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A Review of the Vibration Analysis Methods for Frame Structures

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Abstract— Frames are basic structural components that appear in civil engineering applications, as well as chemical, mechanical and aerospace fields. With the size and complexity of modern-day structures and machinery increasing, frames are now required to withstand much larger cyclic loads. This article attempts to review some of the literature from the past twenty-one years, on how researchers analysed the vibrations in structural frames. This review also places emphasis on the methods used to analyse frames with semi-rigid connections, due to their impact on structural response. The theories used by authors to model beam and column elements, along with the methods used to solve the equations of motion are covered. Sections outlining the vibration and damage monitoring methods are also presented in this article. Other sections cover the research into soil structure interactions, the use of shape memory alloys (SMAs) and piezoelectric devices, as well as physical experiments that were conducted.

Keywords— Euler-Bernoulli beam theory, Planar frames, Spatial frames, Timoshenko beam theory, Vibration analysis.

I. INTRODUCTION

Structural frames are used for many engineering applications today, ranging from reinforcements in concrete building structures, to supports for engines, motors, tools, cranes, etc. The geometry of the frames can vary widely based on the entity being supported, and the loads they are required to withstand. Frames are composed of multiple beams and columns that may be joined via connectors that can be assumed to be completely rigid, or semi-rigid during analysis. A major engineering problem is predicting the behavior of the frames with semi-rigid connections under the influence of dynamic excitation. Some reviews have been done throughout the years covering the vibrations of structures. Methods for detecting damages in frames by using vibration monitoring were reviewed by [1]. A review on the vibration monitoring techniques used to determine the health of structures in the manufacturing field was conducted by [2]. Vibration based; condition monitoring was also reviewed by [3]. The review focused on measuring changes in the time, frequency, and modal domains. Reference [4] covered the methods used to measure and illustrate the ambient vibrations in structures. Reference [5] reviewed the structural heath monitoring and damage detection methods used, with focus given to composite structures. Reference [6] reviewed the methods used to analyze the vibrations in straight and curved beams. Reference [7] reviewed the methods for designing a frame foundation structure and dynamically analyzing them. Researchers often assumed the connections in frames to be fully rigid during calculations, however, this is not an accurate representation of what occurs in reality. Joints usually behave in a semi-rigid manner; hence, it is important that this factor is taken into consideration when attempting to accurately determine the dynamic response of frame structures. This review covers the research from the past twenty-one years (2000-2021), on the vibration analysis methods used for frame structures, with emphasis given to frames containing semi-rigid connection.

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II. BEAM THEORIES

Frames are structures that are typically made up of multiple beam and column structures joined together with varying connection methods (bolted, welded, special connections, etc.). When dealing with these structures (portal, X-braced, L-shaped, K-shaped, etc.), researchers typically apply beam theories to model the elements of the frame. These theories are used to describe the motion of each element, and hence, predict the mode shapes and natural frequencies. To build these formulations, researchers often used stiffness parameters to account for bending, torsion, and in some cases, the shear deformation of the beams. In most cases the use of bending stiffness or a form of shear stiffness is used.

A. Stiffness parameters

Reference [8] modelled braced frame members with bending stiffness, (EI_b) and racking shear stiffness, (GA_b) when developing equations for the natural periods of vibrations. Results were found to be within 4% of those obtained from finite element methods (FEM). When dynamically analyzing a suspended-dome frame, [9] also used bending stiffness paraments in their double element model. Bending stiffness equations were also used by [10] to model semi-rigid frames under seismic action. They found that increasing stiffness, decreased lateral displacements. References [11]-[13] also treated the frames as isotropic homogeneous members, applying the same stiffness parameters. Reference [14] modelled semi-rigid joints by means of an initial stiffness equation, which was a function of the bending stiffness and a known fixity factor. In computer

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implementation it was noted that the stiffness of the joints could be updated for each load step. Reference [15] proposed that the joint stiffness parameters of frames be determined by finite element updating (FEMU), through a reduction of error in natural frequencies. They found that the first three mode shapes were in good agreement but began deviating at higher modes because of poor updating parameters.

B. Euler-Bernoulli beam theory

Euler-Bernoulli beam theory assumes that the cross section of the beam stays plane and perpendicular to the neutral axis after deformation occurs. The effects of rotary inertia and shear deformation are neglected, which is acceptable for determining lower modes of vibration. Reference [16] used separation of variables on the (EB) beam equations of motion to formulate expressions for the vibration analysis of frames with inclined members. The equations developed can be applied to frames with rigid, hinged, and fixed connections. Additionally, it was found that asymmetric and symmetric modes alternated, but this pattern was broken when frequencies passed over the axial vibration frequencies of the bar. This research was also used to analyze X-Braced, and multi-story X-Braced portal frames. Reference [17] obtained the seismic parameters of a T-shape frame with semi-rigid connections by using a closed-form solution. The differential equations of motion for a (EB) beam were solved directly, using the Fourier transform and complementary solutions. Results showed that increasing system stiffness, increases the natural frequency, and natural frequencies of a T-shape frame are equal to a simply supported beam. Reference [18] analyzed the mode shapes and resonant frequencies of an ultrasonic elliptical vibration tool based on a portal frame structure by using a transfer matrix approach to solving the (EB) beam vibration equations. The dynamic behavior of the tool was successfully modelled and extended to analyze the dynamics of the tool during operation. Variational calculus was applied to the equations of motion of a (EB) beam by [19] to investigate the dynamic characteristics of a steel L-frame with cracks. This investigation showed that expressions developed by [20] could be applied to the modelling of cracks in a plane flexural problem. Reference [21] used (EB) beam theory to analyze the vibrations of a jib crane. The equations of motion were solved using separable solutions and Newton-Raphson iterations to give the frequencies of the model. In the end, the investigation successfully developed approximate mode equations by expanding mode shapes as the expansion function for the beam. Reference [22] investigated the vibration characteristics of a plane steel frame using a corotational updated Lagrangian formulation. The equations of motion for a (EB) beam were solved using both Newmark's implicit time integration method and Newton-Raphson technique to find the natural frequencies. They found that imperfections in the structure can greatly impact vibration amplitude and that the P-Δ and P-δ effects can reduce structural stiffness. Basic Displacement functions (BDF’s) were developed by [23] for analyzing a non-prismatic semi-rigid frame with elements that followed (EB) beam theory. They successfully formulated the exact shape functions and solutions for the model at faster computational times. This method can also be applied to the non-linear, and dynamic analysis of frames. Reference [24] used a combination of both analytical and numerical methods to conduct a dynamic analysis of planar serial-frame structures. Numerical implementation of a transfer matrix solution to the equations of motion for a Euler-Bernoulli (EB) beam were employed. This resulted in only six unknown coefficients leading to faster computation speeds. The equations of transverse and longitudinal motion for Euler-Bernoulli beam theory used by [24] are given by (1a) and (1b) respectfully.

$$EI\frac{\partial^4 Y_i(X,T)}{\partial X^4}+\rho A\frac{\partial^2 Y_i(X,T)}{\partial T^2}=0 \tag{1a}$$

$$E\frac{\partial^2 U_i(X,T)}{\partial X^2}+\rho\frac{\partial^2 U_i(X,T)}{\partial T^2}=0 \tag{1b}$$

Where, E is the Young’s modulus of the frame material, I is the moment of inertia of the cross-section of the beam, ρ is the density of the material and A is the cross-sectional area.

C. Timoshenko Beam Theory

Timoshenko beam theory was typically used by researchers when dealing with thick beams, where the effects of inertia and shear deformation could not be neglected. Timoshenko beam theory can also determine the frequency of higher modes to a greater degree of accuracy than Euler-Bernoulli beam theory. Reference [25] used Timoshenko theory to model the bending vibrations of space frames when using the wave-based analytical approach. The analytical results were shown to be in good agreement with an experimental two-story space frame proving that is a viable method in analyzing the complex vibrations in space frames. Timoshenko beam theory was employed by [26] to develop an algorithm to analyze the non-linear characteristics of a portal frame supported by an actuator. The results of the algorithm were verified using ANSYS software, indicating that it was a reliable and efficient method to apply to frames. Reference [27] used Timoshenko beam theory to model and determine the natural frequencies of a steel frame with an inclined member. Results of the investigation indicated that the analytical and experimental approach yielded smaller frequencies, when compared to FEM. Reference [28] based their spectral bending element model on Timoshenko beam theory when analyzing the vibration bandgap of periodic frames. It was observed that SEM used in this manner produced highly accurate results, specifically at higher frequencies when compared to FEM. Reference [29] used Timoshenko beam theory to model the displacements of a beam when developing a frame element with semi-rigid connections. This proved to be simpler, in both obtaining solutions for the natural frequencies and modelling frame with semi- rigid connections, when compared to FEM. Reference [30] investigated the effects of flexible and eccentric connections on the dynamic behavior of plane steel frames. Timoshenko theory and a power series expansion were used to model the beam for the analysis.

During this investigation the development of finite element matrices that incorporated eccentricities and flexibility effects was achieved. Reference [31] used Timoshenko beam theory in their new approach of modelling a unified fully conforming plane stress rectangular finite element for thick beams. A fully conforming 32dof planar finite element formulation was successfully developed to determine the natural frequencies of frames, or other steel structures containing thick beams. Reference [32] used Timoshenko beam theory to formulate higher order elements when performing a modal analysis on small frames. Upon analyzing a small L-frame, it was concluded that a quadratic Timoshenko beam element was best suited for analyzing a frame with components where the length is relatively short compared to the width. The use of both Timoshenko bending theory and EB theory was employed by [33]. A wave vibration approach was used to analyze the in-plane, coupled bending, and longitudinal vibrations of portal and L-frames. Comparisons were made between both theories which indicated that Timoshenko beam theory was more suitable for higher frequencies, but the 5 values obtained were slightly smaller than those obtained from EB beam theory. The equations of motion for Timoshenko beam theory are taken from [33].

$$GAk\left[\frac{\partial\psi(x,t)}{\partial x}-\frac{\partial^2 y(x,t)}{\partial x^2}\right]+\rho A\frac{\partial^2 y(x,t)}{\partial t^2} = q(x,t) \qquad (2a)$$

$$EI\frac{\partial^2\psi(x,t)}{\partial x^2}+GA\left[\frac{\partial y(x,t)}{\partial x}-\psi(x,t)\right]-\rho I\frac{\partial^2\psi(x,t)}{\partial t^2} = 0 \qquad (2b)$$

$$\rho A\frac{\partial^2 u(x,t)}{\partial x^2}-EA\frac{\partial^2 u(x,t)}{\partial x^2} = p(x,t) \qquad (2c)$$

Where x, is the position along the beam axis, t is time, $y(x,t)$ and $u(x,t)$ are the transverse and longitudinal deflections of the center lines of the beam respectively, $q(x,t)$ and $p(x,t)$ are the externally applied transverse and longitudinal forces respectively, G is the shear modulus and κ is the shear coefficient.

III. METHODS FOR DETERMINING NATURAL FREQUENCIES

A. Dynamic Stiffness Method

Reference [34] developed a dynamic stiffness matrix to analyze how the behavior of plane steel frames were affected by nodal flexibility and damping. The formulations developed, could be extended from 2D element analysis to 3D element analysis. A dynamic stiffness matrix was also developed by [35] to model and analyze the seismic response of a beam with viscoelastic hinges at both ends. The study found that formulations could be extended to model and dynamically analyze a steel frame with viscoelastic connections. Reference [36] obtained the exact dynamic stiffness matrix of a beam element, for their investigation into the dynamic responses of small-size frames. The Wittrick-Williams method was used to determine the natural frequencies of the nano-frames. The author stated that this method can model each member of the frame by a single exact element without internal meshing. The combined use of the Wittrick-Williams algorithm and dynamic stiffness method was also employed by [37] to determine the natural frequencies of a Timoshenko frame. This investigation confirmed that the natural frequencies of the Timoshenko beams can be calculated by the Wittrick-Williams algorithm as functions of the material parameters. Reference [38] produced a computational model of an indefinitely long 2D portal frame by using the dynamic stiffness method and periodic structure theory. Their investigation allows for the dynamic analysis of base-isolated buildings to be performed by standard personal computers due to higher computational efficiency.

B. Differential Transform Method

Reference [39] applied the differential transform method and Fourier transform to solve for the natural frequencies when analyzing the free vibrations of a portal frame that was assumed to be a special case gabled frame. The method was verified by comparing the results obtained, to those of portal frames from existing literature, as well as FEM. Reference [40] also applied the differential transform method when analyzing the in-plane vibrations of a frame with four arbitrary inclined members. Formulations were obtained for frequency parameters and mode shapes, the accuracy of which was validated using FEM. The method was also extended to dynamically analyze a standard portal frame.

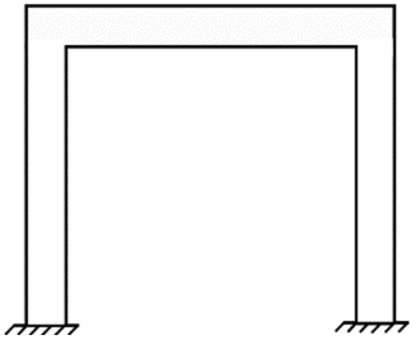

Fig. 1. Example of basic portal frame

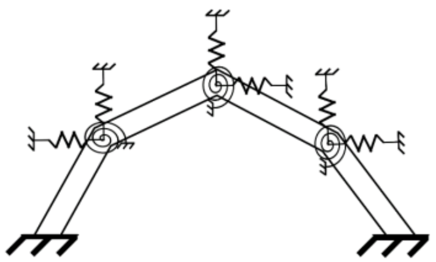

Fig. 2. Example of plane frame with arbitrarily inclined members and semi-rigid joints

C. *Transfer Matrix Approach*

Reference [41] implemented the transfer matrix method of multi-body systems when analyzing portal frames. The investigation successfully achieved computing times that were one-seventh that of ANSYS finite element methods. Reference [42] proposed a method to analyze the vibration of asymmetric plane steel frames. The transfer matrix method and boundary conditions were applied to solving the equations of motion which gave the natural frequencies. The results obtained by the study were found to be in good agreement with those in literature and errors less than 5% were achieved.

D. *Newmark method*

To determine the dynamic response of frames subjected to moving point loads [43] made use of the numerical time integration and finite element methods. The study also applied this method to analyze frames with springs attached, subjected to moving loads. The method also proved to be highly accurate when compared with previous literature. The dynamic response of three semi-rigid frames were determined by [44] in an effort to evaluate the seismic performance of frames. The Newmark method was applied to solving the equations of motion which yielded accurate results. The Newmark implicit numerical integration method was also used by [45] to solve the differential equations of motion for slender frames with semi-rigid connections. Results indicated that this method could accurately determine the effects of the connection stiffness and the important role it plays in engineering applications. The Newmark method was also applied by [46] when solving the equations of motions for frames with semi-rigid joints. They validated the method by applying it to a practical case study from Eurocode 8. Reference [47], [48] used both the Newmark and Newton-Raphson methods to determine the second order effects of joint rigidity in steel frames impacted by dynamic loads. The method was applied to analyzing several frames, including L-shaped frames and six story Vogel frames. Their analysis showed that the method was efficient and accurate for calculating the realistic effects of dynamic loading on semi-rigid joints. Reference [49] also combined the Newmark and Newton-Raphson methods to determine the nonlinear response of frames with semi-rigid connections. The method was able to produce accurate results even though a poor finite element mesh was used. The natural frequencies of spatial steel frames were calculated by [50] via the Newmark and Newton-Raphson methods. The method was able to efficiently, and accurately calculate the nonlinear behavior of steel frames subject to earthquake excitation. Reference [51] used the Newmark method to solve the equations of motion when dynamically analyzing multi-story steel frame structures with semi-rigid connections. The method allowed the analysis to be performed faster and yield accurate solutions. In an effort to optimize the seismic design of steel frame structures, [52] used the Newmark method of direct integration to determine the structural responses. The method was found to be highly accurate as well as reduced the amount of hand calculations necessary. Reference [53] investigated the two-dimensional analysis of plane frames under arbitrary ground motions. Newmark's method was implemented in the form of MATLAB code to find the natural vibrations. The code used, can be forwarded to designing multi-story and multi-bay frames.

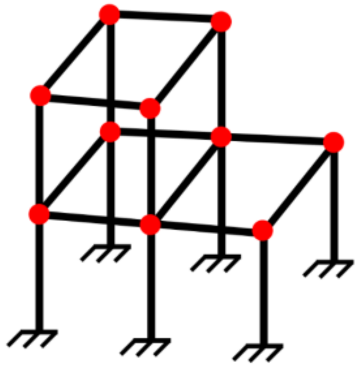

Fig. 3. Example of a spatial frame with two bays

E. *Newton-Raphson Method*

Reference [54] used the Newton-Raphson together with an arc-length approach to calculate the modal amplitudes and frequencies of plane frames subjected to base excitation. They found that the method developed could produce resonance curves with less processing power and high precision. Reference [55] applied the Newton-Raphson method to solve the equations of motion for flexibly connected steel frames under earthquake conditions. Their model was able to maintain the same number of degrees of freedom as a fully rigid system making it efficient and simple. Reference [56] performed a nonlinear inelastic time-history analysis of three-dimensional semi-rigid steel frames. The Newton-Raphson combined with the Hilber–Hughes–Taylor method was used to solve the nonlinear equations of motion. Efficiency and accuracy were verified by applying the method to analyze various frame structures. It was also found that the natural periods of the frame could be accurately predicted. Reference [57] analyzed the seismic performance of steel portal frames with semi-rigid connections. The frequencies of the frames were found by using the Newton-Raphson method to solve the non-linear equations. When compared to past literature the results were found to be in good agreement.

F. *Additional Techniques used to Determine Modal Characteristics*

Reference [58] used the Hilber-Hughes-Taylor method to solve the equations of motion when dynamically analyzing frames with semi-rigid and eccentric joints. They introduced a corrective stiffness matrix to the standard stiffness matrix to account for the effects of the joint semi-rigidity. Reference [59] used the Hilbert-Huang Transformation to determine the time dependent frequencies of steel frames. This method was able to determine the instantaneous frequencies of the steel frame. Reference [60] investigated the static and dynamic response of steel frames with semi-rigid connections. They used a member discrete element method and solved the equations of motion with the central difference method. The method was able to accurately predict the behavior of the semi-rigid connections. A subspace iteration method was used by [61]

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to solve the eigenvalue problems for steel-concrete composite frames. Their model determined the frequencies considering the effects of the semi-rigid joints and interface slip. Reference [62] used modal analysis to determine the natural periods of semi-rigid frames with different types of connections. The study found that flexibility of connections can decrease frequency while increasing the magnitude of the period. Reference [63] analyzed the dynamic properties of plane steel frames with different setbacks. Modal analysis was used to determine the natural periods of several multi-story frames. Results indicated that natural periods of vibrations were not only functions of the height of the structure. Reference [64] dynamically analyzed plane frames with different models for the semi-rigid connections. Modal analysis was used to find the dynamic characteristics of the systems. Results showed that connection flexibility increased the periods of vibrations while decreasing frequency. A decrease in natural frequencies was also noted by [65] who used modal analysis to investigate the effects of semi-rigid connections on steel structures. Modal analysis was also used by [66] to determine the natural frequencies and mode shapes of plane frames. Generalized MATLAB code was also developed to determine the natural periods of frames with an arbitrary number of stories. Reference [67] developed models of reinforced concrete (RC) framed buildings with varying heights subjected to seismic loads. Spectral analysis was used to determine the natural periods and seismic response of the RC frames. It was noted that displacements measured by the spectral analysis were greater than those of the modal analysis. Modal analysis was used by [68] to determine the dynamic response due to vertical irregularities at the top of a steel tower. They found that when some beam members were removed the frequencies of the modes increased.

IV. EXPERIMENTAL INVESTIGATIONS

Reference [69] used a shake table to apply dynamic loads to steel frames when analyzing joint stiffness. Accelerometers were used to measure the acceleration and displacements of the frame. The model was also developed and tested in ANSYS yielding similar results to the experiment. Additionally, the experiment can be extended to analyzing the dynamics of damaged steel frames. The shaking table test was also used by [70] to investigate the seismic behavior of a half scaled two story braced steel frame. Accelerometers were used to measure the accelerations and of the structure. They noted that higher forces were developed due to inertial loads created by the rocking of the frame.

V. FRAMES MADE WITH SMART MATERIALS

A. *Piezoelectric frames*

The vibration suppression of steel frames structures with piezoelectric rods and their dynamic response was investigated by [71]. Spectral element method was used to determine the vibration response of the system. The study concluded that the accuracy and efficiency of SEM are better than those obtained from FEM. They also determine that piezoelectric rods can effectively suppress the near and far field vibrations in steel frame structures.

B. *Frames with shape memory alloy*

The implementation of super elastic NiTi shape memory alloy (SMA) wires and bars, for the structural control of buildings subjected to earthquakes was investigated by [72]. The study showed that the alloy was able to resist any permanent deformation due to its recentering capability. Reference [73] used NiTi SMA wire dampers to reduce the seismic response of steel structures. A shake table test was used to apply the excitation with results indicating that higher excitations reduced the effectiveness due to martensitic hardening. Reference [74] investigated the seismic performance of super elastic SMA bolts being used to connect modular steel braced frames. They found that the use of super elastic SMA bolts proved effective when placed in the right locations. The use of SMA braced framed was also investigated by [75]. A nonlinear time history analysis was conducted on different multi-story buildings with results indicating that residual roof displacement and inter-story drifts are reduced with SMA braces. Reference [76] investigated the use of SMAs as the connections at the plastic hinge regions of the beams. A nonlinear time history analysis was done on frames subjected to earthquake ground motions using Seismostruct software. Results showed that using SMAs as connections, was more effective than using them as bracings. Reference [77] investigated the effectiveness of SMA dampers in frame structures. Finite element method was used to perform a free and forced vibration of the frame and results showed that SMA dampers have good potential as energy dissipating devices. A nonlinear time history analysis was performed on a 9-storey, steel frame building equipped with SMAs, [78]. They also found that SMAs reduced inter-story drift and residual drift. A new use of SMAs as reinforcements for concrete frames was investigated by [79]. Finite element programs were used to assess the seismic performance of two eight-story structures. Results indicated that the SMA reinforced frames were able to reduce the inter and top story drifts of the frames.

VI. DAMAGES IN FRAMES

Damages in frames can lead to stress concentrations developing in the structure. This can have minor or drastic effects on the natural periods of vibration of the frames. Some research has been conducted in determining the impact that cracks and other damages may have on the natural frequencies. The research reviewed, also focuses on how the location of damages can be detected using vibrations. Reference [80] conducted experiments to assess the impact of damages on the dynamic characteristics of steel frames. They found that the natural frequency decreases as the severity of the crack increases. Reference [81] used modal analysis and experiments to determine the change in dynamic characteristics of damaged, reinforced concrete frames. They observed that lower mode frequencies saw a greater reduction than higher modes. Reference [82] investigated the effects of crack depth and location on the vibration response of frame structures. Finite element method was used to analyze the frames with results showing that natural frequency saw the biggest drop when cracks were located near the nodal connections. The effects of corrosion on the dynamic response of reinforced concrete (RC) beams were investigated by [83]. Experimental results showed that stiffness and natural frequencies decreased. The results were also forwarded to monitoring the health of RC bridge structures. Reference [84] experimentally investigated how cracks in steel frame structures can affect their dynamic response. They noted that the damaged structure exhibited irregular responses as well as lower structural stiffness. A cracked frame element based on a force formulation method, and EB beam theory was proposed by [85]. The element could be applied to crack detection and provides exact results for the dynamic analysis of cracked steel frames. Reference [86] analyzed the vibrations of cracked frames with viscous damping, they used EB beam theory to develop their beam elements. Their results aided in determining the parameters for the most effective damping of the frame. Reference [87] conducted a free vibration analysis of frames with multiple cracks using EB beam theory and the dynamic stiffness method. The method was verified thorough previous literature, it can also be forwarded to determining the location of cracks in frames. The behavior of damaged steel structures was analyzed by [88]. The element was based on EB beam theory, and the transfer matrix approach was used to determine the stiffness matrix, as well as mode shapes of the frames. Results were found to be in good agreement with those from previous literature. Reference [89] derived the stiffness matrix for a Timoshenko beam element when investigating the vibration characteristics of a plane frame with a single edge crack. They found that as crack dept increases the bending moment moved towards the stiffer parts of the structure. Reference [90] investigated the use of a nonlinear programming, based on a simplified dynamic stiffness model to detect cracks in structures. The problem was solved by using MATLAB optimization toolbox, with numerical results proving the efficiency and simplicity of the model.

VII. VIBRATION MONITORING

Reference [91] proposed a method to measure the vibrations in 3D steel frame structures by means of smartphones. They found that the results obtained from smartphones were in good agreement with those obtained from piezoelectric devices. In some cases, the smartphones were able to monitor structures with low natural frequencies more effectively. A review of the advances in structural health monitoring was done by [92]. Reference [93] took vibration measurements from a 17-story steel framed building, which was monitored by an accelerometer network. Reference [94] proposed a new method to detect damages in steel frames by means of piezoelectric strain gauges and accelerometers. Reference [95] developed a dynamic strain-based sensing system, using piezoelectric film sensors, to monitor and detect seismic damage in steel buildings. The study was verified via vibration tests, using a one to four scale testbed. A new approach to vibration-based damage detection was proposed by [96]. The method made use of a one-dimensional neural network which allowed for the real-time damage monitoring. Reference [97] proposed a combination of both an artificial neural network and genetic algorithms for vibration-based structural damage identification. They verified the method by performing experiments on a scaled 3-storey spatial frame which pinpointed the location and severity of the damage. An algorithm for detecting damages in building frames subjected to base excitation was also proposed by [98]. Their algorithm identified the dynamic characteristics of the steel frame as well as any damages sustained. Reference [99] used vibration displacement and parametric based neural networks for damage identification in steel frame structures. The method was verified by an experimental shake table test. EB beam theory and the spectral element method was used by [100] to detect the cracks in frame structures. They made use of the impacts that cracks had on wave propagation to determine severity and location of the cracks.

VIII. OTHER FACTORS

A. *Frames with added loads*

Reference [101] experimentally, investigated the change in natural frequencies of a 5-storey steel-frame structure with mass added to each story. They determined the physical parameters required to find the natural frequency of the structure. Reference [102] used ANSYS software and a shake table test to dynamically analyze a scaled down model of a steel frame with added mass. They stated that a shaking table can be used on small scale models with added mass affected only by uniform ground motion. A shake table was also used by [103] to apply the excitation to a steel frame with various added masses. They noted that the method was able to mimic wind excitation thorough the use of the shake table.

B. *Damped frames*

Reference [104] experimentally investigated the impact of viscoelastic dampers in steel frames. The experiments lead to the development of a bilinear model with modal parameters which can be used to obtain the dynamic response of damped structures. Shake table tests were carried out by [105] to investigate the dynamic behavior of frames with viscoelastic dampers. Their experiments provided data which allowed for the prediction of the seismic response of damped steel frames. Reference [106] investigated the effectiveness of a new type of viscoelastic damper in steel frames, through experiments and finite element analysis. The dynamic response of viscoelastic frames was also investigated experimentally by [107]. They found that the first mode of the structure predominated over other modes. Reference [108] used modal analysis to analyze higher mode effects, of viscoelastic damped frames. They noted that the modal analysis was more conservative than other methods when determining the frequency of higher modes.

C. *Frame and Soil Interactions*

Reference [109] presented a parametric analysis on how soils affected the performance of moment resisting frames. Both a modal spectral analysis, and static non-linear analysis were carried out to observe the effects of the soil on the structure's natural periods. Multiple frames of varying stories were tested, results indicated that for loose soils the period of vibration and top displacements increased. Reference [110] investigated the effects of vertical components on soil structure interactions (SSI) for multiple story frames. The soil structure was created using a cone model and the simulations were carried out using OpenSees software. They concluded that vertical ground motion should be included for reliable seismic assessments. Reference [111] conducted a numerical investigation into the dynamic behavior of unbraced steel frames resting on soft ground. Modal analysis was used to determine the dynamic response of the structure. It was concluded that the base shear for frames on soft ground is less than that of frames with fixed bases.

IX. SUMMARY

Over the course of this literature review, 110 articles from the years 2000 to 2021, covering the topic of vibrations in frame structures were summarized. Upon reviewing the articles, some observations were made with respect to the methods employed by authors when analyzing the various frame structures. When formulating elements, 2-dimensional EB or Timoshenko beam theory was preferred, with very few researchers opting for higher-order beam theories. Researchers placed importance on simulating joint semi-rigidity, with approximately 20% of investigations covering the topic. When solving the equations of motion for frames with semi-rigid joints, the Newton-Raphson and Newmark methods accounted for approximately 50% of the techniques used. It is worth noting that researchers preferred Newmark's method or modal analysis overall, as these made up more than a quarter of all methods applied. Table I further summarizes the analysis methods used by researchers and the types of frames investigated. Authors also investigated the use of SMAs as dampers, joint connections, and bracings, with analysis being performed via FEM, as well as shaking-table tests. There was little information gathered with respect to physical experiments, which made up less than 8% of articles reviewed. There was also very little information available about RC frames, with few articles in this review covering the topic. When investigating vibrations and vibration-based, damage monitoring, authors made use of advances in technology. They employed devices such as smartphones or built neural networks and algorithms to measure and analyze vibrations in damaged and undamaged structures. Three articles on the topic of frames with added mass were reviewed. They made use of shake-table tests and finite element software to analyze the structures. Researchers also investigated other factors such as damped frames, the use of piezoelectric vibration suppression devices and the impacts of SSI. Upon reviewing the literature, future research should be directed towards dynamically analyzing fiber reinforced composite frame structures as well the use of piezoelectric devices in frame structures.

TABLE I:
METHODS USED BY RESEARCHERS TO ANALYZE THEIR RESPECTIVE FRAMES

Type of frame analysed	Method used to calculate natural frequencies	Reference
Plane Steel Frame	Dynamic Stiffness Method	Ref. [34]
	Transfer Matrix Approach	Ref. [42]
	Newmark's Method	Ref. [53]
	Additional Modal Analysis Techniques	Refs. [59],[60],[62]
Portal Frame	Dynamic Stiffness Method	Ref. [38]
	Transfer Matrix Approach	Ref. [41]
Gabled Frame	Differential Transform Method	Ref. [39]
Frames with Semi-Rigid Connections	Newmark's Method	Refs. [44]-[49],[51]
	Newton-Raphson	Refs. [55]-[57]
	Additional Modal Analysis Techniques	Refs. [58],[61]
Spatial Steel Frames	Newmark's Method	Ref. [50]
Reinforced Concrete Frames	Additional Modal Analysis Techniques	Ref. [63]

APPENDIX

A. Notation

A	cross-sectional area
E	Young's modulus of an isotropic material
G	shear modulus
I	area moment of inertia of cross-section
p, q	externally applied transverse and longitudinal loads respectively
t	time
x	position along beam axis
y, u	transverse and longitudinal displacements along the center line of the beam respectively
κ	shear coefficient
ρ	density of material

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