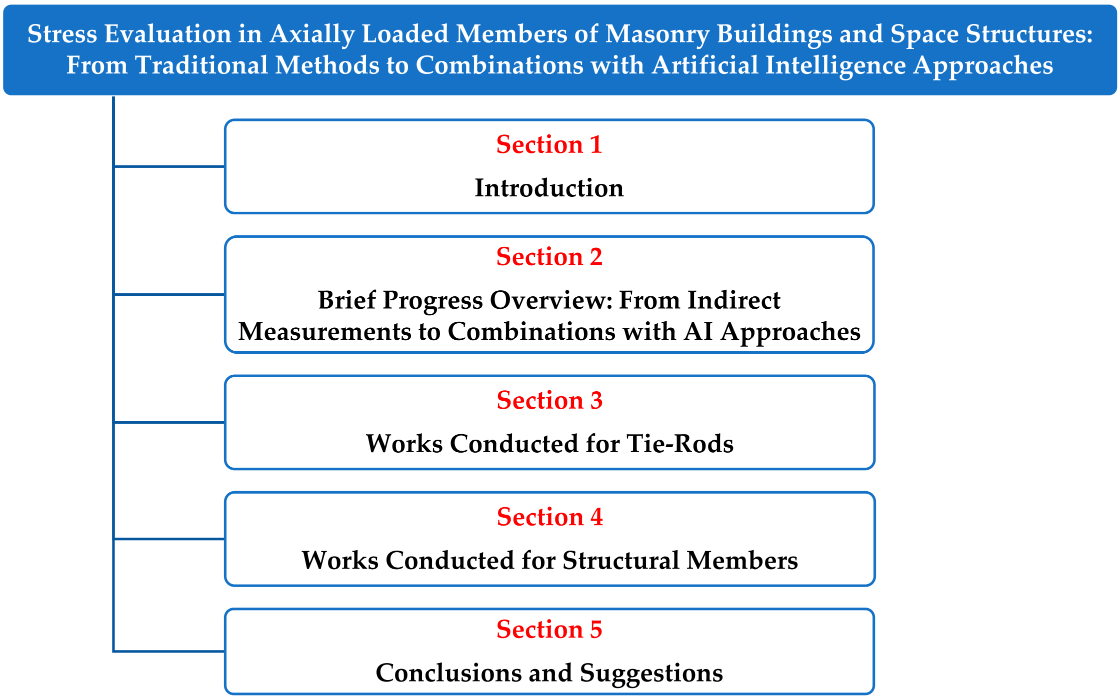

Figure 2. Workflow of the present work.

Methodology

The author reviewed a total of 85 book chapters, conference and journal contributions, principally related to dynamic-based axial stress evaluation in tie-rods and structural members, including 52 articles on traditional methods and 11 articles on new devices and combinations with emerging AI techniques (Figure 3). The methodology for screening these contributions has been synthesized and reported as follows:

- The articles have been gathered from well-known databases including the ASCE Library, IEEE Xplore Digital Library, Sage, Science Direct, Scopus, Web of Science and Wiley Online Library.
- The literature search has been executed using keywords such as "artificial intelligence-based axial load identification", "axial load identification", "axial stress identification", "dynamic-based axial load identification", "nondestructive-based axial load identification", "stress identification in axially-loaded structural member", "stress identification in axially-loaded tie-rod", etc.

- The journal articles selected were published between 1994 and 2023. Works on structural damage methodologies (e.g., impedance-based methods) were excluded since they are beyond the scope of this manuscript. Additionally, articles related to dynamic-based damage identification methods in civil structures were disregarded.
- Pertinent contributions from prominent conferences such as the 13th World Conference on Non-Destructive Testing, Elsevier (1992); the 2014 IEEE Workshop on Environmental, Energy, and Structural Monitoring Systems; the 7th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII 2015); and the 10th International Conference on Structural Analysis of Historical Constructions (SAHC 2016) were chosen and reviewed.

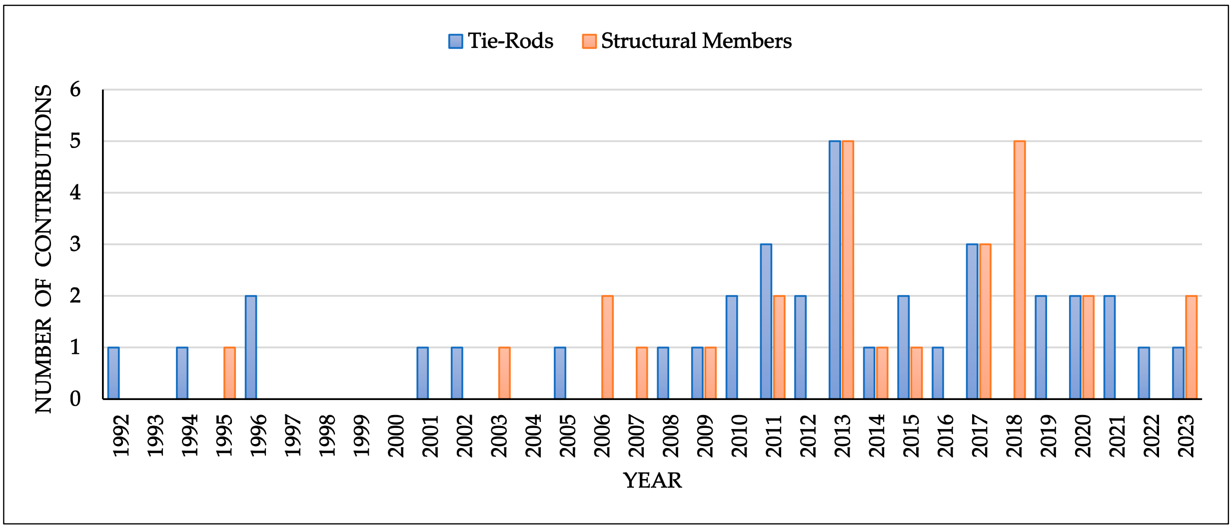

Figure 3. Number of contributions vs. the last decades related to dynamic-based axial stress evaluation in tie-rods and structural members, including traditional methods, new devices and combinations with AI techniques.

2. Brief Progress Overview: From Indirect Measurements to Combinations with Artificial Intelligence Approaches

Measurements of acceleration, deflection, strain and numerous physical parameters are of basic importance in the field of applications of SHMA [15]. In particular, the dynamic parameters of a space grid structure, i.e., damping, natural frequency and mode shape, have always been key indicators. E.g., for a recently constructed square pyramid space roof truss, one could be interested in measuring the corresponding few frequencies for model updating, i.e., for reducing the difference between the real and the Finite Element (FE) model employed during designing [16,17]. An accurate modeling of a space structure is also needed for structural control aimed at counterbalancing the excitations caused by earthquakes or wind gusts. However, for a space roof truss, a regular assessment of the modal properties furnishes the most useful information for determining the degradation in its different parts, including the decrease in stiffness, settlement in supports, breakage in connections, or deterioration in metal materials, due to long-term corrosion, weathering or earthquakes [18]. Furthermore, the identification of defects by static deflection measurements has also become significant for the service life preservation of a structure or infrastructure, enabling its decision-making in terms of maintenance and retrofitting. For a bridge in use, e.g., the static deflection, with an accuracy equal to 0.01 mm, is crucial because its limit is used as a control index of its global behavior and, moreover, it is the key parameter for prestressing loss identification [19,20]. Thus, amongst the vibration-based methods, axial stress evaluation using static deflections has additionally been demonstrated to be a reliable technique for structural members. In fact, such deflections take precisely into account the changes in geometry of the member due to the axial force variation on the equilibrium conditions [21]. Laboratory investigations were firstly performed on the tie-rods and members of small-scale space frames and trusses by using three-point bending tests [22–25]. This technique, conversely to dynamic-based methods, does not require selecting the experimental damping, frequency or mode shape for use in algorithms but, unfortunately, the application of the point load can practically result in an arduous process.

On-site measurement procedures, such as the ambient, forced and impact vibration test, have often been performed to identify the dynamic parameters of a space grid structure. These methods rely on the global response, which requests quite a high number of vibration sensors to be mounted. Similarly, the direct approach is typically planned on a one-system-per-tie-rod basis which, in turn, demands quite a high number of sensors be installed on the single tie-rod. Furthermore, on-site instrumentation is generally laborious, time consuming and is not maintenance free. The other disadvantage is that, once the nondestructive method is concluded, the assessment system tailored for one space structure or tie-rod can hardly be relocated to another one.

To overcome the above issues, the concept of extracting the dynamic parameters with the help of an AI technique or using a new device has been attempted, where only the fundamental frequency of the structural member or tie-rod is usually assumed [26]. E.g., efforts have been devoted to the development of methods for automated output-only modal analysis algorithms for vibration-based monitoring [27,28]. Vice versa, in the work proposed by Camassa et al. [29], the interferometric radar was suggested for tensile stress evaluation in tie-rods, since only a small number of sensors are required to be deployed. Notably, in the field of geomechanics, Esmaeili-Falak and Benemaran [30] instead suggested two hybridized Extreme Gradient Boosting (XGB) models for forecasting the resilient modulus of pavement materials subjected to wet–dry cycles, instead of performing conventional experiments that need time and money, along with special devices. In particular, the two XGB models have been implemented for estimation purposes, where determinative variables have been optimized using Particle Swarm Optimization (PSO) and the black widow optimization algorithm. The XGB approach has also been suggested by Li et al. [31] to predict the unconfined compressive strength of marine clay modified with recycled tiles. Specifically, four hybridized models have been developed with the integration of an adaptive neuro-fuzzy inference system, support vector regression, Random Forest (RF) and XGB with Aquila optimizer algorithm. Moreover, in order to restore steel frame structures, Shi et al. [32] have developed some techniques using a hybridized RF method on collected carbon fiber reinforced polymer (CFRP)-steel single-shear experiment data to estimate the bond strength of CFRP-steel. In fact, the bond strength between the CFRP and steel, along with the mechanical properties of the CFRP, is crucial to the final strengthened effectiveness. The RF hyper parameters have been tuned using the COOT optimizer, arithmetic optimization algorithm and improved arithmetic optimization algorithm.

3. Works Conducted for Tie-Rods by Researchers Worldwide

Metallic tie-rods are mainly utilized to prevent the out-of-plane collapse of the masonry walls of buildings, or to counteract the horizontal thrusts exercised by arches and vaults [33]. Especially, the tensile stress in tie-rods can considerably decrease the force exerted on the abutments by the arches subjected to common vertical loading [34]. However, the tensile force in the tie-rod is evidently higher than the masonry arch thrust decreased by the buttress force exerted by the abutments (Figure 1b). As for the seismic vulnerability of the arches, the model developed by Giuriani et al. [9] has furnished evaluations of both the tie over-tension and the collapse multiplier in the transverse arch rocking condition. An accurate assessment of the tensile stress in the tie-rod must be linked with calculation tools with the aim of keeping the structural element in the elastic range and limiting the global deformation of the arch rocking mechanism, such as those implemented by Fraternali et al. [35], Fraternali [36,37] and Milani and Tralli [38]. Yet, with flourishing sensing technology and computing power for applications in the field of SHMA [39], vibration-based tensile stress evaluation methods in tie-rods have been combined with hybrid numerical and experimental approaches, optimization techniques or with the use of new devices. In particular, to propose identification procedures that are computationally straightforward (the numerical framework has to be easy to implement), the following algorithms have been introduced: the Genetic Algorithm and the Artificial Neural Networks, as illustrated in Figure 4 and Section 3.3.

Section 3

Works Conducted for Tie-Rods

3.1. Traditional Methods

- Analytical approaches
- Automated operational modal analysis algorithm
- FE-model-based calibration formulas
- Numerical approaches
- Numerical-dynamic approaches
- Pure dynamic-based nondestructive methods
- Static-based nondestructive methods
- Static-dynamic-based nondestructive methods

3.2. Methods combined with New Devices

- Pure dynamic approach with the use of microphone
- Pure dynamic approach with the use of interferometric radar

3.3. Methods combined with AI Approaches

- Numerical-dynamic methods combined with an AI approach
    - *Artificial Neural Networks*
    - *Genetic Algorithm*
    - *Optimization Algorithms*

Figure 4. Sketch of the methods currently in use for evaluating the axial stress in tie-rods (Sections 3.1–3.3).

3.1. Investigations Including Traditional Methods

In the last decades, static and dynamic nondestructive methods have been developed for tie-rods in which the reference model has firstly been assumed to simply be a supported beam with rotational end constraints with the goal of reproducing the incidence that the masonry offers to the parts of the element merged within the walls [4,5,22,40–45]. Static approaches have made use of deflections (and/or deformations) along the tie-rod, subjected to one or more point loads, with an accuracy usually equal to 0.01 mm. In references [5,40], a point load was applied at the midspan and deflections, as well axial deformations at the two opposite sides of the cross section; these were measured at three positions, giving rise to nine different measurements. In detail, Beconcini [42] suggested three distinct static tests with deflections measured at the quarter sections of the tie-rod. Later on, the tensile stress can be obtained by minimizing the sum of the square errors between the analytical and experimental data. Instead, Tullini et al. [22] presented a static approach that made use of the deflections recorded at three specific cross sections in a three-point bending test. Accordingly, the axial stress as well as the flexural stiffness coefficients of the end constraints were estimated if the restraints had infinite translational stiffness (which is a restrictive supposition). Conversely, in dynamic approaches, researchers resorted to vibration experiments, making use of the beam model parameters. In references [4,41], an approximate method was presented which uses both static deflections and natural frequencies. Using the first three natural frequencies, a numerical method was instead implemented by Lagomarsino and Calderini [43] on the basis of a minimization procedure of an error function. Moreover, in reference [45], the analytical solution of the beam vibration and the Rayleigh–Ritz method were adopted to predict the natural frequencies of the tie-rod as a function of the tensile stress according to numerical simulations.

More sophisticated models have made use of FE-based calibration formulas where the unknown parameters have included the tie-rod length, concentrated masses, and an elastic Winkler foundation simulating the interconnection between the tie-rod and masonry wall [26,46–48]. Furthermore, Campagnari et al. [49] developed a FE model based on the experimental identification of the tie-rod mode shapes and eigenfrequencies at a specific number of cross sections. Unfortunately, no uniqueness of estimated parameters may arise in these approaches. In fact, tie-rod extremities are merged in masonry walls, making the length and the position of the restraints doubtful, so that the corresponding stiffness can hardly be determined.

To overcome the aforementioned problems, Tullini [23], Li et al. [50], Li et al. [51], Maes et al. [52], Rebecchi et al. [53] and Duvnjak et al. [54] presented some methods to evaluate the tensile stress in tie-rods with unknown boundary conditions. These approaches allowed us to overtake the issue of determining the effective length that is free to vibrate, the end constraints and the masses of the junction systems made to tighten the tie-rods (typical of the traditional methods). In particular, Maes et al. [52] and Rebecchi et al. [53] evaluated the axial stress of a tie-rod with known flexural stiffness, making use of any vibrational bending frequency and five amplitudes of the related mode shape. Duvnjak et al. [54] developed a vibrational approach that combines on-site measurements and a numerical-updating technique based on the tie-rod model with unknown flexural stiffness and boundary conditions. Vice versa, the experimental investigation of ancient tie-rods executed by Calderini et al. [55] indicated that a mean estimated elastic modulus comparable to that of modern steel (209 GPa) may occur, but with a considerable standard deviation of 76 GPa, and a variation coefficient of around 36%.

The procedure elaborated by Tullini and Laudiero [44] and Rebecchi et al. [53] has been practically improved by some researchers. E.g., Rainieri and Fabbrocino [28] developed an automated operational modal analysis algorithm for vibration-based tensile stress evaluation according to dynamic measurements, which also made the technique suitable for continuous monitoring rather than periodic checks only. The procedure has also provided interesting opportunities for cheap and fast quality checks during the construction phase. Gentile et al. [56,57] estimated the tensile stress in 112 tie-rods of the Milan Cathedral using only their fundamental frequency. In particular, among the 112 tie-rods, the anomalous phenomenon of the splitting of fundamental frequency was observed on 2 tie-rods, which was then associated with the presence of small damages, i.e., thin cracks corresponding to the welding joints [57]. Cescatti et al. [58] executed numerous laboratory and numerical tests by considering a set of 224 configurations of tie-rods, including different methods of vibration, boundary conditions and stress states, observing that pertinent errors may occur for high tensile forces only. This result has been related to the problem of recording small vibrations when increasing values of the tensile force make the tie-rod stiffer and stiffer [23]. Rainieri and Aenlle [59] instead investigated the accuracy of the method proposed by Rebecchi et al. [53]. Specifically, 27 FE models of tie-rods with different end constraints, lengths and axial stress values have been examined. The inaccuracy in the estimation of the flexural stiffness has been taken into account by assuming a 14% underestimation of the elastic modulus of the metallic material. Conversely, the error in the material density evaluation has been considered to be equal to 0.6%. Also, an error of $\pm$1%, affecting the fundamental frequency of the 27 FE models, has been assumed. Thus, the influence of measurement errors on axial stress estimations has been lower than 4%. Similarly, Tullini et al. [60] studied the accuracy of the procedure. The influence of measurement errors, as well as of inaccurate estimates of the flexural stiffness on the accuracy of the tensile stress identification, have been considered. For the natural frequencies and mode shape amplitudes, measurement errors of ±1% have been assumed, whilst an error of 15% with respect to the elastic modulus value has been considered. Furthermore, it has been underlined that the reliability of tensile stress identification, using one flexural mode shape, relies on the measurement errors rather than on accurate guesses regarding the elastic modulus. Very interesting is also the vibration-based method presented by Ruccolo and Gentile [61], which differs from the one developed by Tullini and Laudiero [44], since the elastic modulus has been considered to be unknown, whilst the natural frequencies of higher modes have been utilized to solve the inverse problem. The practical application has been demonstrated with reference to the long-term monitoring of some tie-rods in the Milan Cathedral, showing the higher tensile stress state (>100 MPa).

The results of the aforementioned works have made evident that the traditional vibration-based methods have been implemented by formulating increasingly accurate reference models, i.e., from simply supported beams with known flexural stiffness and rotational end constraints [4,5,22,40–45] to those with unknown flexural stiffness and rotational and translational boundary conditions [54,61]. It is also worth noting that the operational modal analysis algorithm proposed by Rainieri and Fabbrocino [28] has opened the path to the creation of long-term vibration-based procedures designed on a one-system-per-tie-rod basis [61]. Environmental conditions, mainly related to the changes in temperature, relative humidity and moisture states which, in turn, may influence the vibration modes of tie-rods, could be assumed within the continuous automatic vibration-based stress identification approaches [62].

3.2. Investigations Including Methods Combined with New Devices

With the numerous advances in sensor technology, the idea of extracting the dynamic parameters of tie-rods using a new device has been attempted, since traditional methods typically demand quite a high number of vibration sensors (Section 3.1). In the work presented by Resta et al. [63], acoustic measurements were adopted as the source of excitation for the frequency response estimation of tie-rods. Specifically, two general-purpose microphones were introduced to efficiently substitute more complex and expensive sensors. Camassa et al. [29] instead suggested the non-contact approach based on the interferometric radar since only a few number of sensors are required to be deployed. Laboratory experiments have demonstrated that, provided that a suitable dynamic evaluation model is used, tensile stress identifications from interferometric radar measurements indicate a very high level of accuracy (i.e., with a mean estimation error <2%), which are comparable with identifications accelerometric measurements. Clearly, the use of the interferometric radar has the advantage of being economical efficient, and quick compared with the traditional approaches (Section 3.1) and especially in the case of tie-rods which are hardly accessible.

3.3. Investigations Including Methods Combined with Artificial Intelligence Approaches

The nondestructive method proposed by Garziera et al. [64] consists in matching the first six natural frequencies of the tie-rod with the corresponding numerical ones. This technique has been executed using an optimization algorithm where the tie-rod length, the presence of point masses along it and an elastic foundation at the restraints are the optimization parameters. Thus, the tensile stress is obtained by an algorithm which minimizes the difference between the experimental and numerical results on the basis of the selection of multiple parameter combinations. Gentilini et al. [65] declared to evaluate the tensile stress, elastic modulus and rotational stiffness at both restraints of a tie-rod on the basis of a dynamic impact test, added masses and Genetic Algorithm. Particularly, the identifications are driven by the Genetic Algorithm in which the objective function is a metric of the discrepancy between the experimentally determined and the numerically calculated natural frequencies of some modified systems achieved from the tie-rod by adding a point mass at specific locations. Conversely, De Falco et al. [66] focused on a sensitivity analysis of the eigenfrequency computing model on which most of the dynamic tie-rod axial stress evaluation methods have been based. Using the application of general

Polynomial Chaos Expansion and the calculation of Sobol' indices, the influence of the flexural stiffness and boundary conditions on the eigenfrequencies of generic tie-rods has been studied. Makoond et al. [67] instead presented a vibration-based method employing Artificial Neural Networks for tie-rods containing discontinuities or irregularities, i.e., in the presence of connectors which unify historical tie-rods made from many segments. In particular, this hybrid approach can be applied to any historical tie-rod by applying a data-driven procedure to a dataset developed through an FE method.

The aforementioned advances have indicated that vibration-based methods combined with AI applications and/or algorithms have been generated to let the tensile stress predictions become more efficient and with strict accuracy. In particular, in the work proposed by Makoond et al. [67], more realistic conditions of historical tie-rods were considered. Furthermore, the approach of the FE simulations has commonly been utilized to calculate the dynamic parameters according to the AI algorithms [65,67]. To summarize Section 3, the main characteristics and information (i.e., year, type of approach, type of test, required and model unknown parameters) of the works conducted worldwide for the axial stress evaluation in tie-rods, above illustrated, have been listed in Tables 1 and 2.

Table 1. Nondestructive traditional methods for evaluating the axial stress in tie-rods (Section 3.1). Note: the contributions have been listed based on the publication year.

Reference	Year	Approach	Type of Test	Required Parameters	Model Unknowns
Briccoli Bati et al. [40]	1992	Static	Bending test	Flexural deflections	Rotational boundary conditions
Blasi and Sorace [41]	1994	Static-dynamic	Bending and free vibration test	Flexural deflections and natural frequencies	Rotational boundary conditions
Beconcini [42]	1996	Static	Bending test	Flexural deflections	Rotational boundary conditions
Sorace [4]	1996	Static-dynamic	Bending and free vibration test	Flexural deflections and natural frequencies	Rotational boundary conditions
Briccoli Bati and Tonietti [5]	2001	Static	Bending test	Flexural deflections	Rotational boundary conditions
Fraternali et al. [35]	2002	Numerical	Seismic analysis	Flexural mode shapes	—
Lagomarsino and Calderini [43]	2005	Pure dynamic	Free vibration test	First three natural frequencies	Rotational boundary conditions
Tullini and Laudiero [44]	2008	Pure dynamic	Free vibration test	Flexural natural frequencies	Rotational boundary conditions
Giuriani et al. [9]	2009	Analytical	Seismic analysis	Flexural mode shapes	—
Amabili et al. [46]	2010	Numerical	FE vibration analysis	Flexural mode shapes	Boundary conditions, length
Fraternali [36]	2010	Numerical	Seismic analysis	Flexural mode shapes	—
Fraternali [37]	2011	Numerical	Seismic analysis	Flexural mode shapes	—
Li et al. [50]	2011	Pure dynamic	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Milani and Tralli [38]	2012	Numerical	Seismic analysis	Flexural mode shapes	—
Tullini et al. [22]	2012	Static	Bending test	Flexural deflections	Rotational boundary conditions
Li et al. [51]	2013	Pure dynamic	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Maes et al. [52]	2013	Pure dynamic	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Rebecchi et al. [53]	2013	Pure dynamic	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Tullini [23]	2013	Static	Bending test	Flexural deflections	Boundary conditions, length
Manzoni et al. [26]	2014	Numerical	FE vibration analysis	Flexural mode shapes	Boundary conditions, length
Belleri and Moaveni [45]	2015	Numerical	Vibration analysis	Natural frequencies	Rotational boundary conditions
Rainieri and Fabbrocino [28]	2015	Pure dynamic	Ambient vibration test	Flexural natural frequencies	Boundary conditions, length
Ottoni and Blasi [47]	2016	Numerical	FE vibration analysis	Flexural mode shapes	Boundary conditions, length
Campagnari et al. [49]	2017	Numerical-dynamic	FE and free vibration test	Flexural mode shapes	Boundary conditions, length
Collini et al. [48]	2017	Numerical	FE vibration analysis	Flexural mode shapes	Boundary conditions, length
Gentile et al. [56]	2017	Pure dynamic	Free vibration test	Fundamental frequency	Boundary conditions, length
Cescatti et al. [58]	2019	Pure dynamic	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Gentile et al. [57]	2019	Pure dynamic	Free vibration test	Fundamental frequency	Boundary conditions, length
Duvnjak et al. [54]	2020	Numerical-dynamic	Numerical and free vibration test	Flexural natural frequencies	Boundary conditions, flexural stiffness, length
Ruccolo and Gentile [61]	2023	Pure dynamic	Free vibration test	Higher natural frequencies	Boundary conditions, flexural stiffness, length

Table 2. Nondestructive methods combined with new devices and artificial intelligence approaches for evaluating the axial stress in tie-rods (Sections 3.2 and 3.3). Note: the contributions have been listed based on the publication year.

Reference	Year	Approach	Type of Test	Required Parameters	Model Unknowns
Garziera et al. [64]	2011	Numerical-dynamic combined with an AI approach	Numerical and free vibration test	First six natural frequencies	Boundary conditions, length
Gentilini et al. [65]	2013	Numerical-dynamic combined with an AI approach	FE and free vibration test	Natural frequencies	Rotational boundary conditions, flexural stiffness
Resta et al. [63]	2020	Pure dynamic with the use of microphone	Free vibration test	Natural frequencies	Boundary conditions, length
Camassa et al. [29]	2021	Pure dynamic with the use of interferometric radar	Free vibration test	Natural frequencies	Boundary conditions, length
De Falco et al. [66]	2021	Numerical-dynamic combined with an AI approach	Numerical and free vibration test	Natural frequencies	Boundary conditions, flexural stiffness, length
Makoond et al. [67]	2022	Numerical-dynamic combined with an AI approach	FE and free vibration test	Natural frequencies	Boundary conditions, length

4. Works Conducted for Structural Members by Researchers Worldwide

The deformations and geometric shapes of space frames and roof trusses are directly influenced by the axial stresses in their structural members [68]. Because of the uncertainties regarding dead loads, internal restraints and boundary conditions, accurate axial stress identifications are relevant in order to assess the safety conditions of the entire space structure (Figure 1a). Similarly to what has been developed for tie-rods (Section 3.3), vibration-based axial stress evaluation methods have been combined with hybrid numerical and experimental approaches, or multi-objective optimization techniques. Specifically, the following algorithms have been established: the Genetic Algorithm and the PSO algorithm, as described in Figure 5 and Section 4.2.

Section 4

Works Conducted for Structural Members

4.1. Traditional Methods

- FE model combined with model updating procedures
- Numerical approaches
- Numerical-dynamic approaches
- Pure dynamic-based nondestructive methods
- Static-based nondestructive methods

4.2. Methods combined with AI Approaches

- Analytical-dynamic methods combined with an AI approach
    - *Artificial Neural Networks*
    - *Genetic Algorithm*
    - *Optimization Algorithms*
    - *Particle Swarm Optimization Algorithm*
- Numerical-dynamic methods combined with an AI approach
    - *Particle Swarm Optimization Algorithm*

Figure 5. Sketch of the methods currently in use for evaluating the axial stress in structural members (Sections 4.1 and 4.2).

4.1. Investigations Including Traditional Methods

Stress identification in axially loaded structural members with any given translational and rotational boundary conditions has firstly dealt with the use of FE simulations matched with model updating procedures. In references [69–75], experimental vibration responses of the entire space structure were adopted to identify the axial stress in all beam members, but the accuracy highly depends on the uncertainty of the FE model. Yet, a weighted least-squares evaluation approach has been proposed by Livingston et al. [69] which alternatively uses the two or three lowest natural frequencies, or the two lowest frequencies with their corresponding mode shapes. Also, to identify both plane- and space-frame forces, sensitivity-based methodologies have been employed in Greening and Lieven [70], Bahra and Greening [71] and Park et al. [72].

The methods presented by Li et al. [50], Li et al. [51], Maes et al. [52] and Rebecchi et al. [53], as previously described in Section 3.1, have secondly been proposed for any beam or truss member with uncertain boundary conditions, such as diagonal braces, short thick cables and struts, and with good precision. FE simulations have been employed to verify the theoretical formulations, accounting for different sensor positions, several utilizations of dynamic parameters and the boundary conditions, but the methods, as explained in Section 3.1, fail in the presence of high values of tensile stress. Subsequently, Lechner et al. [76] investigated the procedure for estimating axial stress in timber beams using vibrational bending measurements, whereas Li et al. [77] improved such a method based on the modified Timoshenko beam theory. In any case, the flexural mode shape of the member to be used in the evaluation process must be properly measured and selected. This issue may not be straightforward for a space structure, where the global modes could interfere with the local modes of the beam/s under investigation. In fact, in the work performed by Luong et al. [78], a preliminary global modal analysis of the space structure is required to determine potential local modal shapes on individual members at closely spaced frequencies. Conversely, Irawan et al. [79] underlined that the estimation error of axial stresses in the compression and tension members belonging to a steel truss varies from 0.26% to 1.99% and from 0.2% to 2.41%, respectively. Nevertheless, these methods require numerous sensors and are particularly sensitive to the selected vibration mode shapes [80]. Kernicky et al. [80] have refined these approaches to integrate six or more natural frequencies, which can be measured through one accelerometer only. Notwithstanding this, this methodology is very challenging to apply to a rigid, short, member-like component because the high-order vibration modes of such elements are hardly activated.

Hermansen and Thomsen [81] suggested two vibration-based methods to evaluate the linear boundary stiffness and damping of structural members, whilst simultaneously identifying their tensile stresses. An evaluation was executed by fitting the model boundary parameters to the recorded modal vibration data. Yet, Brøns and Thomsen [82] suggested a technique which consists in attaching an external mass with rotational inertia to one beam restraint. According to this concept, the natural frequencies of the structural member, measured by a single sensor only, change without varying the boundary stiffness and axial tensile stress. Combined with a few repetitions of frequency measurements without the external mass, the procedure furnishes information to be used in a regression model, without imposing additional unknown parameters. The external mass adds a known asymmetry, allowing a distinction between left and right, and for each added mass the number of experimental frequencies needed to achieve a reliable evaluation is roughly halved. Conversely, the problem of evaluating axial stress in members with non-uniform cross sections and unknown boundary conditions has been investigated by Zhang et al. [68]. Primarily, a dynamic coefficient was inserted into an inverse model of a stepped beam with elastic supports to overtake the numerical buckling often encountered in conventional exact methods. Subsequently, a new approach has been established to estimate the measurement error of the axial stresses in a real stepped beam through the inverse analysis of unknown boundary condition parameters using only one or two measured frequencies.

The findings of the above-mentioned researchers have underlined that there has been a significant implementation up to now, since Zhang et al. [68] explored predicting axial stress in members with non-uniform cross sections and unknown end constraints. Furthermore, Kernicky et al. [80] and Brøns and Thomsen [82] have reduced the number of sensors to be mounted to one, thus decreasing the time needed for on-site instrumentation (which is typically related to large buildings). However, such nondestructive approaches still remain sensitive to the selected vibration mode shapes of the member/s under investigation [50–53,76–79] and unworkable when the member/s belonging to the space structure is/are rigid and short. Moreover, according to the literature review, no long-term vibration-based stress estimation method designed on a one-system-per-space structure basis has been developed yet.

4.2. Investigations Including Methods Combined with Artificial Intelligence Approaches

The inverse method proposed by Talic et al. [83] consists in identifying dynamic parameters, including damping, as well as the axial stress from a few vibrational measurements along a structural member, modelled as an Euler–Bernoulli beam, using a multi-objective optimization formulation and solved via a Genetic Algorithm. To calculate output errors, the Euler–Bernoulli equation was discretized through finite differences in space and time, and reformulated to a state space system. The identifiability was additionally verified by checking the regularity of the Fisher information matrix. Yet, the methodology implemented by Luong et al. [84] also allowed us to identify the joint rigidity of axially loaded members belonging to generic space trusses using vibrational responses. In detail, the procedure has been based on the FE model updating combined with nature-inspired optimization techniques, particularly the PSO. The numerical model of the space truss has been calibrated through natural frequencies and mode shapes from free vibration tests, as well as additional information of the axial stress in the specific members based on the identified experimental modal parameters. Regarding the modeling of the joints, the numerical model of the space truss incorporates rotational springs of variable stiffness to describe the semi-rigid connections. Also, a fixity coefficient has been established for the joint flexibility evaluation. Subsequently, the researchers have calibrated the model of the space truss through a Genetic Algorithm and specific validation criteria [85]. In this case, the validation criteria have been established according to the identified natural frequencies and five amplitudes of the corresponding local mode shapes of the single members under investigation. Similarly, a PSO-algorithm-based axial stress and boundary rigidity evaluation approach has been proposed by Ding et al. [86] for structural members of space structures using multi-order natural frequency measurements. Furthermore, Dudenhausen et al. [87] also investigated an identification method on the basis of an iterative optimization procedure capable of determining the axial stress acting in compression members. In particular, a series of dynamic parameters, including the compressive stress, have iteratively been adjusted until the best agreement between the vibrational measurements and a theoretical analysis was gained. A deviation function has been established and an innovative algorithm—in this case facilitating a PSO—has been adopted to solve the optimization procedure. Six steel beam specimens have been tested in the laboratory under four distinct compressive stresses each. The average deviation over all the 24 experiments between the optimized stress and the effective one directly measured by a load cell was obtained as 7.4%.

The aforementioned progress has shown that the vibration-based methods combined with AI optimization techniques and algorithms have mainly been capable of identifying the joint rigidity and axial stress acting along structural members of space structures with rigorous procedures [84–86]. Notably, in the work presented by Dudenhausen et al. [87], the axial stress prediction in compression members has been investigated with significant improvements in terms of data interpretation. To synthesize Section 4, the principal characteristics and information (i.e., year, type of approach, test structure, type of test, required and model unknown parameters) of the works conducted worldwide for axial stress prediction in structural members, above described, have been itemized in Tables 3 and 4.

Table 3. Nondestructive traditional methods for evaluating the axial stress in structural members (Section 4.1). Note: the contributions have been listed based on the publication year.

Reference	Year	Approach	Test Structure	Type of Test	Required Parameters	Model Unknowns
Livingston et al. [69]	1995	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Greening and Lieven [70]	2003	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Bahra and Greening [71]	2006	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Park et al. [72]	2006	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Flores et al. [73]	2007	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Bahra and Greening [74]	2009	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Bahra and Greening [75]	2011	Numerical-dynamic	Space structure	FE and free vibration test	Two or three lowest natural frequencies	Boundary conditions, length
Li et al. [50]	2011	Pure dynamic	Space truss	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Lechner et al. [76]	2013	Pure dynamic	Timber beam member	Free vibration test	Flexural mode shapes	Boundary conditions, length
Li et al. [51]	2013	Pure dynamic	Space truss	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Maes et al. [52]	2013	Pure dynamic	Space truss	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Rebecchi et al. [53]	2013	Pure dynamic	Space truss	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Turco [21]	2013	Static	Space frame or truss	Bending test	Flexural displacements	Boundary conditions, length
Irawan et al. [79]	2014	Pure dynamic	Space structure	Free vibration test	Flexural mode shapes	Boundary conditions, length
Li et al. [77]	2017	Pure dynamic	Space truss	Free vibration test	Flexural mode shapes	Boundary conditions, length
Bonopera et al. [24]	2018	Static	Space frame	Bending test	Flexural displacements	Boundary conditions, length
Bonopera et al. [25]	2018	Static	Space truss	Bending test	Flexural displacements	Rotational boundary conditions
Hermansen and Thomsen [81]	2018	Pure dynamic	Beam member	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Kernicky et al. [80]	2018	Pure dynamic	Space structure	Free vibration test	First six (or more) natural frequencies	Boundary conditions, length
Luong et al. [78]	2018	Numerical	Space structure	Vibration analysis	Flexural mode shapes	Boundary conditions, length
Brøns and Thomsen [82]	2020	Pure dynamic	Beam member	Free vibration test	Flexural natural frequencies	Boundary conditions, length
Zhang et al. [68]	2023	Pure dynamic	Stepped beam member	Free vibration test	Flexural natural frequencies	Boundary conditions, length

Table 4. Nondestructive methods combined with artificial intelligence approaches for evaluating the axial stress in structural members (Section 4.2). Note: the contributions have been listed based on the publication year.

Reference	Year	Approach	Test Structure	Type of Test	Required Parameters	Model Unknowns
Talic et al. [83]	2015	Analytical-dynamic combined with an AI approach	Beam member	Analytical and free vibration test	Natural frequencies	Boundary conditions, length
Luong et al. [84]	2017	Numerical-dynamic combined with an AI approach	Space truss	FE and free vibration test	Flexural mode shapes and natural frequencies	Rotational boundary conditions
Luong et al. [85]	2017	Analytical-dynamic combined with an AI approach	Space truss	Analytical and free vibration test	Flexural mode shapes and natural frequencies	Boundary conditions, length
Ding et al. [86]	2020	Analytical-dynamic combined with an AI approach	Space structure	Analytical and free vibration test	Natural frequencies	Boundary conditions, length
Dudenhausen et al. [87]	2023	Analytical-dynamic combined with an AI approach	Compression beam member	Analytical and free vibration test	Flexural mode shapes	Boundary conditions, length

5. Conclusions and Suggestions

The research works carried out worldwide on evaluating stress in the axially loaded tie-rods of masonry buildings and structural members of space structures have been described in this article (Figure 1a,b). Numerous dynamic-based prediction methods, which rely on modal characteristics (damping, mode shape and natural frequency) as axial stress-sensitive features, have been developed, resulting in several findings. In particular, the methods have been analyzed from three categories, including the investigations into traditional ones, new devices and combinations with AI approaches (Figures 4 and 5). The latter mainly consists of hybrid methods, optimization techniques and deep learning algorithms (Artificial Neural Networks, Genetic Algorithm and PSO algorithm). Early in the text, a brief progress overview, i.e., from indirect measurements in the field of SHMA to combinations with AI approaches, was presented (Section 2). The reviewed studies have also been analyzed in terms of type of approach, test structure, type of test and required and unknown parameters (Tables 1–4). Within the limitations of this work and according to the literature review conducted, the following have been summarized as major conclusions:

- The development of long-term automatic dynamic-based approaches designed on a one-system-per-tie-rod or space structure basis is encouraged, since variations in temperature, relative humidity and moisture conditions may influence the corresponding modal characteristics.
- The development of dynamic-based methods for tie-rods and structural members with non-uniform cross sections and unknown boundary conditions is also encouraged. In the case of handmade traditional tie-rods, non-homogeneities and non-uniform cross sections can be present.
- Researchers have started to combine AI approaches with traditional dynamic-based methods to develop evaluation techniques that require a lower need for data preprocessing or hand-crafted feature extraction, thus decreasing the time needed for the overall process (Sections 3.3 and 4.2). In terms of shorter computational time, the Artificial Neural Networks are preferred over the metaheuristic approaches, i.e., the Genetic Algorithm and the PSO algorithm [88].
- The traditional dynamic-based methods remain sensitive to the selected mode shapes of the tie-rod or structural member and, unfortunately, fail in the presence of high axial stress values. This is related to the difficulty of measuring small vibrations when increasing the values of axial stress makes the element stiffer and stiffer. Furthermore, the impact force cannot be indefinitely increased if yielding must be prevented [60]. Therefore, the mode shape must be properly selected. In this respect, Rebecchi et al. [53] suggested choosing flexural mode shapes with amplitudes with the same sign. On the contrary, local mode shapes close to a straight line must be disregarded. A dynamic-

based method combined with an AI approach can make the evaluation procedure somewhat feasible (Sections 3.3 and 4.2).

- The traditional dynamic-based methods could be impracticable when the structural members are rigid and short. In this case, the combination with an AI approach can properly be employed. Vice versa, if the combination is made with a static-based vertical deflection method, a suitable way to apply the point load along the span member must be found (Section 4.1).

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