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STRUCTURAL DAMAGE DETECTION BY PSO METHOD

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Abstract: *Detecting structural damage is necessary for ensuring the safety and long service life of civil infrastructure. In this paper, a method for structural damage detection and localization utilizing the Particle Swarm Optimization (PSO) technique is proposed. Through numerical simulations, the effectiveness of PSO-based damage detection in detecting structural damage has been demonstrated. This study contributes to the advancement of structural health monitoring practices, highlighting the potential of PSO in improving structural integrity assessment. This study underscores the potential of the PSO method as a powerful tool for enhancing the reliability and efficiency of structural health monitoring systems, thereby contributing to the advancement of structural integrity assessment and maintenance practices in civil engineering.*

Keywords: PSO method, FEM model, damage detection.

1. Introduction

Civil infrastructure plays a key role in sustaining modern society, which includes a vast network of bridges, buildings, and other structures important for transportation, commerce, and public safety. However, infrastructure aging and exposure to various environmental loads pose significant challenges to its integrity, necessitating effective monitoring and maintenance strategies to ensure continued functionality and safety (Farrar and Worden, 2007; Hester and González, 2017; Sofi et al., 2022; Sohn et al., 2001).

Structural damage resulting from factors such as material degradation, environmental deterioration or extreme loading is a critical threat to the performance and safety of civil infrastructure (Âroch et al., 2016), (Lamperová et al., 2020; Venglár, 2018). Detection and assessment of structural damage in its early stages is essential to prevent catastrophic failures and minimizing the risk of loss of life and property (Nicoletti et al., 2022).

Over the years, considerable research efforts have been focused on developing advanced techniques for structural damage detection and health monitoring (Marwala, 2010; Sofi et al., 2022). Traditional methods, including visual inspection, finite element analysis, and modal analysis, have limitations in terms of accuracy, efficiency, and applicability to real-time monitoring (Marwala, 2010; Ventura et al., 2005). Consequently, there is a growing interest in the use of computational intelligence and optimization algorithms for enhancing the effectiveness of structural health monitoring systems (Kang et al., 2012; Zhang et al., 2014).

One such optimization algorithm that has gained prominence in recent years is the Particle Swarm Optimization (PSO) method (Kenedy and Eberhart, 1995). Inspired by the social behavior of organisms such as bird flocking and fish schooling, PSO is a population-based stochastic optimization technique that

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iteratively updates the position and velocity of particles within a search space to converge towards an optimal solution (Kennedy and Mendes, 2002; Krohling, 2005; Marton et al., 2021).

The inherent parallelism and global search capabilities of PSO make it particularly suitable for addressing complex optimization problems, including structural damage detection. By integrating sensor data with computational models, PSO can effectively identify and localize damage within a structure, offering advantages such as robustness to noise, uncertainties, and nonlinearities (Li et al., 2014).

In this paper, a new approach for structural damage detection using the PSO method is proposed. The paper is focused on the numerical simulation of damage to the truss beam and demonstrates the effectiveness of PSO-based damage detection in the accurate identification and localization of this damage. This study contributes to the advancement of structural health monitoring by exploiting the potential of PSO to increase the reliability and efficiency of damage detection techniques.

2. Methodology

2.1. Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a metaheuristic optimization algorithm inspired by the social behavior of bird flocks or fish schools. It operates by iteratively updating the position and velocity of a population of particles within a search space to converge towards an optimal solution (Kenedy and Eberhart, 1995). In PSO, each particle represents a potential solution, and its movement is guided by its own experience (personal best) and the collective knowledge of the swarm (global best).

2.2. Finding solution based on the objective function.

Structural damage detection using PSO involves comparing the eigenfrequencies and eigenmodes in an objective function. This comparison allows to identify inconsistencies caused by structural damage, which is manifested by changes in stiffness parameters. The goal is to minimize the difference between the frequencies and the eigenmodes obtained from the numerical model for each iteration with the reference data. In this case, the damage was applied to the undamaged numerical model to obtain the reference data (simulated damage). At each iteration, the positions of the PSO swarm particles are updated and the value of the fitness function is evaluated - the best position within the iteration is selected. This gradually approaches the optimal solution, which represents the sought parameters and at the same time corresponds to the eigenfrequencies and eigenmodes obtained from the reference model. The fitness of the objective function is mathematically defined as

$$Fitness = \sum_i wf_i \left(\frac{FC_i - F\ \ _i}{FD_i}\right)^2 + \sum_i wms_i \left(\frac{\left(1-\sqrt{MAC_i}\right)^2}{MAC_i}\right), \tag{1}$$

where:

wf_i	is the weight factor for the i^{th} frequency,
$\left(\frac{FC_i - F\ \ _i}{FD_i}\right)^2$	is the quadratic difference between the calculated frequency FC_i and the frequency FD_i, from damaged model normalized with respect to the frequency FD_i from damaged model,
MAC_i	is the Modal Assurance Criterion for the i^{th} frequency (Pastor et al., 2012),
wms_i	is the weight factor of each MAC_i,
$\left(\frac{\left(1-\sqrt{MAC_i}\right)^2}{MAC_i}\right)$	is the MAC comparison.

3. Case study

The case study investigates a two-span steel truss consisting of 12 sections, with the first span consisting of 8 sections and the second span consisting of 4 sections. A numerical finite element model of this structure was created. In this case, structural damage was intentionally introduced to sections 3, 8, and 9 (0). the Young's modulus E of these sections was reduced by 30 % by multiplying by the stiffness coefficient (values of k_3, k_8 and k_9 were 0.7) (Lamperova et al., 2023; Lehký et al., 2023).

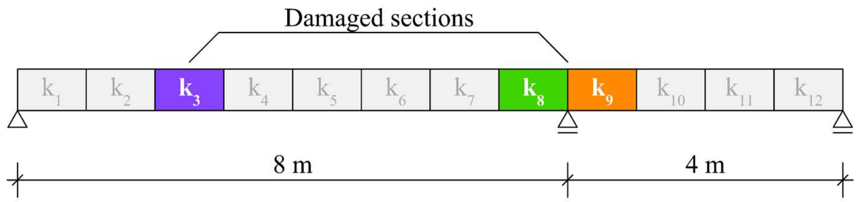

Fig. 1: Numerical model of a double-span truss.

Further information on the progress and results of the optimization is shown in 0, which shows the evolution of the objective function and the stiffness coefficient of each section of the truss beam. It is clear from the figure that the optimization process produced promising results that show good agreement with the objectives of the study. It is essential to emphasize that these simulations were performed exclusively in a theoretical framework using numerical models to evaluate the structural response to damage.

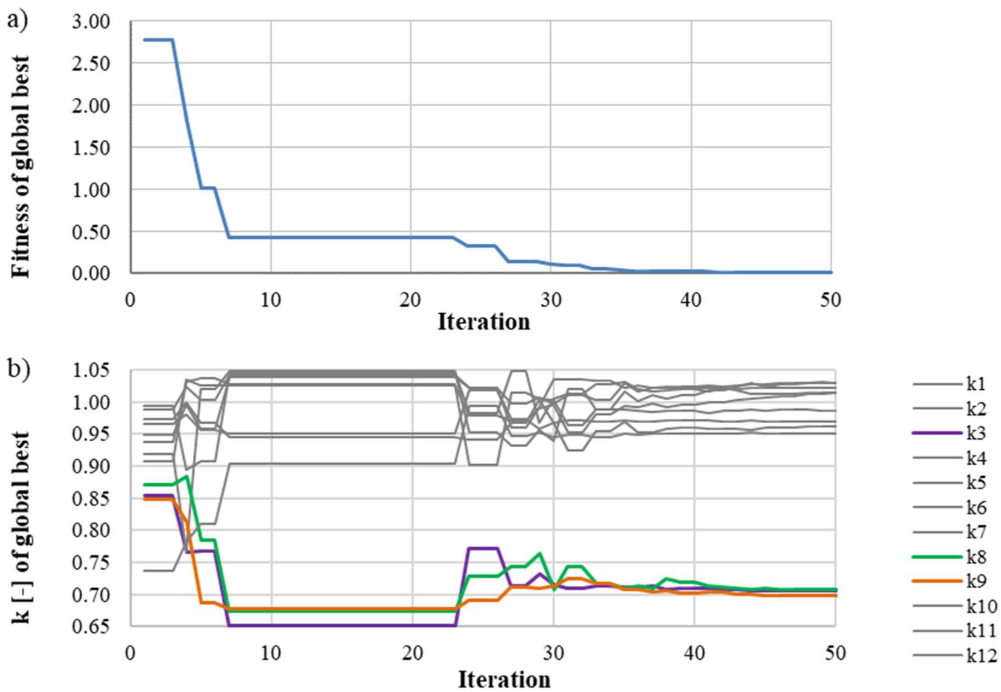

Fig. 2: Evolution of a) the objective function, b) the stiffness coefficients.

4. Conclusions

In this paper, a new approach for structural damage detection using the Particle Swarm Optimization (PSO) method applied to a double-span steel truss was presented. Through numerical simulations, the effectiveness of the proposed methodology was demonstrated in the accurate identification and localization of structural damage.

The research was aimed at optimizing the stiffness parameters of the truss structure by comparing the eigenfrequencies and eigenmodes obtained from the numerical models with those from the damaged model. By formulating the optimization problem within the framework of PSO, satisfactory agreement was achieved in simulated scenario with artificially induced damage. The results obtained from the case studies show the potential of PSO-based damage detection techniques in enhancing the reliability and efficiency of structural health monitoring systems. By leveraging computational intelligence and optimization algorithms such as PSO, challenges associated with traditional methods can be mitigated and the accuracy of damage detection in civil infrastructure can be improved.

Looking to the future, further research efforts should explore the application of PSO and other optimization algorithms in real-world scenarios with complex structural geometries and varying environmental conditions.

In conclusion, this study contributes to the growing body of knowledge in structural health monitoring and optimization techniques and offers valuable insights for engineers and researchers seeking to increase the safety and resilience of civil infrastructure.

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References

Ároch, R., Sokol, M. and Venglár, M. (2016) Structural Health Monitoring of Major Danube Bridges in Bratislava. *Procedia Engineering*, *156*, 24–31.

Farrar, C. R. and Worden, K. (2007) An introduction to structural health monitoring. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *365*(1851), 303–315.

Hester, D. and González, A. (2017) A discussion on the merits and limitations of using drive-by monitoring to detect localised damage in a bridge. *Mechanical Systems and Signal Processing*, 90, 234–253.

Kang, F., Li, J. J. and Xu, Q. (2012) Damage detection based on improved particle swarm optimization using vibration data. *Applied Soft Computing Journal*, 12(8), 2329–2335.

Kenedy, J. and Eberhart, R. (1995) *Particle Swarm Optimization*. *The Industrial Electronics Handbook - 5 Vol. Set*, 1942–1948.

Kennedy, J. and Mendes, R. (2002) Population structure and particle swarm performance. In: *Proc. of the Congress on Evolutionary Computation,* CEC 2002, 2, 1671–1676.

Krohling, R. A. (2005) Gaussian particle swarm with jumps. In: *IEEE Congress on Evolutionary Computation*, 2, 1226-1231, vol. 2.

Lamperova, K., Lehky, D. and Slowik, O. (2023) Structural damage identification using optimization-based FE model updating. In: *Current Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems - Proc. of the 8th International Conference on Structural Engineering, Mechanics and Computation,* 1844–1850.

Lamperová, K., Sokol, M. and Timková, B. (2020) Identification of Bearings State on the Bridge Checked by Dynamic Tests. *Strojnicky Casopis*, 70(2), 67–76.

Lehký, D., Šplíchal, B., Lamperová, K. and Slowik, O. (2023) Inverse Analysis and Optimization-based Model Updating for Structural Damage Detection. *Ce/Papers*, 6(5), 1228–1233.

Li, W. M., Jiang, Z. H., Wang, T. L. and Zhu, H. P. (2014) Optimization method based on Generalized Pattern Search Algorithm to identify bridge parameters indirectly by a passing vehicle. *Journal of Sound and Vibration*, 333(2), 364–380.

Marton, M., Sokol, M., Bekö, A. and Maosen, C. (2021) Identification of Damage on Stringers By the PSO Method. *Slovak Journal of Civil Engineering*, 29(3), 9–14.

Marwala, T. (2010) *Finite-element-model Updating using Computational intelligence Techniques* (vol. 148).

Nicoletti, V., Arezzo, D., Carbonari, S. and Gara, F. (2022) Vibration-Based Tests and Results for the Evaluation of Infill Masonry Walls Influence on the Dynamic Behaviour of Buildings: A Review. *Archives of Computational Methods in Engineering*, 29(6), 3773–3787.

Pastor, M., Binda, M. and Harčarik, T. (2012). Modal assurance criterion. *Procedia Engineering*, 48, 543–548.

Sofi, A., Jane Regita, J., Rane, B. and Lau, H. H. (2022) Structural health monitoring using wireless smart sensor network – An overview. *Mechanical Systems and Signal Processing*, 163, 108113.

Sohn, H., Farrar, C. R., Hemez, F. and Czarnecki, J. (2001) A Review of structural health. *Library Lanl. Gov*, 1–7.

Venglár, M. (2018) Dynamic Tests and System Identification of Bridges. *Dissertation Thesis*, 129.

Ventura, C. E., Lord, J. F., Turek, M., Brincker, R., Andersen, P. and Dascotte, E. (2005) FEM updating of tall buildings using ambient vibration data. In: *Proc. of the 6th European Conference on Structural Dynamics*, 4–7.

Zhang, J., Cai, J., Meng, Y. and Meng, T. (2014) Genetic algorithm particle swarm optimization based hardware evolution strategy. *WSEAS Transactions on Circuits and Systems*, 13, 274–283.