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DAMAGE LOCALIZATION IN THE MAIN STRUCTURAL ELEMENTS OF STEEL HALLS APPLYING DYNAMIC STRUCTURAL RESPONSE SIGNAL AND DISCRETE WAVELET TRANSFORM†

Anna KNITTER-PIĄTKOWSKA, Olga KAWA, Michał GUMINIAK*

Institute of Structural Analysis of Poznan University of Technology, Poznan, Poland
*corresponding author, *michal.guminiak@put.poznan.pl*

This study presents a method for detecting damage in steel lattice structures, steel hot-rolled I-section or concrete columns being a part of a whole structure based on the discrete wavelet transform (DWT). The structure's response signal may be a discrete set of displacements measured at selected points of the considered structure. The response signal defined in this way is subjected to DWT. This can have significant advantages in the field of estimation of the occurrence of a weakened part of a structure. The structural dynamic behavior is represented as a series of displacements or angles of rotation which can be implemented by given different dynamic loads, for example, short term concentrated load or seismic accelerations.

Keywords: steel lattice girders; steel welded girders; concrete bars; dynamic response signal; discrete wavelet transform.

1. Introduction – dynamic analysis of halls

The analysis will cover steel and mixed steel-reinforced concrete elements of the structures. The analyzed constructions are real objects that are in the design and implementation phase. The signal of the structural response will be the displacements or angles of rotation of discrete points caused by a dynamic load. An example of such a load is the dynamic action generated by an earthquake. This dataset is a series of data from the 1986 Bucharest earthquake which is simulated by the computational FEM program (Axis VM). This input data set is directly implemented in the Axis VM program. It contains data in time intervals of 0.02 s, and the total duration of the function is 20.42 s. The set is dimensionless and it is the so-called load factor function. The acceleration of the support included in the calculations is determined by multiplying a given function by the (constant) acceleration value for a given direction. To obtain the values recorded at the earthquake site, an acceleration value of $1\,\mathrm{m/s^2}$ should be assumed. The FEM procedures with a bar and shell model of the structure will be utilized in the numerical analysis of the issue.

2. Foundations of the discrete wavelet transform

In the presented discrete wavelet transform (DWT) analysis, a one-dimensional wavelet transform will be used to localize defected parts of the structure. The wavelet transform has already been applied into similar problems, e.g., (Garcia-Perez *et al.*, 2013; Wang *et al.* 2013). Below,

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standard wavelet function notations are used, which were also used in previous works, e.g., (Guminiak & Knitter-Piątkowska, 2018; Kamiński *et al.*, 2025; Knitter-Piątkowska *et al.*, 2025). Let there be a given function $\psi(t)$, which is continuous and lies within the $L^2(\mathbf{R})$ space. This is the so-called mother function (wavelet function) and is required to meet the admissibility condition (Mallat, 1999). Real-valued wavelet functions are applied to the analysis. The wavelet family is derived through the translation and scaling of the mother wavelet ψ (Knitter-Piątkowska *et al.*, 2025; Guminiak & Knitter-Piątkowska, 2018):

$$\psi_{a,b} = \frac{1}{\sqrt{|a|}} \cdot \psi\left(\frac{t-b}{a}\right), \tag{2.1}$$

where t serves as a time or spatial coordinate, while a and b represent the scaling and translation parameters, respectively. The variables $(a, b \in (\mathbf{R}))$, $a \neq 0$. Finally, the DWT procedure will be applied by the substitution $a = 1/2^j$ and $b = k/2^j$ in Eq. (2.1):

$$\psi_{j,k}(t) = 2^{(j/2)} \cdot \psi\left(2^j \cdot t - k\right), \tag{2.2}$$

where k and j correspond to the scaling and translation parameters, respectively.

The DWT of the structural response data is defined through the relation

$$Wf(j,k) = 2^{j/2} \cdot \int_{-\infty}^{\infty} f(t) \cdot \psi(2^j \cdot t - k) \cdot \mathrm{d}t = \langle f(t), \psi_{j,k} \rangle . \tag{2.3}$$

The decomposing procedure of a signal registered in discrete points is performed while utilizing the Mallat pyramid algorithm (Mallat, 1999):

$$f_J = S_J + D_J + \ldots + D_n + \ldots + D_1, \tag{2.4}$$

where J, D_J, S_J, D_1 express in turn: the level of multiresolution analysis (MRA), the detailed and approximation components of the transformed structural response, with the most detailed one as the last term in Eq. (2.4). The Mallat pyramid algorithm is shown in Fig. 1.

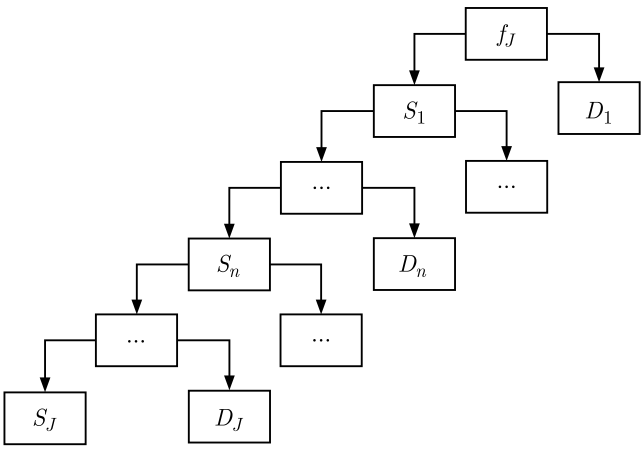

Fig. 1. Mallat pyramid algorithm.

3. Numerical examples

In this analysis, selected elements of various types of structures are considered: steel lattice and steel column, which are subjected to the dynamic load. The signal subjected to DWT is a difference between displacements or angles of rotation measured in discrete points in undamaged and defective structures.

3.1. Example 1 – deterioration of the steel column

The steel hall with plane welded girders is considered. The arrangement of girders together with the damaged column under consideration is shown in Fig. 2. The structural properties are: width – 24 m, length – 40 m, height – 10 m, frame spacing – 5 m. The upper beam of the frame is constructed from the IPE 450 and column from the HEA 400, steel: S355 (Young's modulus 210 GPa). The introduced defect is in the form of 20 % reduction of moment of inertia in one FEM element of the column. The results of DWT calculation are shown in Fig. 3. Two-node 3D frame finite elements with six degrees of freedom per node (three mutually perpendicular translational displacements and three rotation angles in three mutually perpendicular planes) are introduced. The number of finite elements in the whole structure is 792, and in the column – 64. The structure is loaded by accelerations applied in supports along x direction.

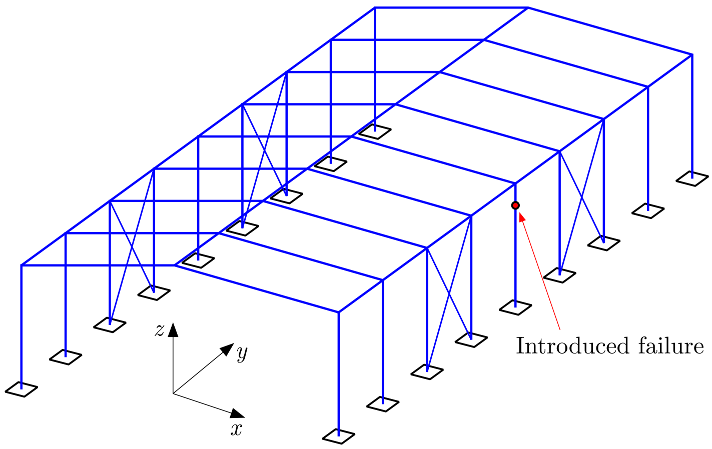

Fig. 2. Considered steel structure and introduced defective element.

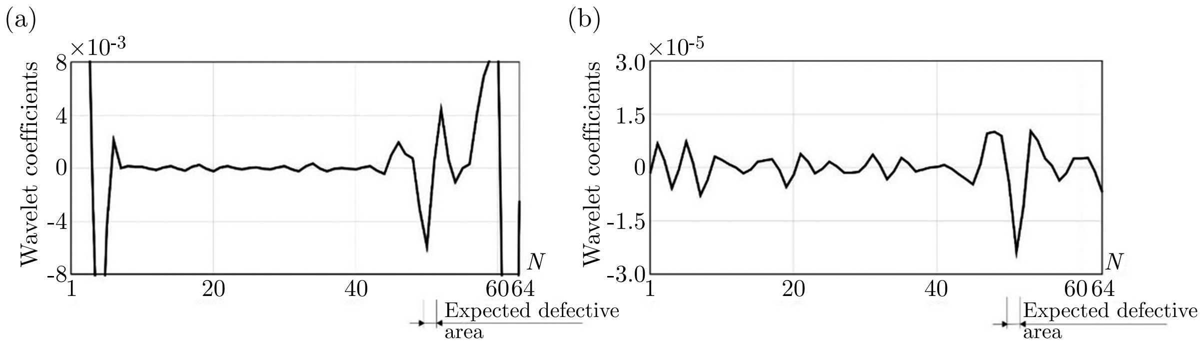

Fig. 3. Results of DWT calculations: (a) Daubechies 4, detail 1, signal – difference between displacements u_x for undamaged and defective structure; (b) Daubechies 6, detail 1, signal – difference in rotation angles φ_y (rotation in x–z plane) for undamaged and damaged structure, N – the number of measurement points.

3.2. Example 2 – deterioration of the truss structure

The steel lattice girder resting on two reinforced concrete columns is considered. The arrangement of girders together with the damaged diagonal under consideration is shown in Fig. 4. The structural properties are: width – 24 m, length – 36 m, height – 11 m, frame spacing – 6 m. The lattice girder's upper chord is made of HEA 140, lower chord – HEA 160 and diagonals – SHS $90 \times 90 \times 5$ and steel S355 (Young's modulus 210 GPa).

The introduced defect is in the form of a broken weld between the diagonal and the lower chord, indicated in Fig. 4 by the circle. The discrete measurement points are also visible. Two-

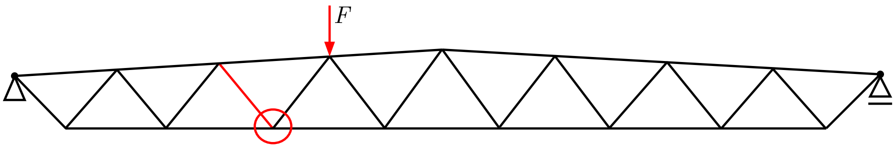

Fig. 4. Considered steel girder and introduced defective connection of diagonal bar in the node.

node frame finite elements with three degrees of freedom per node (horizontal and vertical displacements and angle of rotation) are introduced. The number of finite elements is 102, and in the lower band – 70. Loading parameters of the external harmonic force: $F = 6.67\,\text{kN}$, time of signal registration $T = 4.6\,\text{s}$. The outcomes of DTW calculation are depicted in Fig. 5.

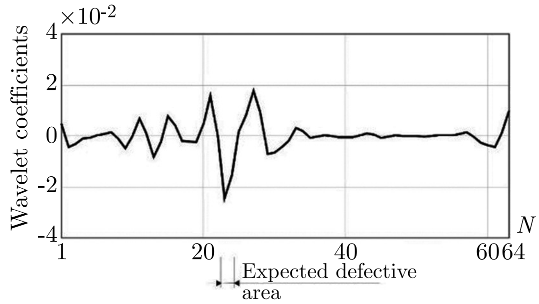

Fig. 5. Results of DWT calculations: Daubechies 6, detail 1, signal: difference in rotation angles φ for undamaged and damaged structures, N – number of measurement points.

4. Conclusions

The aim of this work was to verify the effectiveness of using discrete wavelet transform in the detection of damage in dynamically loaded structures. The calculation results presented in the previous sections allow the following conclusions to be drawn:

- DWT is highly effective for damage recognition, offering numerical efficiency and the ability to identify subtle disturbances in the response signal of a defective structure. However, in dynamic loading scenarios, referencing a signal from an undamaged structure may be necessary;
- different types of structural discrete response (i.e., translational displacements, angles of rotation) can be used for wavelet transformation in order to localize damage;
- correct damage localization may be possible regardless of the type of defect.

Acknowledgments

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