

WavStructDams Benchmark

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GENERAL INFORMATION

BENCHMARK SCOPE

The benchmark consists of the algorithms of various types of wavelet transforms and supporting tools, which can be applied to the measurement or simulation data obtained during vibration-based testing of composite structures in order to detect various types of damage. For the purposes of testing of various wavelet-based approaches in diagnostics and damage assessment of composite structures 143 example problems were implemented. It is also possible to upload own user data for performing the analysis. The benchmark was programmed in Matlab® as a GUI application, which allows for simple and quick analysis of data using the implemented processing tools.

OBJECTIVES

Comparing wavelet-based algorithms applied for the structural diagnostics and damage assessment of composite elements as well as analysis of detectability of various damage types (including cracks, delaminations, voids, impact damage) using the vibration-based testing and wavelet-based processing of measurement data. The benchmark is intended to be applied for supporting the vibration-based structural diagnostics both in laboratory and industrial environment.

FUNCTIONALITY AND ASSUMPTIONS

The benchmark is based on the Matlab® environment with using the Matlab® Wavelet Toolbox™. This toolbox is required for proper work of the WavStructDamAs benchmark.

The benchmark covers the following wavelet transforms for 1D problems:

- Continuous Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Discrete Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Stationary Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Undecimated Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Complex Wavelet Transform (based on routines developed by Ivan Selesnick and his team at the Brooklyn Polytechnic University, Brooklyn, NY, USA¹)
- Discrete Fractional Wavelet Transform (based on routines developed by Michael Unser and his team at the Biomedical Imaging Group, School of Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland²)

for 2D problems:

- Discrete Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Stationary Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Undecimated Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Complex Wavelet Transform (based on routines developed by Ivan Selesnick and his team at the Brooklyn Polytechnic University, Brooklyn, NY, USA¹)

¹ Information about the project and Matlab® routines developed by Ivan Selesnick and his team is available online at: <http://eeweb.poly.edu/iselesni/WaveletSoftware/index.html>

² Information about the project and Matlab® routines developed by Michael Unser and his team is available online at: <http://bigwww.epfl.ch>

- Discrete Fractional Wavelet Transform (based on routines developed by Michael Unser and his team at the Biomedical Imaging Group, School of Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland³)
- Discrete Multiwavelet Transform (based on routines developed by Bessam Al-Jewad from the Advanced Technology Systems Co., McLean, VA, USA⁴)
- Quincunx Wavelet Transform (based on routines developed by Gabriel Peyre from the Université Paris-Dauphine, Paris, France⁵)

for 3D problems:

- Discrete Wavelet Transform (based on Matlab® Wavelet Toolbox™)
- Complex Wavelet Transform (based on routines developed by Ivan Selesnick and his team at the Brooklyn Polytechnic University, Brooklyn, NY, USA⁶)

Additional processing tools for removing the boundary effect during wavelet transform and for performing isotropic wavelet analysis were developed by Andrzej Katunin using Matlab® Wavelet Toolbox™ functions.

SUPPORT

The benchmark was prepared under the realization of the research project financed by the National Science Centre (Poland) granted according the decision No. DEC-2011/03/N/ST8/06205 and under the realization of computational grant No. MNiSW/IBM_BC_HS21/PŚłaska/012/2013 on the supercomputer IBM BladeCenter HS21 in the Academic Computer Centre CYFRONET AGH provided by the Ministry of Science and Higher Education of Poland.

LICENSE AND AVAILABILITY

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³ Information about the project and Matlab® routines developed by Michael Unser and his team is available online at: <http://bigwww.epfl.ch>

⁴ Information about the MultiWavelet Tools routines package developed by Bessam Al-Jewad is available online at: <http://www.mathworks.com/matlabcentral/fileexchange/11105-multiwavelet-tools>

⁵ Information about the Matlab® routines for quincunx wavelet transform available as a part of the Toolbox Wavelets developed by Gabriel Peyre can be found at: http://www.mathworks.com/matlabcentral/fileexchange/5104-toolbox-wavelets/content/toolbox_wavelets/html/content.html

⁶ Information about the project and Matlab® routines developed by Ivan Selesnick and his team is available online at: <http://eeweb.poly.edu/iselesni/WaveletSoftware/index.html>

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INSTALLATION AND USAGE

INSTALLATION AND INITIALIZATION

WavStructDamAs is distributed in three versions:

- as executable set of content-obscured Matlab® routines
- as a stand-alone application, which does not require Matlab®
- as open source Matlab® routines

If WavStructDamAs is to be launched from the Matlab® unpack the archive and run the file *start.p* located in the root directory of the unpacked benchmark. The benchmark performs the initialization automatically and sets the paths to the necessary directories. Then the main frame will be launched. The benchmark is ready to be used. This option of installation can be chosen by the users not intended to modify source code or unexperienced Matlab® users, since the WavStructDamAs Benchmark is a fully GUI-based application and does not require any coding.

If WavStructDamAs is to be used as a stand-alone application run the self-extracting package file *WavStructDamAs_pkg.exe*. Firstly, the Matlab® Compiler Runtime will be installed on your system in order to execute Matlab®-based routines. When the installation is finished you can run *WavStructDamAs.exe*.

If the user is intended to analyze and/or modify the source code of WavStructDamAs the third option of benchmark distribution should be selected. In this case unpack the archive and run the file *start.m* located in the root directory of the unpacked benchmark. The benchmark performs the initialization automatically and sets the paths to the necessary directories. Then, the main frame will be launched. The benchmark is ready to be used.

USAGE OF THE BENCHMARK

LOADING THE PROBLEM

WavStructDamAs is based on GUI interface, which allows for simple and quick navigation and performing analysis without necessity of coding. At the beginning you can select the example problem(s) or upload your own problem data for the analysis.

In case when you intend to run exemplary problem you should first select the dimension of the problem. The example problems are sorted by the dimension in the upper menu (see Figure 1 ①). Then, you can select the specific problem you are interested in. Each problem name consists of the type of data in parentheses, where 'num' denotes numerical data and 'exp' denotes experimental data.

In the case when you intend to upload your own problem data you should select **File → Load own problem...** or use **Ctrl+O** shortcut. In the opened window press the button 'Load data...' (see Figure 2) in order to upload the files (multiple selection is allowed). Then, select the data files with **.mat* extension and press the 'Open' button. After uploading the files their names will be visible in the listbox on the left. Note that all uploaded files should concern the same problem and data stored in them should have same dimensions. You can check it by clicking on each file – the problem dimensions as well as data size and type will be shown in the appropriate windows on the right. After finishing the uploading and checking procedure press 'OK' to proceed.

After loading the problem its visualization will be viewed in the left window. Above the window the dropdown list will become visible with two buttons: 'Apply' and 'Undock' (Figure 1 ②). In the dropdown list the loaded modes will be available for analysis. For viewing the modes one should select the mode from the dropdown list

and then press 'Apply' button. If you want to extract the figure from the benchmark frame press 'Undock'. A new figure with a current visualization will be created. If you select one of the 3D exemplary problems or upload your own 3D problem the slider with a textbox will become visible instead of the dropdown list. In this case you can use the slider or type the value in the textbox in order to handle the slices of a 3D data array (Figure 3 ①). Note that depending on a size of 3D data array and capabilities of used hardware the loading process may take some time.

When the problem is loaded the information about it becomes visible in the 'Data information' panel (the problem name and data size and type information). The problem description and information on frequency response function and natural frequencies for the loaded problem are available by pressing 'Browse problem description...' and 'Browse FRF...' buttons, respectively (Figure 1 ③). If you upload your own problem the two latter functions will be unavailable.

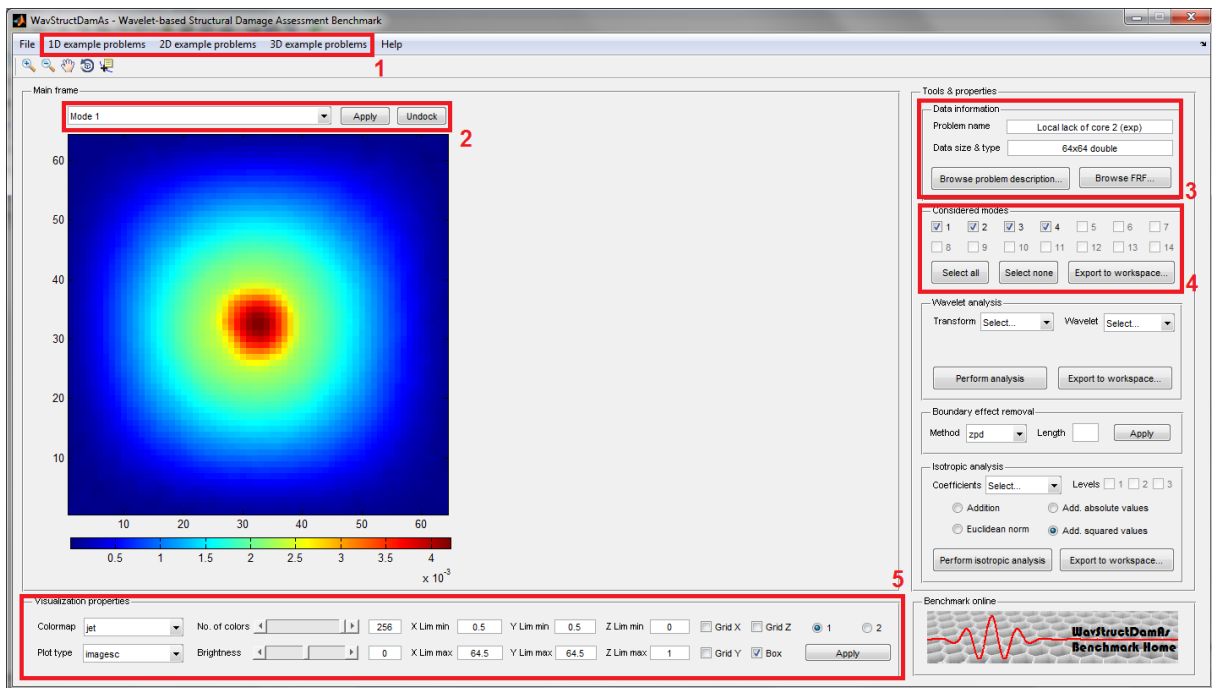


Figure 1. Handling the loading and viewing the problems

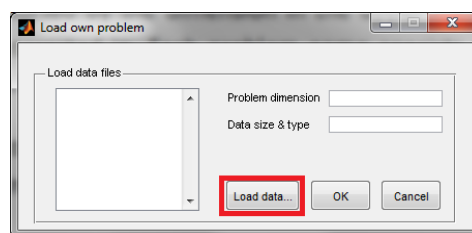


Figure 2. Uploading data files of the own problem

Depending on quantity of considered modes in the analysis the appropriate checkboxes become active and checked (Figure 1 ④). You can handle the considered modes over the whole analysis procedure by checking and unchecking the active checkboxes. For convenience you can use 'Select all' and 'Select none' buttons. If you intend to use the data outside the benchmark you can use 'Export to workspace...' button (in Matlab®-based versions) or 'Export to file...' button (in the stand-alone version).

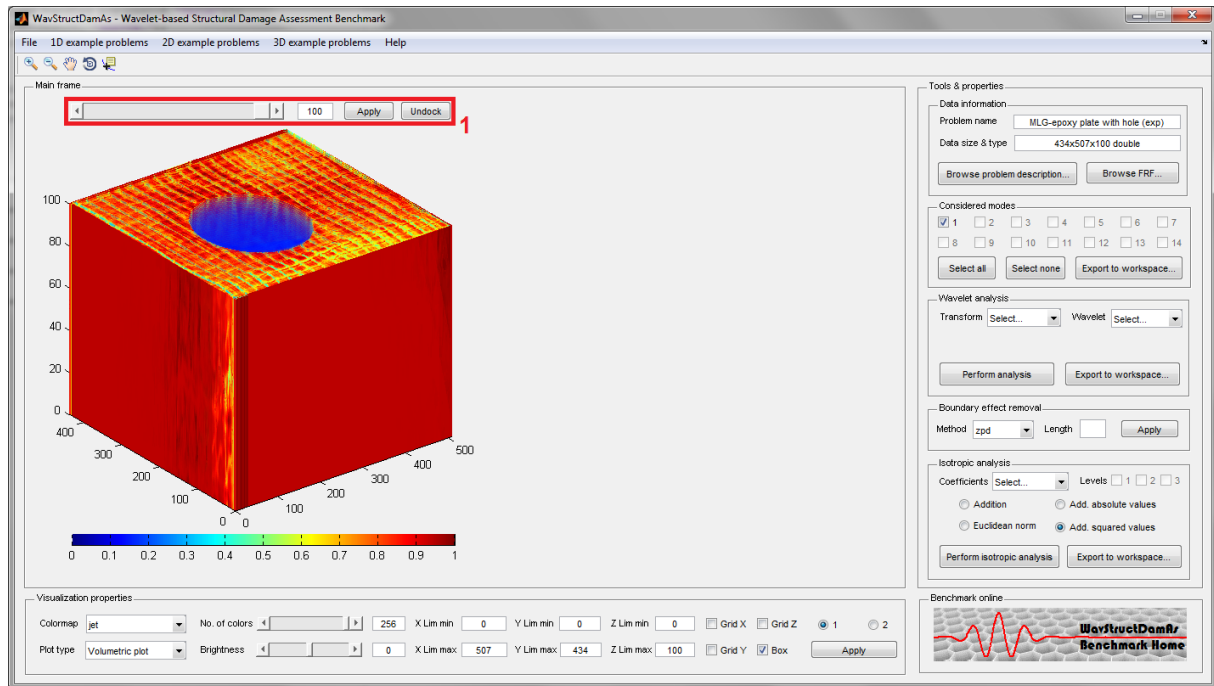


Figure 3. Loading of 3D problems

The visualization properties become available after loading the problem (Figure 1 ⑤). Depending on the problem dimension you can apply various plot types, colormaps (for 2D and 3D problems) with setting the number of colors and brightness, handling the axis limits of the visualized data and setting the grids and box in the figure. After changing the properties one should press the 'Apply' button.

For convenience one can use the tools from the upper Toolbar, namely 'Zoom in', 'Zoom out', 'Pan', 'Rotate' and 'Data cursor'. These tools work the same as when handling figures in Matlab® and can be used in the problem visualization window as well as in the results window, which is described in the next sections.

PERFORMING THE ANALYSIS

Depending on the dimension and data size of a selected/uploaded problem the benchmark automatically selects the appropriate wavelet transforms for data processing. You can select a transform from the dropdown list in the 'Wavelet analysis' panel (Figure 4 ①). When the transform is selected the next dropdown list is filled with the wavelet names suitable for the selected transform. You can change the selection of a wavelet if necessary. Depending on a type of selected wavelet the additional dropdown lists and/or editable textboxes will appear. In the case of Discrete, Stationary and Undecimated Wavelet Transforms you can select the wavelet, its order and a decomposition level. In the case of Complex Wavelet Transform you can define only the level of decomposition. In the case of Discrete Fractional Wavelet Transform (with a causal version of wavelets) you can define the order of wavelet, its shift parameter and decomposition level. In the case of Quincunx Wavelet Transform you can select the order of wavelet, its type and decomposition level. In the case of Discrete Multiwavelet Transform you can select only the multiwavelet type. Note that the number of decomposition levels, in cases where it is a selectable parameter of analysis, is limited. In the problems of structural diagnostics and damage assessment usually a single-level decomposition is enough for the analysis, however the further decomposition can be performed up to the level 3.

After setting up all parameters of selected transform press 'Perform analysis' button in the 'Wavelet analysis' panel (Figure 4 ①), which results in appearance of a second window with visualization of results. Above the window the dropdown list becomes visible with two buttons: 'Apply' and 'Undock' (Figure 4 ②). In the dropdown list the resulted coefficients for the considered modes will be available for selection.

For viewing the coefficients one should select the set of coefficients from the dropdown list and then press the 'Apply' button. If you want to extract the figure from the benchmark frame press 'Undock'. The new figure with a current visualization of results will be created. If you select one of the 3D exemplary problems or upload your own 3D problem besides the dropdown list with sets of resulted coefficients the textbox with 'Apply' button will become visible. In this case you can type the value in the textbox in order to handle the slices of a 3D data array (Figure 5 ①). If you intend to use the results outside the benchmark you can use 'Export to workspace...' button (in Matlab®-based versions) or 'Export to file...' button (in the stand-alone version). Note that depending on size of 3D data array and capabilities of used hardware the calculations may take some time.

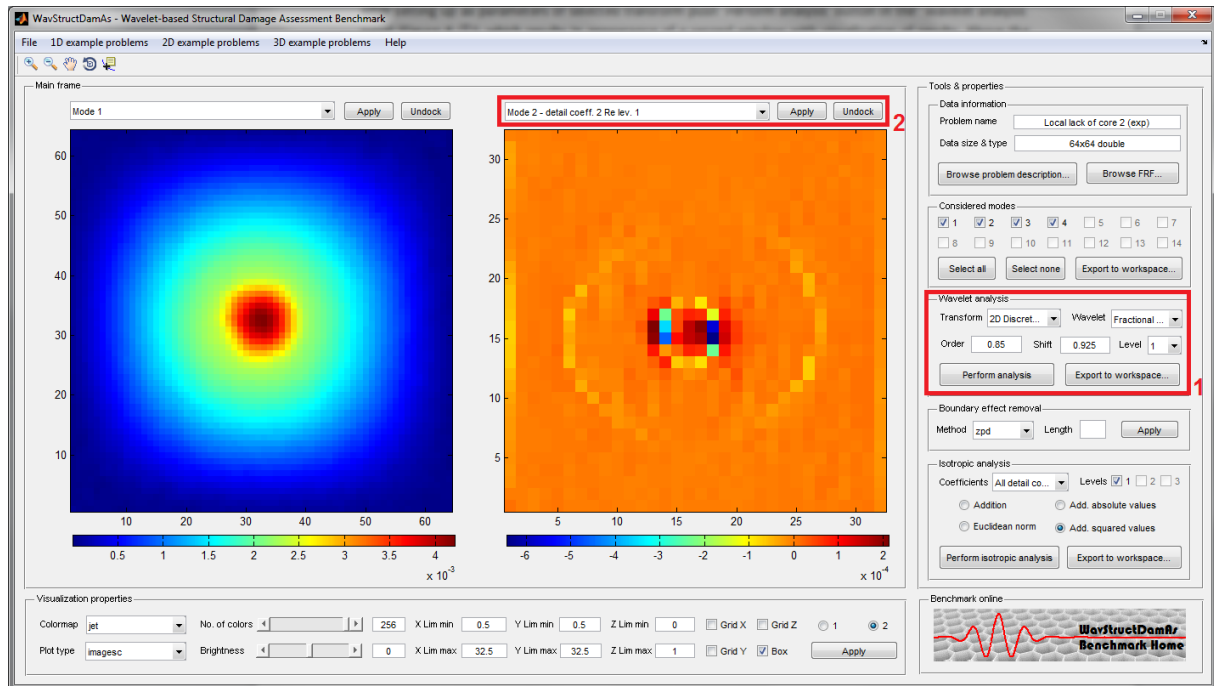


Figure 4. Setting up and performing the analysis and handling the analysis results

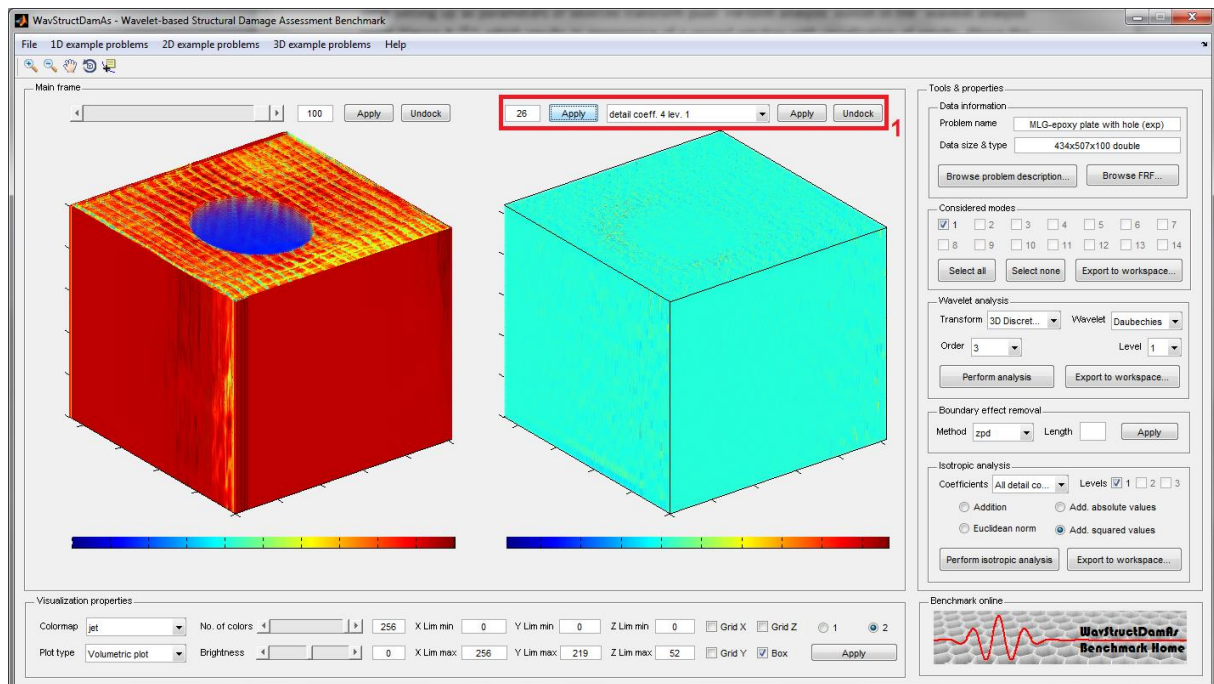


Figure 5. Handling the analysis results for 3D problems

REMOVING THE BOUNDARY EFFECT

The boundary effect occurs during wavelet analysis due to the finite length of the investigated signals and thus, appearance of zero-values of a signal outside this signal. When the wavelet function is shifted from zero to non-zero values obtained coefficients at the boundaries of the signal become large with respect to the rest of coefficients. The regions biased by the boundary effect should be excluded from the analysis. However, for enhancing the visualization quality (e.g. visualization of detected damage) the boundary effect removal procedure can be performed.

Performing the boundary effect removal procedure is possible after performed wavelet analysis. In the 'Boundary effect removal' panel one can select the method from the dropdown list and type the number of samples in the textbox on the right which are to be removed at each boundary of the signal and replaced by a signal extension procedure following the selected method. In order to perform the boundary effect removal procedure one should set these parameters and press 'Apply' button (see Figure 7 ①). The resulted coefficients will be updated automatically. Exemplary results of boundary effect removal are shown in Figures 6, 7 and Figures 8, 9 for 1D and 2D cases, respectively.

The methods of boundary effect removal are similar to the Matlab® signal extension functions. The description of the methods symbols are presented in the table below. For more information see the Matlab® Help.

Method	Description
'zpd'	Zero extension
'sp0'	Smooth extension of order 0
'spd'	Smooth extension of order 1
'sym'	Symmetric-padding (half-point): boundary value symmetric replication
'symw'	Symmetric-padding (whole-point): boundary value symmetric replication
'asym'	Antisymmetric-padding (half-point): boundary value antisymmetric replication
'asymw'	Antisymmetric-padding (whole-point): boundary value antisymmetric replication
'ppd'	Periodized extension (1)
'per'	Periodized extension (2)

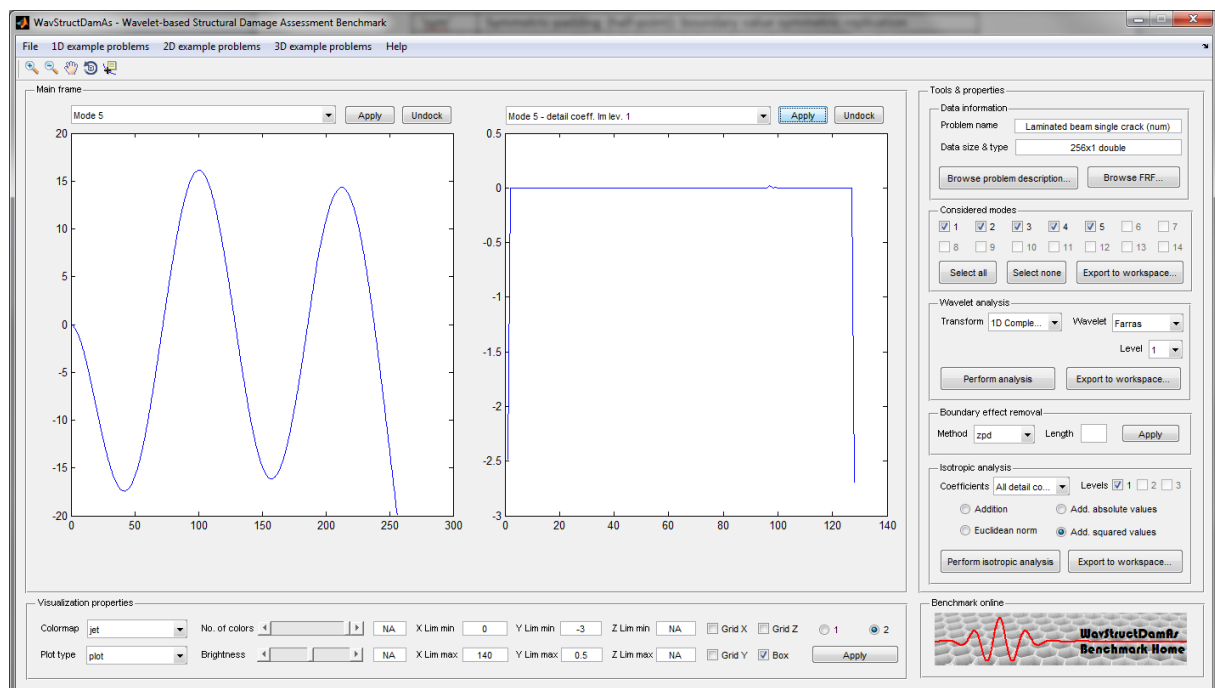


Figure 6. Analysis results of 1D case before boundary effect removal

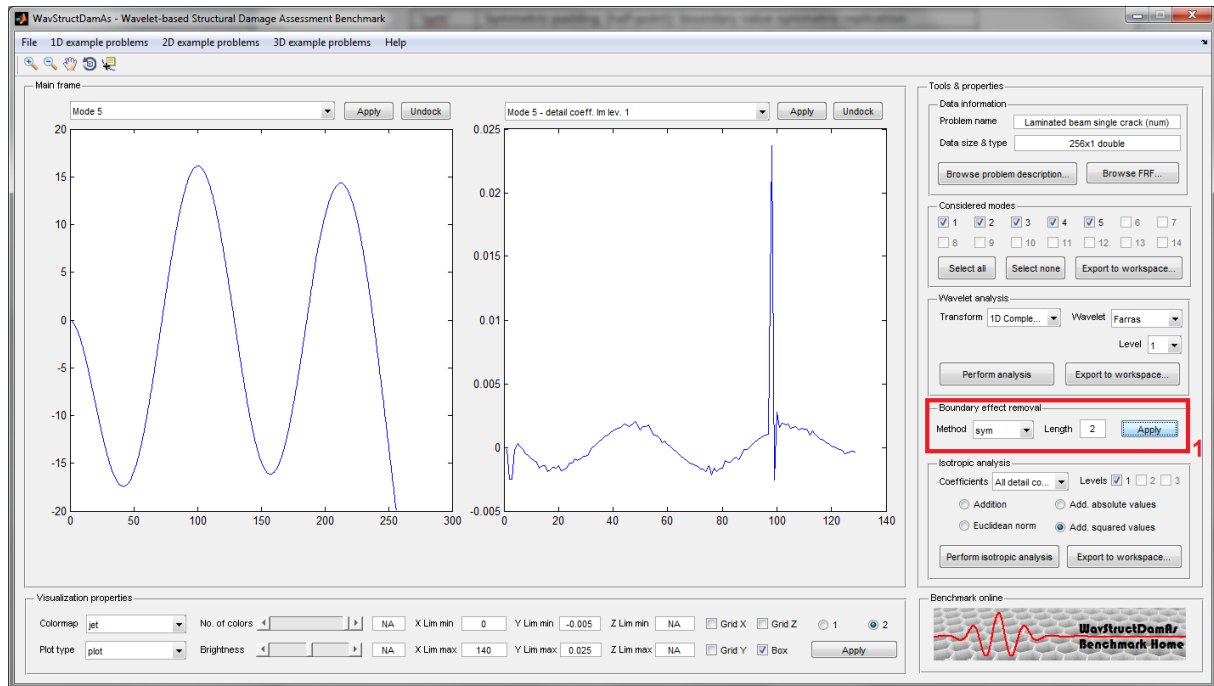


Figure 7. Analysis results of 1D case after boundary effect removal

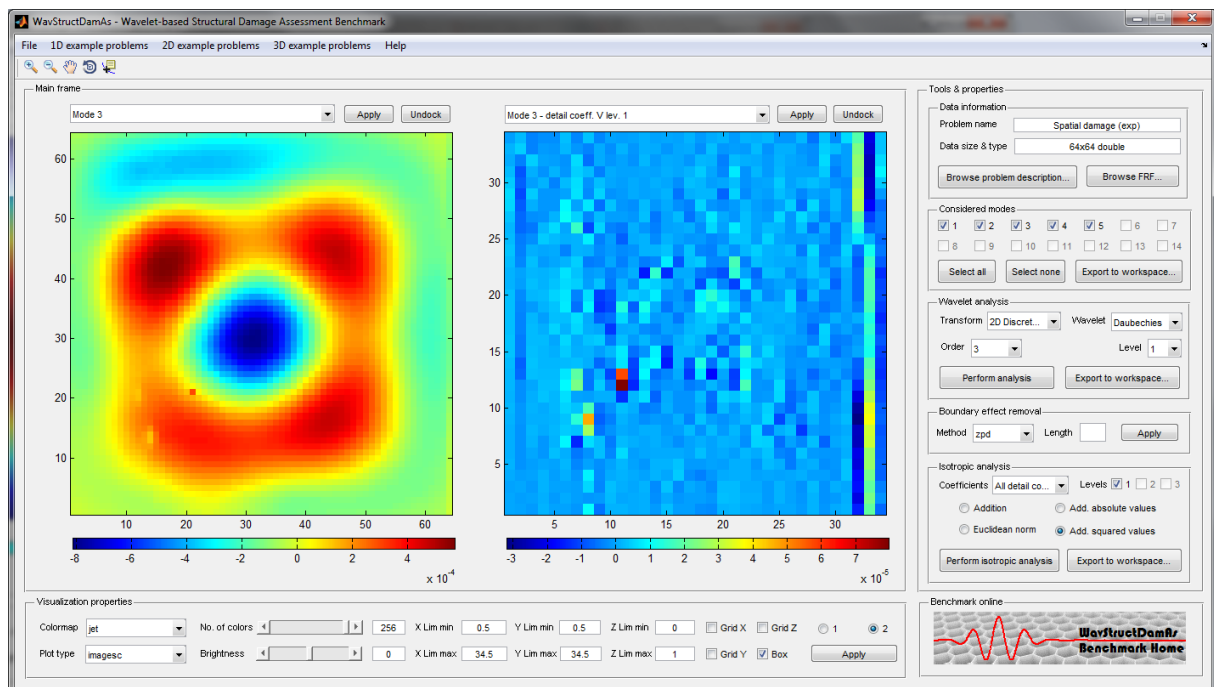


Figure 8. Analysis results of 2D case before boundary effect removal

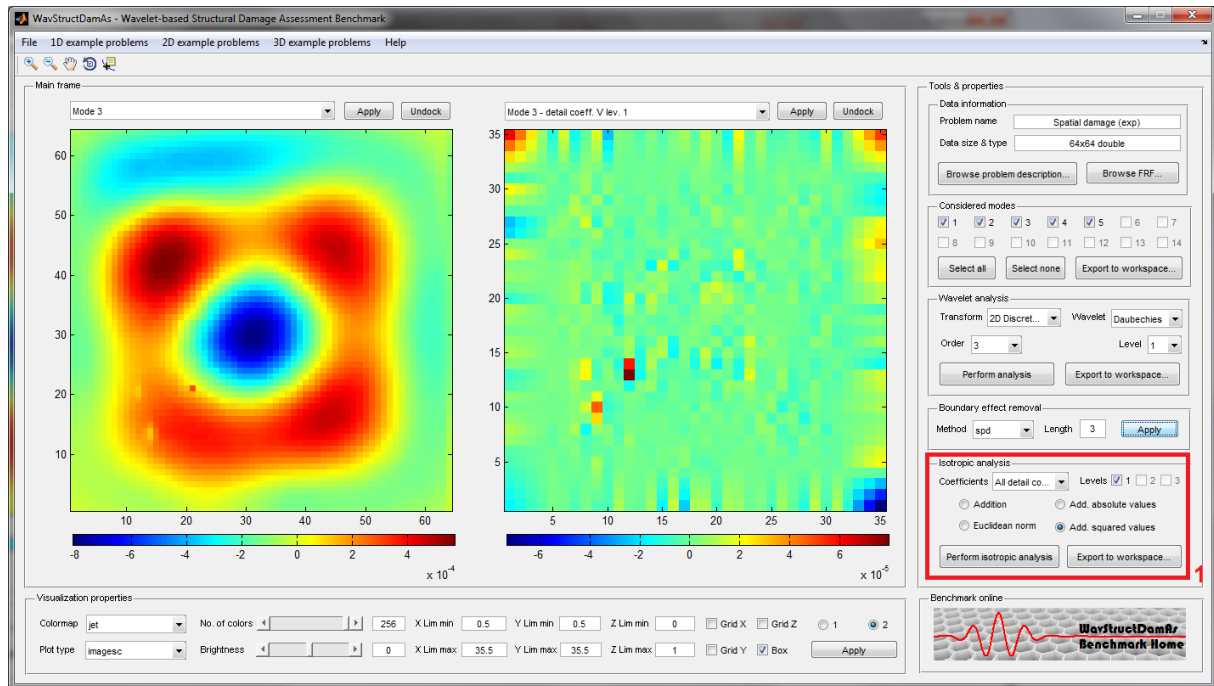


Figure 9. Analysis results of 2D case after boundary effect removal

ISOTROPIC ANALYSIS

Considering a fact that some wavelet transforms which are based on tensor-product wavelets give directional-oriented coefficients (2D transforms and beyond) and a fact that magnitudes of modal shapes are strongly connected with magnitudes of resulted detail coefficients (and thus the results of damage detection and identification may differ between particular modal shapes) the resulting damage detection, localization and identification can be obtained by using the isotropic analysis. This analysis is based on addition of selected detail coefficients using various approaches.

The benchmark allows performing the isotropic analysis for various levels, various detail coefficients and using various approaches by setting up the parameters in 'Isotropic analysis' panel (Figure 9 ①). Depending on type of selected wavelet transform one can select all obtained detail coefficients or their specific types. Four addition procedures are available: simple addition, addition of absolute values, calculation of Euclidean norm from the selected coefficients and addition of squared coefficients. The procedure is performed separately for each level of decomposition, which can be selected/unselected using checkboxes in 'Isotropic analysis' panel. After setting up all parameters of isotropic analysis one should press the 'Perform isotropic analysis' button. The new set(s) of coefficients will then be calculated and added at the end of dropdown list above the results visualization window. The last sets of new coefficients will be viewed in this window (see examples in Figure 10 and Figure 11 for 1D and 2D cases, respectively). If you intend to use the obtained results outside the benchmark you can use the 'Export to workspace...' button (in Matlab®-based versions) or 'Export to file...' button (in the stand-alone version).

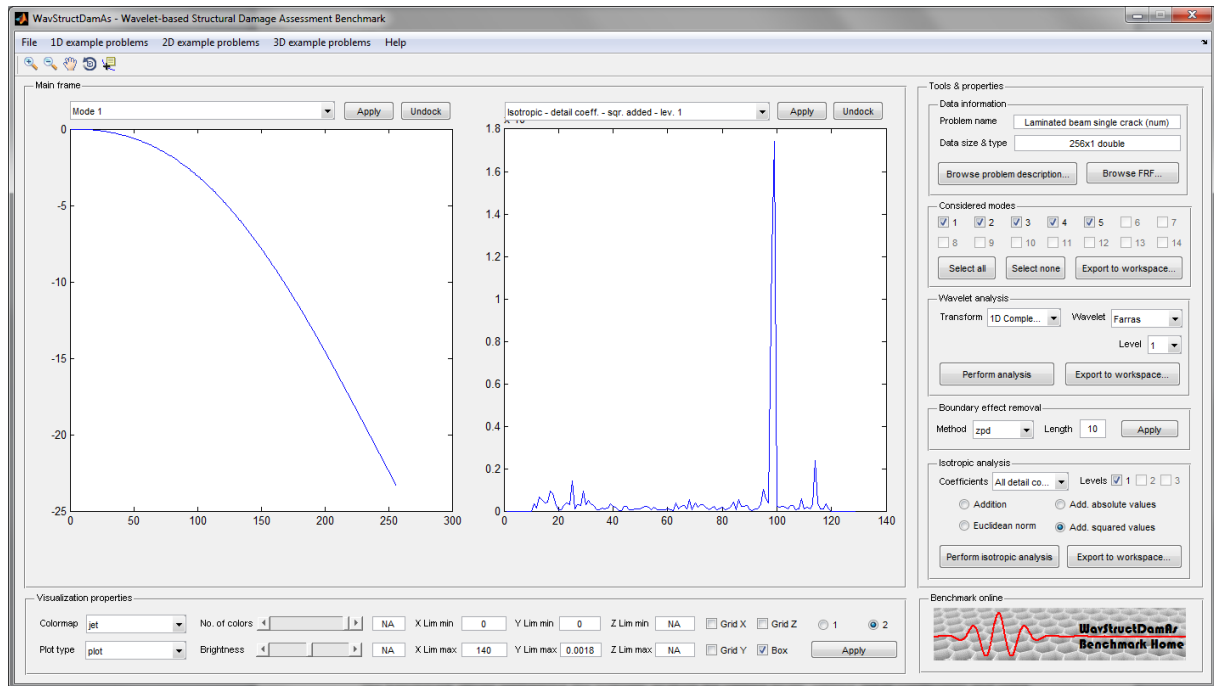


Figure 10. Results of isotropic analysis for 1D problem

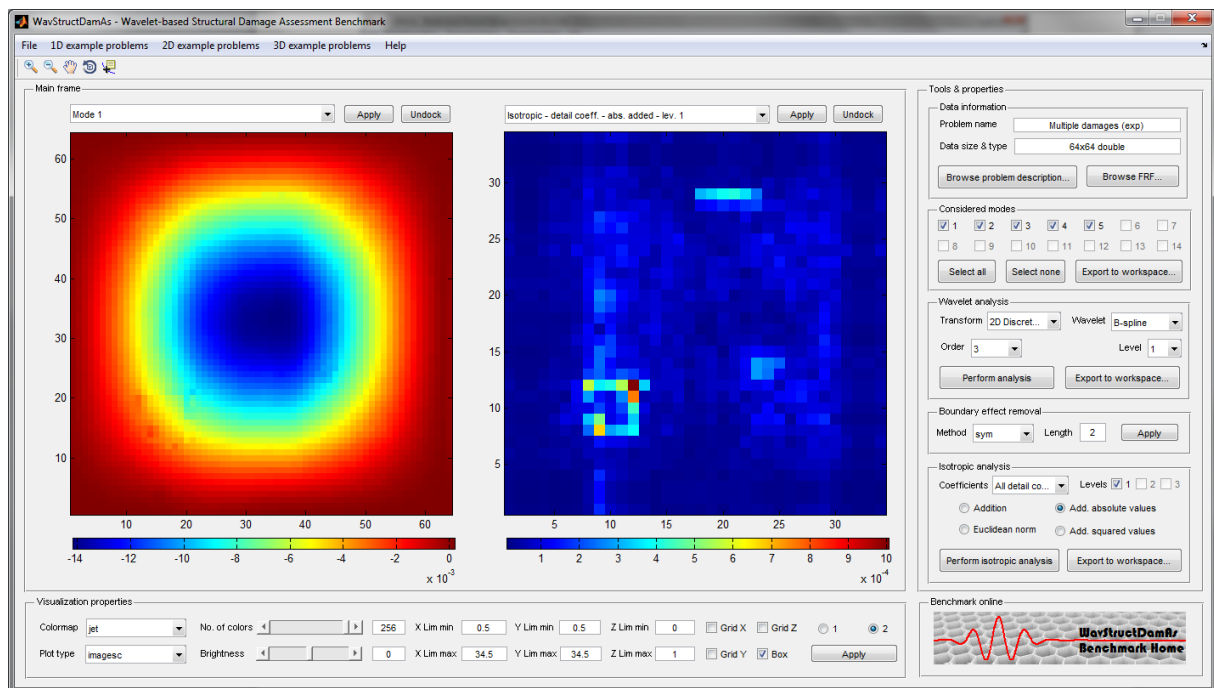


Figure 11. Results of isotropic analysis for 2D problem

OTHER FUNCTIONALITIES

The 'Visualization properties' panel allows for handling the colormap with selection of number of colors and brightness, a type of a plot (automatically updated for the specific problem dimension), axes limits, viewing/hiding the grids in specific directions and a box of a plot. In order to change visualization properties for specific window use radio button controls '1' and '2' for left and right window, respectively. When all necessary parameters are changed press the 'Apply' button.

The 'Benchmark online' panel contains the logo of WavStructDamAs benchmark. Click on logo to open the home page of WavStructDamAs benchmark in your internet browser, where the additional information can be found.

In several 2D problems (plates with circular geometry) the data and results are visualized in polar coordinates (see Figure 12). The data stored in data files has a form of square/rectangular matrices, however, for clarity of visualization of data and analysis results these problems are presented in polar coordinates (transformed to this coordinate system after loading the data/performing the analysis). In the case of data and results export one obtains square/rectangular matrices.

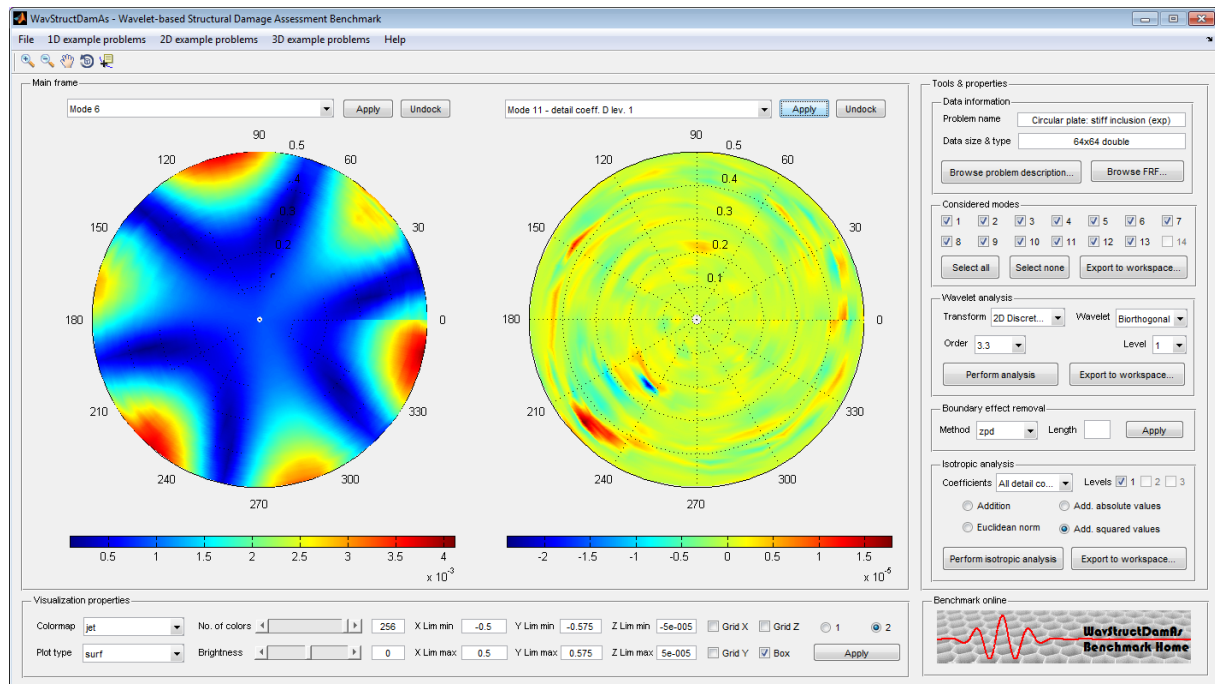


Figure 12. Visualization of problem data and results of analysis in polar coordinates

For 1D problems a Continuous Wavelet Transform is available. One can define a single value of the scale parameter or the range of scale parameter values. In the first case one should type an integer value in the appropriate textbox, while in the second case one should type two values, which constitute a range following the scheme <number>:<number> (see Figure 13 ①).

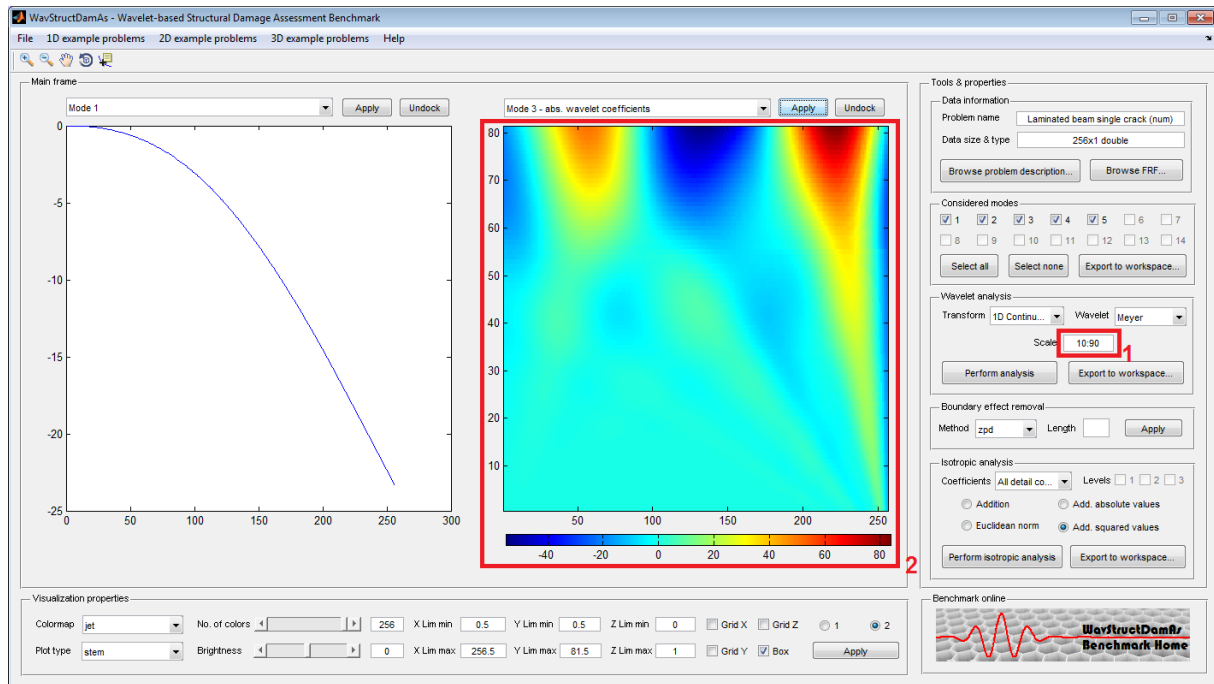


Figure 13. Performing analysis using Continuous Wavelet Transform algorithm

Depending on the selected way of input one obtains a line plot (1D) or an image plot (2D) in the results visualization window (see Figure 13 ②).

All example problems contain the descriptions (brief information on material, its main properties and character of damage) available when pressing the 'Browse problem description...' button in the 'Data information' panel (Figure 1 ③). The typical window with a picture and main parameters of the selected example problem is presented in Figure 14. The bottom part of this window may contain the hyperlinks to papers with more deep description and results of damage identification using selected wavelet transform.

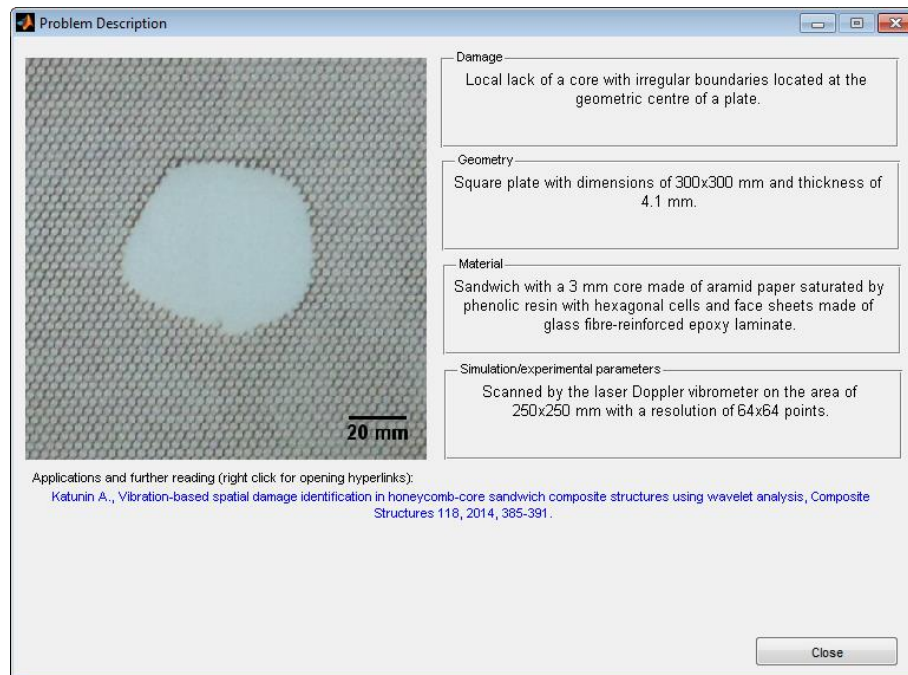


Figure 14. Typical problem description window

Moreover, the 'Browse FRF...' button is available for example problems (see Figure 15). The most of experimental examples contains the frequency response function (FRF) for the selected example problem with

highlighted modes selected for specific problem. Below, corresponding natural frequencies are presented. The testing parameters like FRF frequency resolution and sampling rate may be available at the bottom part of the figure. For numerical example problems only the values of natural frequencies can be displayed.

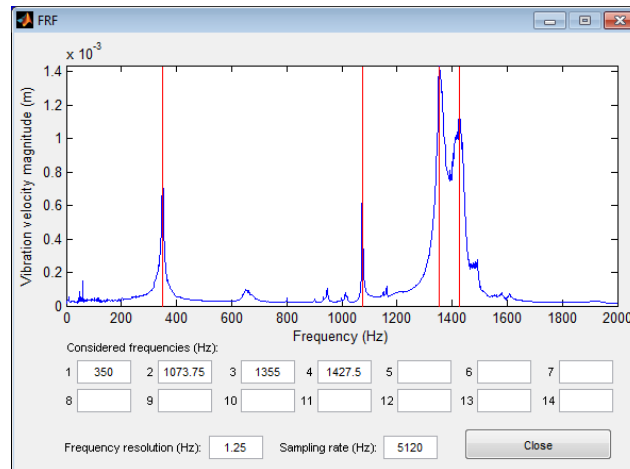


Figure 15. Typical FRF window

EXAMPLE PROBLEMS

The example problems consist of 1D, 2D and 3D datasets of damaged composite structures obtained experimentally during laboratory tests and simulated in the FEM-based software. The characteristics of example problems implemented in the benchmark are stored below.

Problem name	Type of data	Size of data	Problem dimension
Laminated beam with single crack	numerical	256x1	1D
Laminated beam undamaged	experimental	44x1	1D
Laminated beam with single crack 1 & 2	experimental	44x1	1D
Laminated beam with multiple cracks 1-3	experimental	39x1	1D
Laminated beam with large area delamination (11 cases – delamination between each pair of layers)	numerical	255x1	1D
Laminated beam with large limited area delamination (11 cases – delamination between each pair of layers)	numerical	255x1	1D
Laminated beam with small area delamination (11 cases – delamination between each pair of layers)	numerical	255x1	1D
Laminated beam with small limited area delamination (11 cases – delamination between each pair of layers)	numerical	255x1	1D
Laminated plate with through-the-width surface crack	numerical experimental	64x64	2D
Laminated plate with spatial surface damage	numerical experimental	64x64	2D
Laminated plate with multiple surface damage (two spatial damage and small crack)	numerical experimental	64x64	2D
Laminated plate with impact damage (24 cases – various impactors and impact energies)	experimental	64x64	2D
Laminated plate with stone impact damage (20 cases – various impactors and impact energies)	experimental	64x64	2D
Hybrid Al-GFRP-Al composite structure with impact damage	experimental	73x51	2D
GFRP structure with impact damage	experimental	59x71	2D
CFRP aircraft stabilizer with delaminations	experimental	73x65	2D
Laminated plates with multiple internal voids 1-7 (various locations on the thickness)	numerical	64x64	2D
Sandwich plate with partial local lack of core	experimental	64x64	2D
Sandwich plate with local lack of core 1-2 (various shapes)	experimental	64x64	2D
Sandwich plate with local crack of core 1-2 (various shapes)	experimental	64x64	2D
Sandwich plate with through-the-width crack of core	experimental	64x64	2D
Sandwich plate with face sheet debonding	experimental	64x64	2D
Sandwich plate with impact damage (16 cases – various impactors and impact energies)	experimental	64x64	2D
Rotor blade with longitudinal crack	numerical	150x250	2D
Rotor blade with transversal crack	numerical	150x250	2D
Laminated circular plate with surface damage 1 & 2 (various shapes and locations)	numerical	51x100	2D
Laminated circular plate with delamination	numerical	51x100	2D
Laminated circular plate with internal void	numerical	51x100	2D
Laminated plate with internal stiff inclusion	experimental	64x64	2D
Laminated plate with hole (delaminations) – data from computed tomography	experimental	452x504x83	3D
Multilayer weft knitted fabrics composite (delaminations) – data from computed tomography	experimental	434x507x100	3D

Numerical problems: 61; experimental problems: 82; 1D problems: 51, 2D problems: 90, 3D problems: 2.

DESCRIPTION OF ERROR MESSAGES

#	Error	Additional description
001	Wavelet Toolbox is not installed on your system! This will cause incorrect work of some benchmark functions.	The Wavelet Toolbox™ is required for using the WavStructDamAs benchmark. Without this toolbox only viewing of the problems and its description is possible.
002	No data available for the analysis!	One should upload own data or select an example problem prior the analysis.
003	The transform was not selected!	One should select the wavelet transform prior the analysis.
004	No data available! Please perform the analysis first.	One should perform the analysis before undocking the visualization window.
005	No data available! Please upload data or select an example problem.	One should upload own data or select an example problem before applying the selection in visualization window.
006	No data available! Please upload data or select an example problem.	One should upload own data or select an example problem before undocking the visualization window.
007	The problem was not selected!	One can browse the problem description only after its selection from example problems.
008	This function is not available for your own problem!	One cannot browse the description for the uploaded data.
009	The wavelet transform should be performed first!	The isotropic analysis is possible only after performing the wavelet analysis.
010	Neither data nor results are available!	One can apply the visualization properties only when the problem is loaded/calculated.
011	No results available! Please perform the analysis first.	One cannot apply the visualization properties to the results window before performing the wavelet analysis.
012	No data available! Please upload data or select an example problem.	One can apply the visualization properties only when the problem is loaded.
013	The problem was not selected!	You can browse FRF and frequencies only for loaded example problems.
014	This function is not available for your own problem!	One cannot browse FRF and frequencies for uploaded data.
015	Input of extension length is incorrect!	One can use only numeric values for signal cutting/extension in boundary effect removal procedure.
016	Extension length is too big for considered case! Please consider the smaller value.	The extension length cannot be greater than half of signal length minus 1.
017	Extension length is too big for considered case! Please consider the smaller value.	The extension length cannot be greater than half of each dimension length of 2D signal minus 1.
018	Extension length is too big for considered case! Please consider the smaller value.	The extension length cannot be greater than half of each dimension length of 3D signal minus 1.
019	The calculations should be performed first!	One should perform the wavelet analysis before applying the boundary effect removal procedure.
020	No data available! Please upload data or select example problem.	One can apply the visualization properties only when the problem is loaded.
021	Neither data nor results are available!	One can apply the visualization properties only when the problem is loaded/calculated.
022	No results available! Please perform the analysis first.	One cannot apply the visualization properties to the results window before performing the wavelet analysis.
023	Please select a wavelet transform!	One should select the wavelet transform before analysis.
024	Please select a wavelet!	One should select the wavelet before the analysis.
025	Please input a wavelet order!	The wavelet order is required for the selected wavelet/wavelet transform.
026	Please input a shift parameter!	The shift parameter is required for the Discrete Fractional Wavelet Transform.

027	Please input scale parameter(s)!	The scale parameter is required for the Continuous Wavelet Transform. One can select a single value or the range of values (e.g. 1:50).
028	Input of wavelet order is incorrect!	One can use only numeric values, decimal sign (dot) and minus sign for defining an order of fractional wavelet.
029	Too small value of the wavelet order!	The value of wavelet order for this type of wavelets cannot be smaller than -0.5.
030	Input of the wavelet order is incorrect!	One can use only numeric values, decimal sign (dot) and minus sign for defining an order of fractional wavelet.
031	Too small value of the wavelet order!	The value of the wavelet order for this type of wavelets cannot be smaller than 2.
032	Input of the shift parameter is incorrect!	One can use only numeric values, decimal sign (dot) and minus sign for defining a shift parameter for fractional wavelet.
033	Input of scale parameter(s) is incorrect!	One can use only numeric values for defining the scale parameter and ':' sign for defining a range of scale parameters.
034	Input of scale parameters is incorrect!	One should use the following notation '<number>:<number>' in order to define the range of scale parameters.
035	You can load no more than 14 data files!	The loading is limited to 14 data files.
036	No data files uploaded!	One should upload own data files before proceeding.
037	Data sizes in loaded files must agree!	All of the loaded files should have the same sizes.
038	Uploaded data must be of integer, single or double type!	Only integer, single or double (with all subtypes) type data can be handled in the benchmark.
039	Input of cutting plane is incorrect!	One can use only numeric integer values for defining the cutting plane in 3D visualization mode.
040	Input of cutting plane is too big!	The inputted value for cutting plane should be lower than the upper limit of Z-axis for loaded data.
041	Input of cutting plane is incorrect!	One can use only numeric integer values for defining the cutting plane in 3D visualization mode.
042	Input of cutting plane is too big!	The inputted value for cutting plane should be lower than the upper limit of Z-axis for loaded data.