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Non-destructive Assessment of the Axial Stress State in Iron and Steel Truss Structures by Dynamic Measurements

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Abstract

This paper is concerned with the inverse identification of the stress state in axially loaded slender members of iron and steel truss structures using measured dynamic data. A methodology is proposed based on the finite element model updating coupled with nature-inspired optimization techniques, in particular the particle swarm optimization. The numerical model of truss structures is calibrated using natural frequencies and mode shapes from vibration tests, as well as additional information of the axial forces in selected truss members based on the experimentally identified modal parameters. The results of the identification are the axial forces or corresponding stresses in truss structures and the joint rigidity in relation to pinned and rigid conditions. Attention is given to several examined aspects, including the effects of the axial tensile and compressive forces on the dynamic responses of trusses, mode pairing criteria, as well as modeling assumptions of joints and the use of a joint rigidity parameter. Considering the pairing of modes, it is performed by adapting an enhanced modal assurance criterion that allows the selection of desired clusters of degrees-of-freedom. Thus, information extracted from the measurements related to specific modes is utilized in a more beneficial way. For modeling of joints, the numerical model of a truss structure includes rotational springs of variable stiffness to represent semi-rigid connections. Moreover, a fixity factor is introduced for practical estimation of the joint flexibility. The effectiveness of the proposed methodology is demonstrated by case studies involving simulated and laboratory experimental data.

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Keywords: Lightweight truss structures; stress state; modal parameters; finite element model updating; nature-inspired optimization techniques

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1. Introduction

The determination of the axial forces and corresponding stresses in truss members is important to ascertain the structural capacity of existing trusses. Lightweight iron and steel truss structures are in use in many constructions, including historic monuments. For example, the iron roof trusses of the State Hermitage Museum in St. Petersburg are greatly revealing ensembles from early days of the European iron construction [1], thanks to a wide variety of structural prototypes and details. The assessment methods require the respect of the original structure and practicability.

In cases of degradation, presence of damages or change in the intended use, safety evaluation of existing trusses is necessary. The estimation of the axial forces in truss structures can be made by means of static calculations, if precise information about parameters such as external loads and joint connections are given. However, limitations often exist in acquiring accurate information or making reasonable assumptions about the uncertain input parameters. Therefore, inverse methods have been applied. In inverse methods, the unknown input parameters, e.g. the load and joint stiffness, are to be determined based on the output parameters of the static and/or dynamic responses of the structures.

Over the past decades, researchers have been exploiting many procedures for the non-destructive inverse identification of the axial forces in structural members. The methods can be categorized according to different types of civil engineering structures, i.e. columns, cables, tie-rods and trusses, or depending whether static, mixed static-dynamic or purely dynamic approaches are applied [2]. Regarding axially loaded members as part of a truss structure, selected relevant work are [3-8]. While these work all use dynamic-based methods, their approaches can be divided into two directions, (i) finite element (FE) modeling coupled with model updating techniques, which concern the multiple axial force identification of a global truss-type structure ([3-4], [8]); and (ii) analytical-based algorithm that estimates the axial force of a single bar with unknown boundary conditions, assuming as member of a structure [5-7]. For clarity and considering the above-mentioned approaches, global analysis is referred in the present work as analysis of a whole truss structure, while local analysis is associated with analysis of single truss members.

The shortcoming of the methods by [3-4] is that by using sensitivity-based techniques, the results are highly dependent on the assumptions of a start point for iteration leading to convergence. In addition, difficulties in modelling joints were noted. The analytical-based algorithms suggested by [5-7], even though they offer a simplified analysis procedure of a single structural member, have the disadvantage that the identified force is subject to small errors of the input parameters. Moreover, the method for single beams do not apply straightforwardly to a truss structure, as an accurate global model of the structure cannot be obtained for predicting the structural responses under alternative loading arrangements. Recently, a methodology developed by [8] uses the FE models and optimization strategies, in particular a genetic algorithm. It demonstrates the advantages of non-dependence of initial values of the target parameters and achievement of multiple member axial forces of global truss-like structures. Nevertheless, the phenomenon related to the coexistence of tensile and compressive forces in trusses with countering effects on the modal parameters has not been investigated.

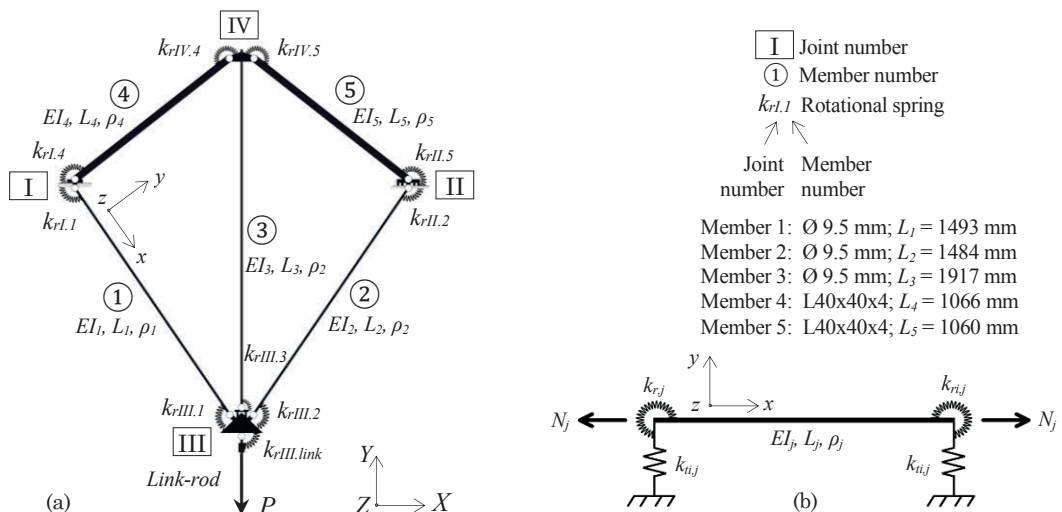


Fig. 1. Five-bar truss structural system: (a) global analysis of the whole truss; (b) local analysis of a single bar as member of the truss.

This paper addresses the identification of the multiple axial forces in truss structures using the FE model updating coupled with a nature-inspired optimization strategy, i.e. the particle swarm optimization (PSO) [9]. So far, PSO is not a regularly referenced methodology in the scope of model updating for the structural parameter estimation of trusses. Thus, the suitability of PSO is studied. The approach of the work is based on the method described in [8] but includes enhancement with respect to the definition of an objective function as well as implementation of an innovative mode pairing criteria based on modal strain energies. Furthermore, the mutual effects of the tensile and compressive forces on the dynamic behavior of trusses are discussed. Besides, the modelling of joints with rotational springs is described. For the verification of the approach, a five-bar truss is examined by numerical study and laboratory experiments.

2. Proposed methodology

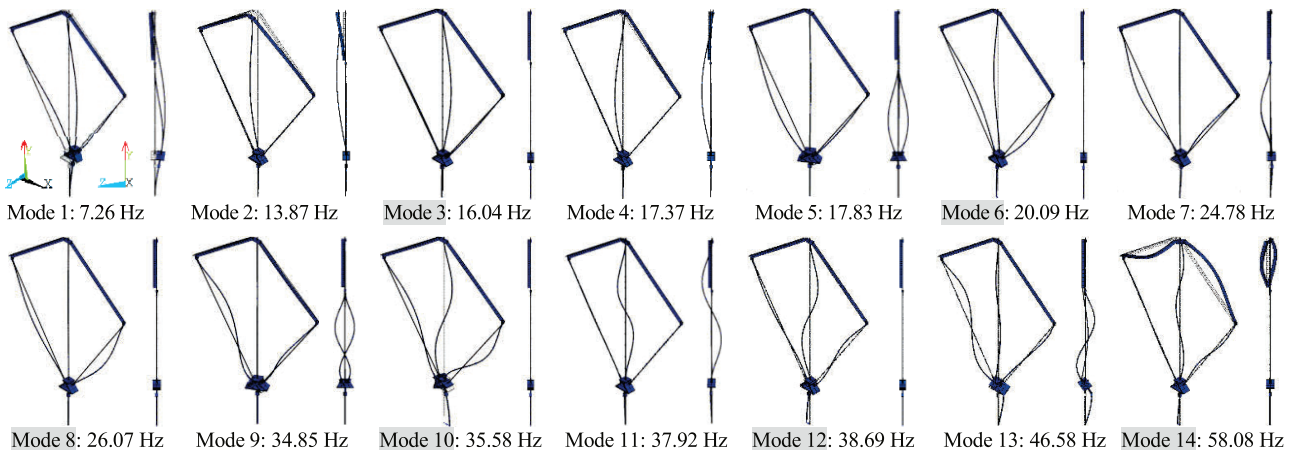
The proposed approach combines the results of a global analysis of a truss structure together with the local analysis of its members. The natural frequencies and mode shapes of the global truss as well as its local members are acquired from vibration measurements. The calibration of the FE model of the truss is carried out based on experimentally identified natural frequencies and global mode shapes. Moreover, the axial forces in selected members of the truss are used. They are estimated from the natural frequencies and five amplitudes of the local mode shapes of individual members using an analytical-based algorithm developed by [7]. The load and rotational spring stiffness of joints are assumed as the unknowns, which are included as updating parameters into an optimization process driven by PSO. PSO is a nature-inspired computational search and optimization method utilizing swarm intelligence. It has wide applications in multi-disciplinary fields. Description and application of PSO are given for instance in [9] and [10].

The objective function is defined to contain the residuals of the differences between the measured and calculated modal properties of the truss, as well as the member axial forces using an analytical-based algorithm

$$f_{obj} = a \sum_{i=1}^{nmodes} \left| \frac{f_i^{num} - f_i^{exp}}{f_i^{exp}} \right| + b \sum_{i=1}^{nmodes} |MAC(\phi_i^{exp}, \phi_i^{num}) - 1| + c \sum_{j=1}^{nbars} \left| \frac{N_j^{num} - N_j^a}{N_j^{ref}} \right| \tag{1}$$

where a , b and c are weighting factors for the terms of the objective function, assuming in this case equal to one; f_i^{exp} , f_i^{num} , ϕ_i^{exp} and ϕ_i^{num} are the experimentally identified and numerically calculated natural frequencies and mode shapes of mode i ; N_j^{num} is the numerically calculated axial force by static load equilibrium in selected member j ; N_j^a is the analytically-based identified axial force based on [7]; N_j^{ref} is the reference axial force i.e. $N_j^{ref} = A_j \sigma_j^{ref}$; σ_j^{ref} is the reference stress in individual member j , assuming in this case at an intermediate level of 50 N/mm². N_j^{ref} is used as the divisor instead of N_j^a because N_j^a may differ significantly at a low or high value of the force.

For the understanding of the assumed unknowns, a five-member truss structure is described in Fig. 1(a). The load P is applied to the truss structure via a connecting link-rod to agree with the experimental setup. Concerning a single



■ Modes used as simulated experimental modes of the first target system in the numerical study of the five-bar truss.
 Fig. 2. Numerical natural frequencies and mode shapes of fourteen modes of the first target system in the numerical study of the five-bar truss.

member of the truss, a beam model with translational and rotational springs is considered in Fig. 1(b). Regarding the modeling of joints, as the joint rigidity affects the dynamic behavior of a structure considerably [8], an accurate numerical model of a truss should take into account the uncertain joint stiffness. Assuming the cases of small moments and deflections of truss connections and excluding the effects of slip and friction, linear elastic rotational springs are used to account for the uncertain joint stiffness. Each joint of the five-bar truss is modeled with a rotational spring. For practical assessment of different joint flexibility, it is beneficial to introduce a fixity factor of the joint stiffness [11]. The fixity factor $\gamma_i = k_{ri}L / (3EI + k_{ri}L)$ takes values from zero to one corresponding to pinned to rigid condition, where k_{ri} is the rotational spring stiffness at i end of a member, EI is the flexural stiffness and L is the member length.

Regarding the effects of the axial forces on the dynamic properties, the influence can be clearly realized in the case of a tie-bar [12–13]. For truss structures, multiple load patterns are existent. When the load is increased, tensile forces increase the frequencies of the tension members; whereas at the same time, compressive forces reduce the frequencies of the members under compression. This phenomenon causes variation of natural frequencies and interchange of modes. Furthermore, truss structures can possess closely-spaced in-plane and out-of-plane modes. Therefore, an enhanced modal assurance criterion (EMAC) proposed by [14] is adopted for the mode pairing, in which desired clusters of degrees-of-freedom can be selected to address the issues of closely-spaced modes and interchange of modes.

3. Numerical verification

Three case studies were considered. The five-bar truss was modelled by the FE method based on Timoshenko beam theory. The material properties are assumed as the Young’s modulus of 205000 N/mm², mass density of 7850 kg/m³ and the Poison’s ratio of 0.30. The unknowns are the applied load P and the stiffness of the rotational springs. The load P were chosen to result in the axial stresses of approximately 25, 100, and 175 N/mm² in the first truss member (Table 1). The rotational spring stiffness were randomly chosen that represent different constraint flexibility (Table 2).

Table 1. True and identified applied loads, member axial forces and tensile stresses of the target systems in the numerical study of the five-bar truss.

Target system	P^{true} * [kN]	P^{id} ** [kN]	Δ [kN]	N_1^{true} [kN]	N_1^{id} [kN]	σ_1^{id} [N/mm ²]	Δ [kN]	N_2^{true} [kN]	N_2^{id} [kN]	σ_2^{id} [N/mm ²]	Δ [kN]	N_3^{true} [kN]	N_3^{id} [kN]	σ_3^{id} [N/mm ²]	Δ [kN]
1	4.41	4.42	0.01	1.77	1.78	25.01	0.01	1.80	1.81	25.37	0.01	1.53	1.54	21.54	0.01
2	18.00	18.29	0.29	7.09	7.20	101.59	0.11	7.18	7.30	102.95	0.11	6.24	6.34	89.43	0.10
3	31.59	31.36	-0.23	12.40	12.30	173.56	-0.10	12.57	12.46	175.84	-0.11	10.95	10.89	153.66	-0.06

*true: defined parameters of the target systems assumed as simulated experimental data; **id: identified parameters by the proposed methodology.

Table 2. True and identified rotational spring stiffness and fixity factors of the target systems in the numerical study of the five-bar truss.

Target system	$k_{rI.1}^{true}$ [kNm/rad]	$\gamma_{krI.1}^{true}$ [-]	$\gamma_{krI.1}^{id}$ [-]	$k_{rIII.1}^{true}$ [kNm/rad]	$\gamma_{krIII.1}^{true}$ [-]	$\gamma_{krIII.1}^{id}$ [-]	$k_{rIII.3}^{true}$ [kNm/rad]	$\gamma_{krIII.3}^{true}$ [-]	$\gamma_{krIII.3}^{id}$ [-]	$k_{rIII.link}^{true}$ [kNm/rad]	$\gamma_{krIII.link}^{true}$ [-]	$\gamma_{krIII.link}^{id}$ [-]	$k_{rIV.4}^{true}$ [kNm/rad]	$\gamma_{krIV.4}^{true}$ [-]	$\gamma_{krIV.4}^{id}$ [-]
1	0.49	0.75	0.75	3.13	0.95	0.95	0.00	0.00	0.38	0.05	0.25	0.24	26.57	0.50	0.51
2	3.13	0.95	0.94	0.05	0.25	0.23	0.13	0.50	0.51	0.16	0.50	0.45	79.72	0.75	0.82
3	0.05	0.25	0.13	0.16	0.50	0.25	0.38	0.75	0.78	0.00	0.00	0.33	504.86	0.95	0.94

Assumptions: $k_{I.1}^{id} = k_{II.1}^{id}$; $k_{III.1}^{id} = k_{III.2}^{id}$; $k_{I.4}^{id} = k_{II.5}^{id} = k_{IV.4}^{id} = k_{IV.5}^{id}$.

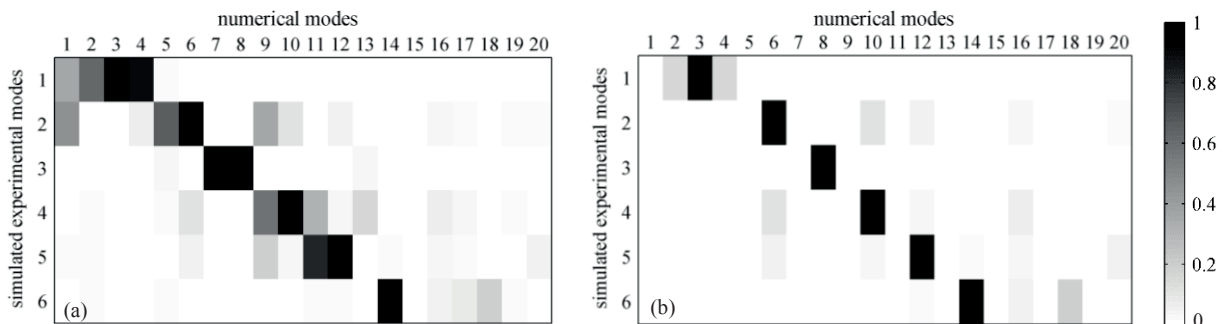


Fig. 3. Pairing of the simulated experimental and numerical frequencies of the first target system in the numerical study of the five-bar truss: (a) Modal assurance criteria (MAC); (b) Energy-based modal assurance criteria (EMAC).

To demonstrate the effects of both the tensile and compressive forces on the modal parameters of the target systems, the first fourteen modes are plotted in Fig. 2 and Fig. 4(a). In Fig. 4(a), interchanges of modes occur as the load varies. It should be noted that the three target systems are not only subjected to the axial force effects but also the effects of joint rigidity. Nevertheless, the influence of the axial forces can be recognised as significant. The effect of the compressive forces in the top chords on the frequencies is seen clearly in the cases of the second and fourteenth modes.

For truss structures, the individual members form a global coupled system. Similar modes of vibration appear, for instance the in-plane and out-of-plane third and fourth modes of the third member, or the seventh and eighth modes of the first two members, and so on. When pairing the simulated experimental and numerical modes, the traditional modal assurance criteria (MAC) is unable to assign reliably the similar modes, as seen in Fig. 3(a). The EMAC [14] allows the classification of the mode shapes taking into account the relative modal strain energies of defined clusters of degrees of freedom, i.e. in this case the in-plane degrees-of-freedom of the truss members. The results in Fig. 3(b) shows correct assignments of the modes. The beneficial use of the EMAC for the mode pairing is thus illustrated.

The results of the identified axial forces by the proposed methodology are given in Table 1. The first five to six simulated experimental modes were used. The identified loads match very well to the true ones. Considering the joint stiffness (Table 2), the identified fixity factors indicate reasonably joint rigidity with respect to hinged or rigid condition.

4. Experimental validation

Laboratory experiments of the five-bar truss of the indicated geometrical properties were carried out. All truss members are made of steel with a mass density of 7850 kg/m³. The Young modulus of the tension members was determined by tensile test as 205000 N/mm². Loads were applied to the truss vertically downward at the end of the link-rod by the hydraulic actuator and measured by a load cell. Increasing loads were performed in five steps, resulting

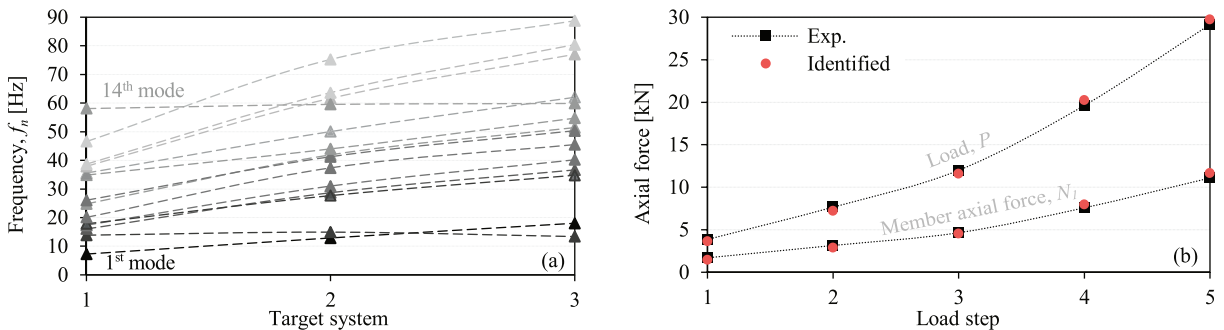


Fig. 4. Numerical and experimental investigation of the five-bar truss: (a) Numerical natural frequencies of correlated modes of the three target systems in the numerical study; (b) Measured and identified loads and axial forces of the first member in the laboratory experiments.

Table 3. Measured and identified applied loads, member axial forces and tensile stresses in the laboratory experiments of the five-bar truss.

Load step	P^{exp} [kN]	P^{id} [kN]	Δ [kN]	N_1^{exp} [kN]	N_1^{id} [kN]	σ_1^{id} [N/mm ²]	Δ [kN]	N_2^{exp} [kN]	N_2^{id} [kN]	σ_2^{id} [N/mm ²]	Δ [kN]	N_3^{exp} [kN]	N_3^{id} [kN]	σ_3^{id} [N/mm ²]	Δ [kN]
1	3.86	3.64	-0.23	1.70	1.47	20.75	-0.23	2.02	1.49	21.05	-0.52	0.56	1.26	17.76	0.70
2	7.66	7.23	-0.44	3.15	2.88	40.56	-0.28	3.42	2.92	41.12	-0.51	1.91	2.50	35.31	0.60
3	12.00	11.57	-0.43	4.65	4.55	64.25	-0.09	4.91	4.62	65.12	-0.30	3.46	3.99	56.29	0.53
4	19.62	20.23	0.61	7.58	7.96	112.30	0.39	7.82	8.07	113.79	0.25	6.54	7.01	98.88	0.47
5	29.14	29.72	0.58	11.09	11.67	164.63	0.58	11.32	11.82	166.81	0.50	10.33	10.30	145.35	-0.03

Table 4. Identified rotational spring stiffness and fixity factors in the laboratory experiments of the five-bar truss.

Load step	$k_{I,1}^{id}$ [kNm/rad]	$\gamma_{I,1}^{id}$ [-]	$k_{III,1}^{id}$ [kNm/rad]	$\gamma_{III,1}^{id}$ [-]	$k_{III,3}^{id}$ [kNm/rad]	$\gamma_{III,3}^{id}$ [-]	$k_{III,link}^{id}$ [kNm/rad]	$\gamma_{III,link}^{id}$ [-]	$k_{IV,4}^{id}$ [kNm/rad]	$\gamma_{IV,4}^{id}$ [-]
1	0.66	0.80	2.10	0.93	0.29	0.69	0.06	0.02	9.26	0.26
2	1.46	0.90	9.73	0.98	7.04	0.98	5.43	0.71	21.98	0.45
3	0.32	0.66	16.41	0.99	0.08	0.37	4.18	0.65	10.25	0.28
4	2.04	0.93	3.38	0.95	0.04	0.24	3.39	0.60	27.69	0.51
5	16.31	0.99	9.42	0.98	2.00	0.94	27.10	0.92	33.39	0.56

Assumptions: $k_{I,1}^{id} = k_{II,1}^{id}$; $k_{III,1}^{id} = k_{III,2}^{id}$; $k_{IV,4}^{id} = k_{IV,5}^{id} = k_{IV,4}^{id}$.

in the tensile stresses of approximately 20 to 160 N/mm² in the first member. The axial forces in the tension members were calculated from the measured strains by three strain gauges installed on the first to third members.

The dynamic tests were carried out with hammer excitations at a sampling frequency of 2048 Hz. Twenty-five accelerometers were installed on the truss members; five on each member. The stochastic subspace identification was used to extract the modal parameters from the measured responses. Four to six experimentally identified modes were included into the optimization. The results of the identified axial forces and joint stiffness are provided in Table 3 and Table 4. Based on the identified joint stiffnesses, common assumptions of all-pinned joints for the truss structure will not be appropriate to achieve accurate dynamic responses. A good agreement between the identified and measured axial forces was acquired at different load states. The effectiveness of the proposed methodology is demonstrated.

5. Conclusions

In this paper, the inverse determination of the axial forces and corresponding stresses in truss structures was investigated. The approach is based on vibration measurements and the FE model updating coupled with the optimization-based PSO. The results of the laboratory tests show that the identified axial forces match well with that from the experiments for different stress levels. Moreover, the joint rotational spring stiffnesses or fixity factors can be identified, which provide useful indication of the joint flexibility in relation to a pinned or rigid condition.

Concerning the axial force effects on the modal parameters, the effects become more complicated for multiple-member systems of increasing complexity. To overcome the issues of interchange of modes at different stress states as well as closely-spaced modes, the pairing of modes is performed by adapting the EMAC with the calculation of the modal strain energies. Regarding the modelling of joints, joints are modelled with linear elastic rotational springs to represent semi-rigid connections, in the cases of small moments and deflections of truss connections. With respect to the model updating strategies, the choice of an appropriate objective function and optimization technique are identified to be highly important. The nature-inspired PSO is considered suitable for the identification problem in this study.

Different laboratory experiments including the tests of the five-bar truss structure have been carried out within the framework of a doctoral research at Brandenburg University of Technology Cottbus-Senftenberg in cooperation with Bauhaus-Universität Weimar and Bundesanstalt für Materialforschung und -prüfung (BAM) [2]. It is intended to integrate the proposed methodology as part of a Structural Health Monitoring approach for existing historic truss structures.

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