UNIVERSAL MECHANISM 9

universal mechanism

User`s manual

# UM Durability Module

**2020**

# Contents

# 13. UM Durability

## 13.1. Introduction

The present paper describes the CAE-based durability analysis that is being implemented in Universal Mechanism software to predict the fatigue damage of parts of mechanical systems. The dynamic simulation of parts is performed using Universal Mechanism. Flexible body representation is considered using external finite element (FE) software. The present version of UM supports two FE software – ANSYS and MSC.NASTRAN. The final durability post-processing analysis is performed using the UM Durability module.

The analysis starts with the dynamical hybrid model in Universal Mechanism. The flexibility characteristics of the structural parts are incorporated into UM model using a modal formulation based upon component mode synthesis. Basically, this method represents the part's flexibility using a modal basis, which is optimized to account for constraint and force locations. The mode shape displacements and stresses are calculated using the finite element programs ANSYS or MSC.NASTRAN.

The UM Durability module combines the stress time history information generated during series of numerical experiments in UM and the material fatigue strength characteristics to generate the predicted life distribution in the part.

Any durability analysis relies on three key inputs:

- Stress loading data – time history of the stresses
- Material data – how the material reacts to repeated stress application at various stress levels
- Durability parameters calculation method.

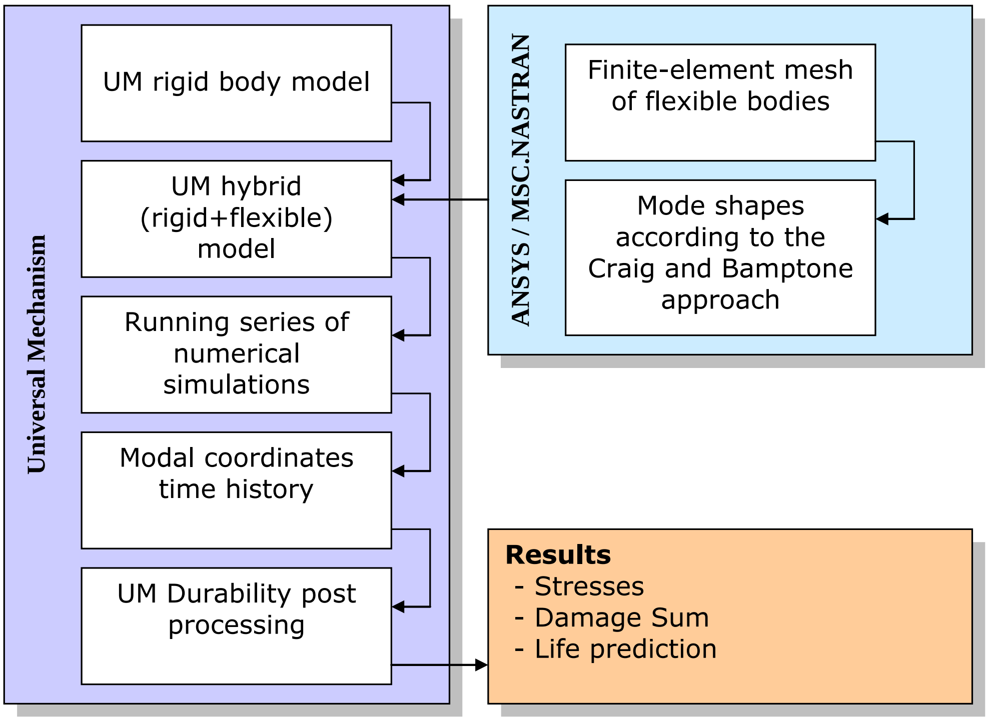
By employing the full finite element representation of the component in the UM model, the local stresses are directly obtained as result of the UM solution. In the UM FEM module, flexible body deformations are modeled as a linear combination of mode shapes. As long as the number of mode shapes selected adequately the modal superposition will model deformations accurately and efficiently.

The idea that the deformation of a flexible body can be represented by the sum of a number of mode shapes scaled by appropriate factors can be extended to stresses in the body as well. These factors or modal coordinates can be used as the scaling factors on the stress solution of each mode shape and the superposition of these scaled stresses represents the body's instantaneous stress state. If the superposition is performed at every node in the finite element model for every time step in the UM solution, the stress time history is defined at every location.

Using the UM FEM tools the modal coordinate time history can be saved for every numerical simulation in UM. Based on this modal time history and file with orthonormalized mode shapes from ANSYS or MSC.NASTRAN the stresses at every node can be obtained.

When UM Durability is started, the user is prompted for the location of modal coordinate time history files and orthonormalized mode shapes files, then the type of analysis required and the material data to be used.

With all of the parameters set, UM Durability performs the stress at every node and then proceeds to multi-channel peak/valley extraction and rain flow cycle counting followed by the damage sum.


Universal Mechanism
UM rigid body model
UM hybrid (rigid+flexible) model
Running series of numerical simulations
Modal coordinates time history
UM Durability post processing
ANSYS / MSC.NASTRAN
Finite-element mesh of flexible bodies
Mode shapes according to the Craig and Bamptone approach
Results
- Stresses
- Damage Sum
- Life prediction

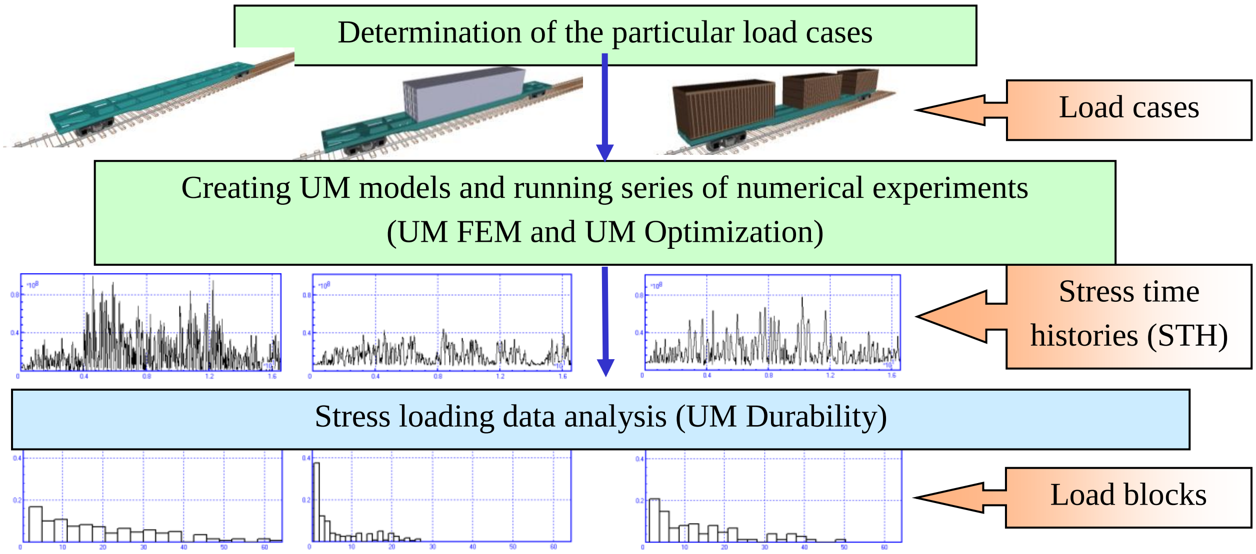
# 13.2. Stress loading analysis in UM Durability

Accurate stress time history for significant load cases is the basis for correct durability analysis and life prediction. It can be obtained directly during full-scale experiments in various load cases of the object. Such an approach has some disadvantages. There are quite high explicit costs and time efforts, necessity of making several full-scale models that makes impossible using such an approach in the beginning of the design process when cost of alteration is minimal. The alternative approach to estimation of stress time history is numerical simulation of dynamics of a mechanical system.

Approach to simulation of dynamics of hybrid mechanical systems according to Craig-Bampton approach is described in Chapter 11 of UM User's Manual “UM FEM module”[1].

## 13.2.1. Approach to stress loading data analysis

Basic steps of stress loading data analysis with Universal Mechanism are depicted in the figure below.




**STH** is a stress time history at a node for the particular load case.

*Load block* is an internal term which means a record of stress loading parameters at a node for the particular load case.

Load block contains the following data:

- STH statistics (maximum, mean, minimum, RMS values, etc.),
- STH cycle count,
- Distribution of stress loading parameters evaluated from the STH.

These data are destined for the preliminary selection of dangerous zones of the object and the further durability parameters evaluation.

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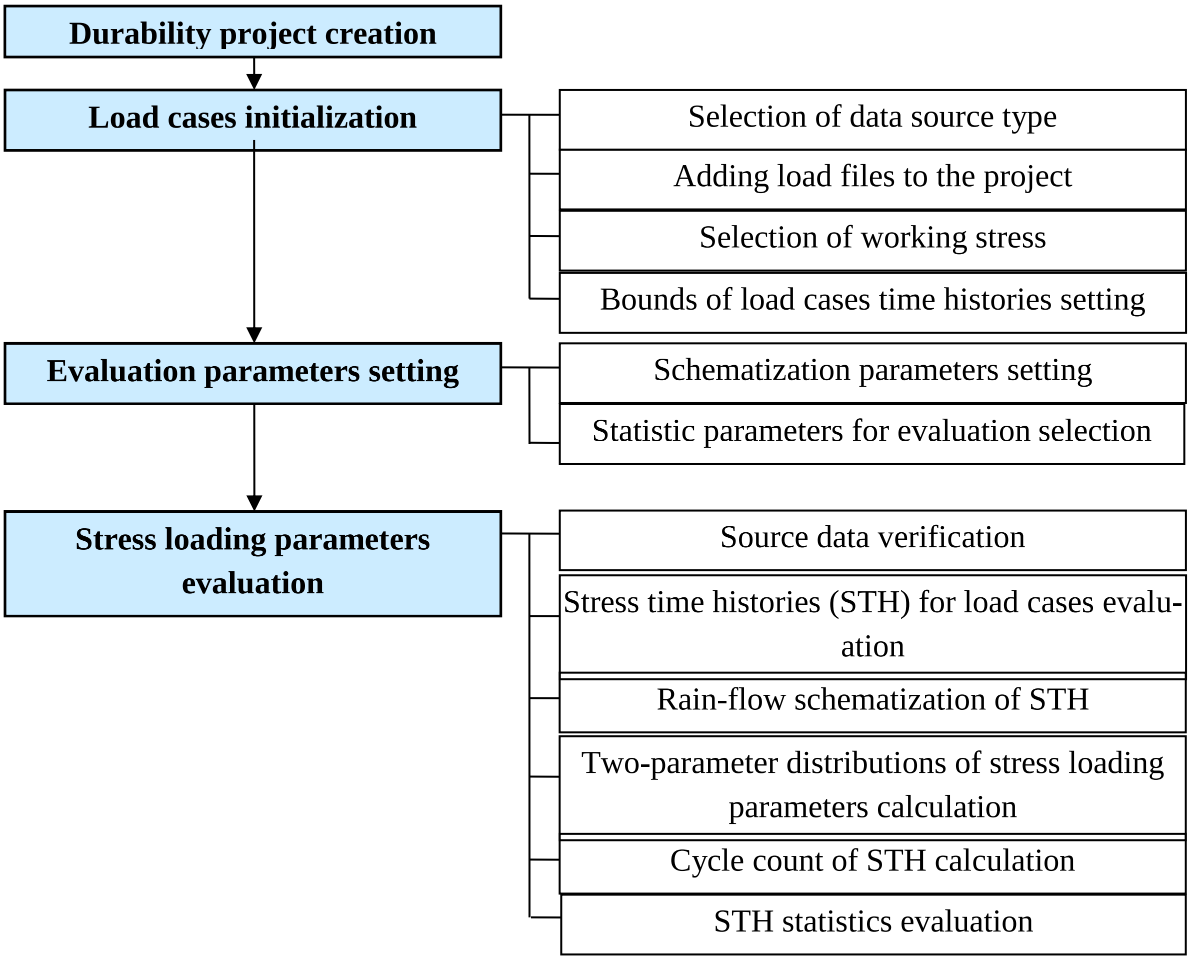
[1] Also available in the Internet at www.universalmechanism.com/download/90/eng/11_um_fem.pdf

Basic steps of stress loading data analysis with UM Durability are depicted in the figure below.



#### 13.2.1.1. Calculation of stress time history

Here let us consider an algorithm that is used to calculate the stress time history in Universal Mechanism.

**Calculation of stress tensor**

To calculate the stress time history in a body this body should be represented in a model as a flexible one. In terms of UM it should be introduced into a model as a flexible subsystem.

The stress history during numerical simulations could be obtained for so called *sensors* only. The sensors are the nodes of FE-mesh for which matrices for calculating the stress tensor from modal coordinates are prepared. Steps of preparing data for flexible subsystem are considered in details in Chapter 11 of UM User's Manual "UM FEM module". To compute the stress tensor the following expression is used:

$$\sigma_i^e = D_i^e B_i^e (x_i^e) u_i^e = D_i^e B_i^e (x_i^e) H_i^e w = D_i^e B_i^e (x_i^e) \sum_{j=1}^{H} h_{ji}^e w_j = \sum_{j=1}^{H} h_{ji}^{e\sigma} w_j = H_i^{e\sigma} w \qquad (13.1)$$

where $\sigma_i^e$ is a column matrix of stress components of i finite elements, $B_i^e$ is a matrix that connected strains of a finite element with nodal displacements, $D_i^e$ is a stiffness matrix of a finite element, $x_i^e$ is a column matrix of coordinates of nodes of finite element, $h_{ji}^e$ is a part of *j* eigenmode that corresponds to *i* finite element.

During numerical simulation modal coordinates of each flexible subsystem are saved to binary *.imc files with fixed time step. Matrices for all sensors of each flexible subsystem are in **input.fss**.

**Choice of stress component**

Classical high-cycle fatigue theory lets estimate life predication for a part in the case of the uniaxial stress state, where the stress tensor has the only nonzero component.

In most cases we have a complex stress state. If one of the components of the stress tensor is much greater than others or all components of the stress tensor change proportionally we can use the same methods to obtain the life prediction.

UM Durability lets the user a possibility to calculate damage characteristics based on various stress:

- Absolute values of maximal principal stress

It is supposed that maximal stretching and pressing force make a contribution to fatigue load.

- Maximal principal stress
- Unsigned *von Mises* by principle stresses

The following expression is used:

$$\sigma = \sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2]} \qquad (13.2)$$

- Unsigned von Mises by normal and shear stresses

$$\sigma = \sqrt{\frac{1}{2}\left[\left(\sigma_x - \sigma_y\right)^2 + (\sigma_x - \sigma_z)^2 + \left(\sigma_y - \sigma_z\right)^2 + 6\left(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{xz}^2\right)\right]} \quad (13.3)$$

### 13.2.1.2. Process schematization

The fatigue analysis supposes the stress time history schematization as the necessary step. The schematization represents the time history as a sequence of stress cycles with some calculated parameters.

The schematization procedure includes the following operations.

**Search of the STH extremums**

The stress time history is represented as a sequence of values with fixed time step, see Figure 13.1.

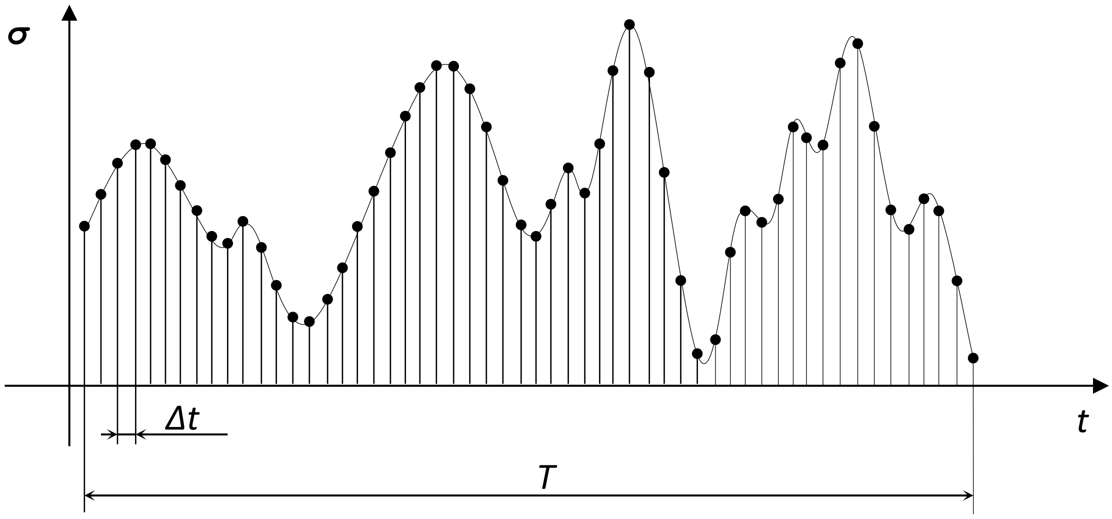



Figure 13.1. Stress time history

The following rules are used. If $\sigma_{j-1} < \sigma_j \geq \sigma_{j+1}$ then the point with $\sigma_j$ is maximum. If $\sigma_{j-1} < \sigma_j \geq \sigma_{j+1}$ then point $\sigma_j$ is considered as minimum.

**Schematization**

The rainflow-counting algorithm (also known as the "rain-flow counting method") is used in the analysis of fatigue data in order to reduce a spectrum of varying stress into a set of simple stress reversals. For each half-cycle, an amplitude and a mean value are fixed.

The rainflow algorithm is as follows:

1. Reduce the time history to a sequence of (tensile) peaks and (compressive) troughs.
2. Imagine that the time history is a template for a rigid sheet (pagoda roof).
3. Turn the sheet clockwise 90° (earliest time to the top).
4. Each *tensile peak* is imagined as a source of water that "drips" down the pagoda.

5. Count the number of half-cycles by looking for terminations in the flow occurring when either:
   - It reaches the end of the time history, for example half-cycle that starts at peak 19;
   - It merges with a flow that started at an earlier *tensile peak*; or
   - It flows opposite a *tensile peak* of greater magnitude. For example half-cycle starts at peak 1 and terminates opposite a greater tensile stress, peak 3.
6. Repeat step 5 for *compressive troughs*.
7. Assign a magnitude to each half-cycle equal to the stress difference between its start and termination.
8. Pair up half-cycles of identical magnitude (but opposite sense) to count the number of complete cycles. Typically, there are some residual half-cycles.

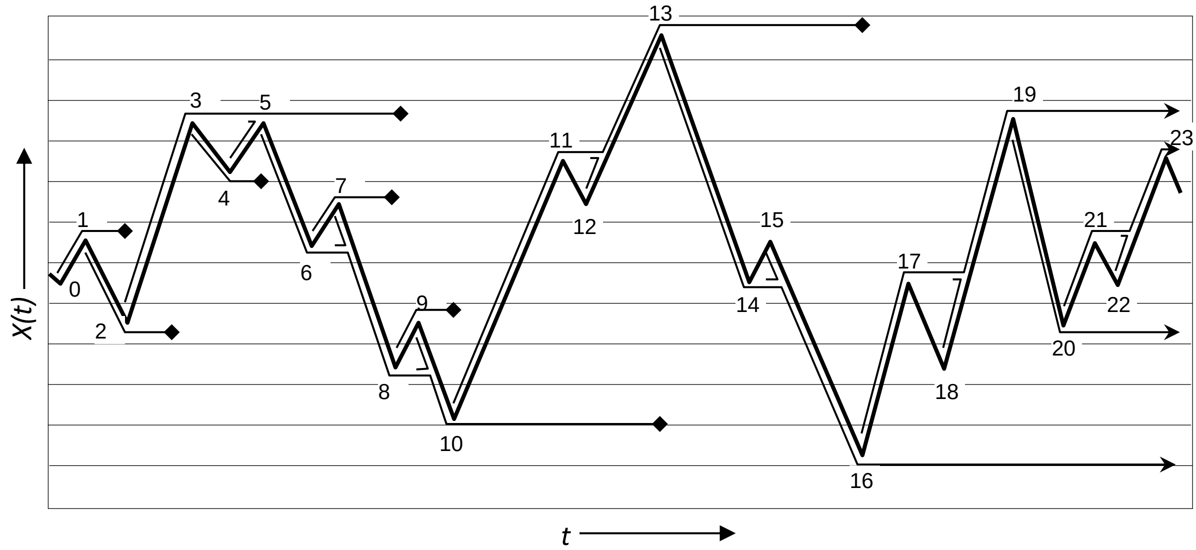



Figure 13.2. Rain-flow cycle counting algorithm

### 13.2.1.3. Stress loading parameters distributions

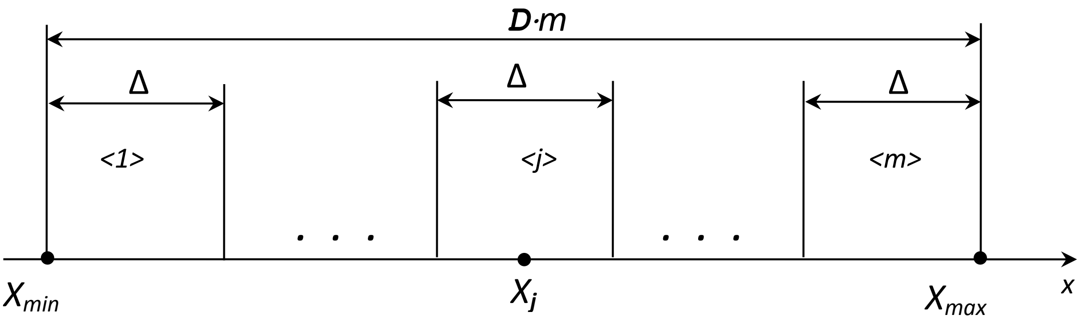
The aggregate of amplitudes and mean values of half-cycles which was obtained as a result of the schematization is statistically analyzed. One- and two-parameter distributions are used in UM Durability.

Basic principles of the distribution calculation procedure can be illustrated for the one-parameter distribution.

**Fundamentals**

It is recommended that the number of intervals should satisfy to the inequality $14 \leq m \leq 32$.

The distribution is formed in such a way that the maximal amplitude is the right bound of the last interval in the block and the minimal amplitude is the left bound of the first interval. Numbering of intervals goes in the direction of increment of values. If the value of amplitude lays on the interval boundary then this value is put to the interval with bigger number.




$X_{min}$ is the minimal value,
$X_{max}$ is the maximal value,
**D** is the width of the interval,
<*j*> is the number of the interval,
$X_j$ is the representative value of the interval.

<u>Distributions forming</u>

Two algorithms of distributions forming are realized in the UM Durability.

- <u>Algorithm with automatic determination of width of intervals</u>

Width of intervals is determined as $\Delta = \frac{a_{max}}{m}$, where $a_{max} = X_{max} - X_{min}$.

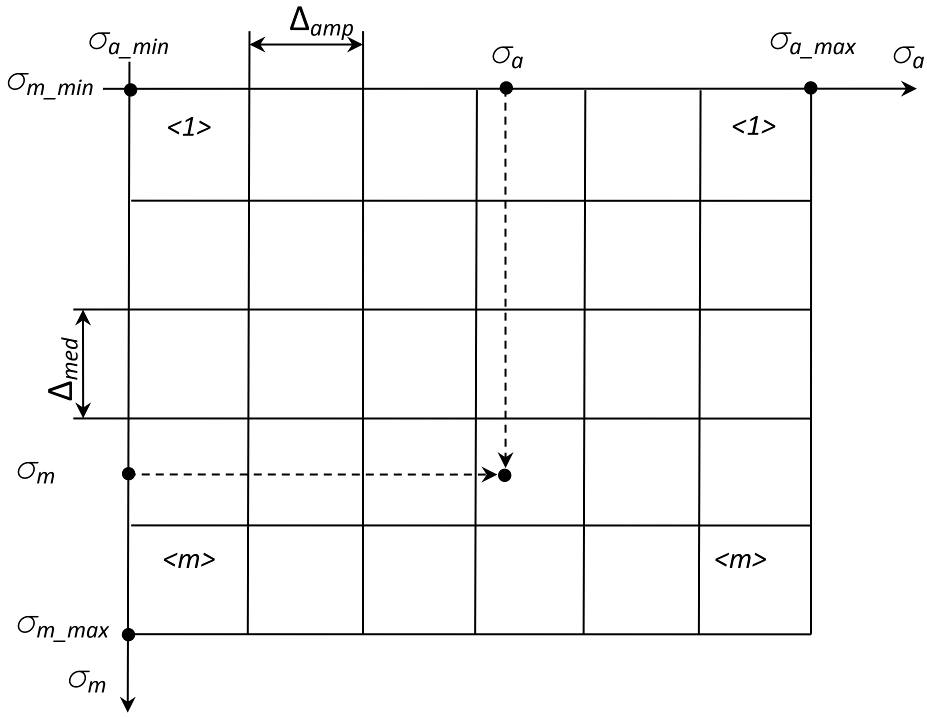
- <u>Algorithm with preset width of interval</u>

If the difference between maximum and minimum values is greater than $a = \Delta * m$ then all values less than $X_{min} = X_{max} - a$ are included in the first interval.

**Representation of the results**

UM Durability uses a correlation diagram of amplitude and mean values for the representation of stress loading parameters.

Every cell of the table corresponds to an interval with an amplitude $\sigma_a$ and median $\sigma_m$. Rows correspond to intervals of mean values, columns – intervals of amplitudes. Relative parts of corresponding intervals of amplitude and mean value are in cells of the table.



## 13.2.2. Source data preparing

The stress time history at some or all points of a structure is source data for fatigue analysis. To determine stresses in any part of a mechanical system during dynamics simulation in UM, it needs that such a part should be represented as a flexible subsystem.

As a result of numerical experiments of a hybrid mechanical system the following files are created:

*<Name of a flexible subsystem>***.imc** is a binary file that contains time history of modal coordinates of the flexible subsystem.

*<Name of a flexible subsystem>***.tmc** is a text header file that contains information for working with corresponding ***.imc** file.

A pair of *.imc/*.tmc files includes the time history of modal coordinates and **input.fss** file includes matrices for computation of stress tensor components in nodes of FE-mesh of a structure based on modal coordinates.

It is recommended that the stress history to be statistically reliable should contain no less than 1000 picks and valleys.

In most cases it is impossible to represent real working conditions of the investigated structure with the help of just one load case. For example a road vehicle runs with various velocities and loads as well as various irregularities also should be considered. The more detailed numerical experiments repeat real working conditions more accurate will be results of the durability analysis. UM Durability lets us represent working conditions with the help of a set of load cases which form working conditions with some weight coefficients.

### 13.2.2.1. Load cases description

You can add/delete load cases to/from a durability project in the **Durability wizard**, see the **Stress loading analysis | Source data | Load cases** tab sheet. Every load case is represented by the corresponding *.tmc file.

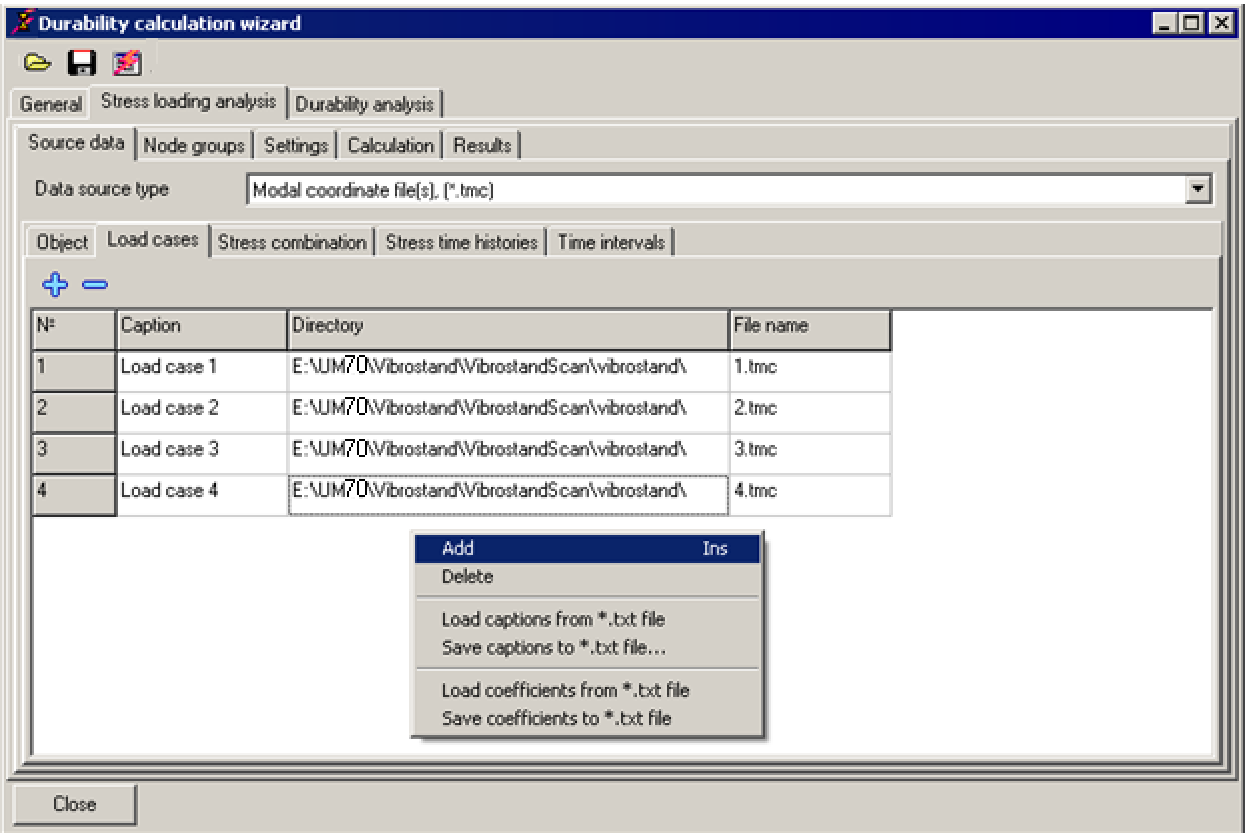



Figure 13.3. Load case list

To **add a load case** click the “plus” button, see Figure 13.3, and then select the *.tmc file (*.tmc files are created as results of the numerical simulation of hybrid system dynamics).

If the selected *.tmc file is created for the hybrid model that contains several flexible subsystems then the corresponding dialog appears. Only one flexible subsystem might be analyzed in the **Durability wizard** at the same time.

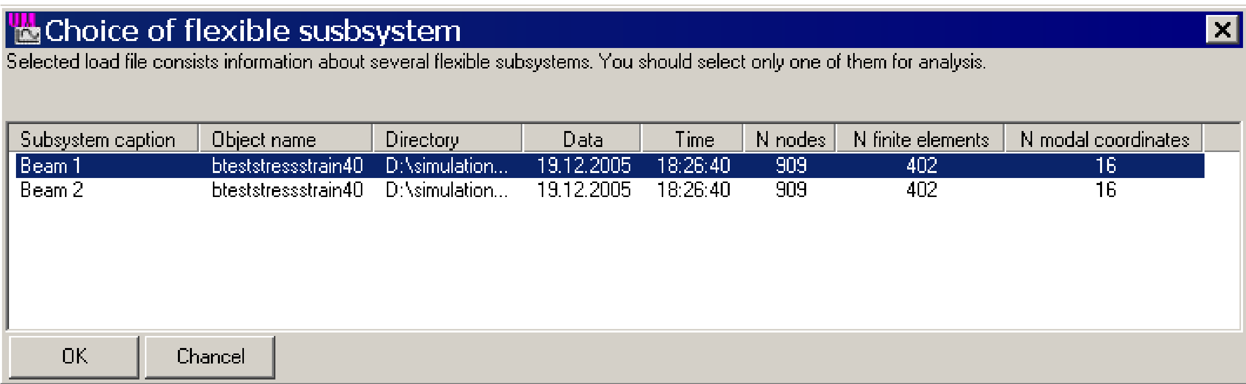



Figure 13.4. The choice of flexible subsystem

If at least one load case is defined then all added *.tmc files are checked for the identity of flexible subsystem. If a new file refers to a different flexible subsystem then the corresponding error message appears.

If new file contains data for several flexible subsystems then the identical subsystem is selected automatically.

Every load case takes a row in the list of load cases and is characterized by the following data.

**Caption** is equal to the file name by default, can be changed by the user.

**Directory** is the path to the directory that contains the selected *.tmc file.

**File name** is the *.tmc file name that actually describes the stress state in the part for the load block and gives stress history.

The context menu of the **Load cases** sheet is depicted in the Figure 13.3 and lets the user a possibility to control the list of load cases and save/load captions to/from text files.

#### 13.2.2.1.1. Usage of the results of multivariant calculation

When the number of separate load cases for representing real working conditions is quite high (decades and hundreds) it is extremely useful to use multivariant calculations (scanning projects) to realize the number of numerical experiments according to the durability analysis program. Scanning is the one of the tools that are implemented in the **UM Optimization** module.

Finished scanning project for the hybrid model with one of more flexible subsystems contains corresponding set of **.imc/*.tmc* files: {N.imc; N.tmc}, where *N* is the internal index of a numerical experiment within the scanning project.

The user can export results of all numerical experiments of the scanning project as load cases to the **Durability wizard**, see the **Fatigue** tab sheet of the **Scanning wizard**.

As soon as you select the necessary flexible subsystem to export for the durability analysis the **Data export** button becomes enable. Click it to open the **Durability wizard** and start export.

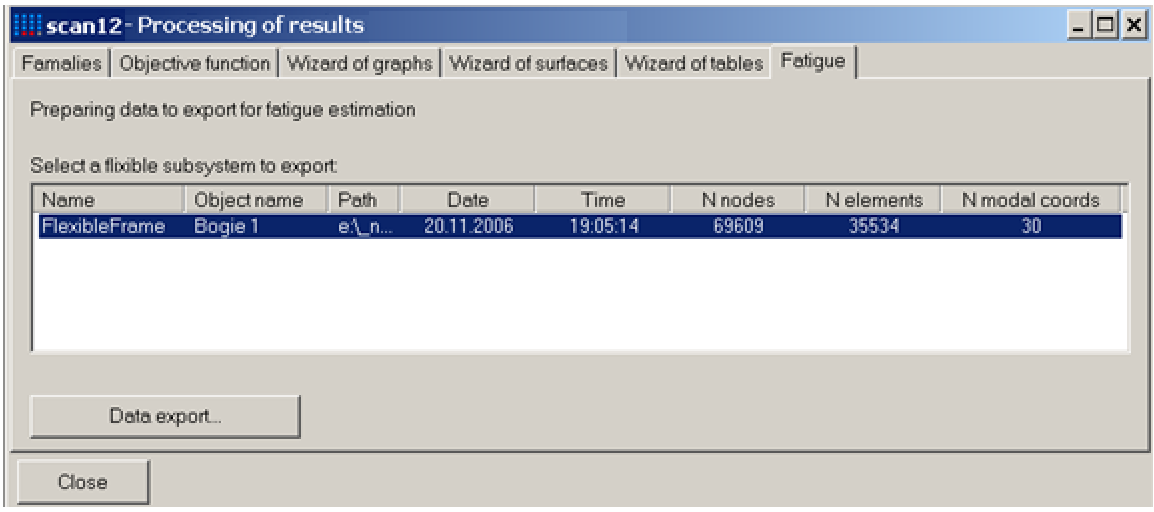



Figure 13.5. Scanning: export results for durability analysis

If the **Durability wizard** at the moment is not empty then the corresponding confirmation appears, see Figure 13.6.

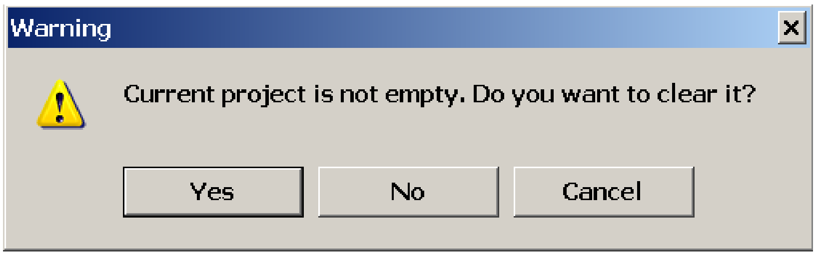



Figure 13.6. Export results: confirmation

Select **Yes** to replace the durability project with new data. You can also not to clear the project of the durability analysis but just add new load cases to the current project. To do that select **No** and after successful checking of the flexible subsystem identity new load cases will be added from the scanning project.

#### 13.2.2.2. Choice of stress combination

Classical S-N damage accumulation rules permit to evaluate durability parameters only for details worked in case of uniaxial stress state whereas most parts are exposed to multiaxial stress state.

There are several rules for stress tensor reducing to uniaxial stress. The **Stress loading analysis | Source data | Stress combination** tab allows choosing a stress component/combination for the further evaluation, see Figure 13.7.

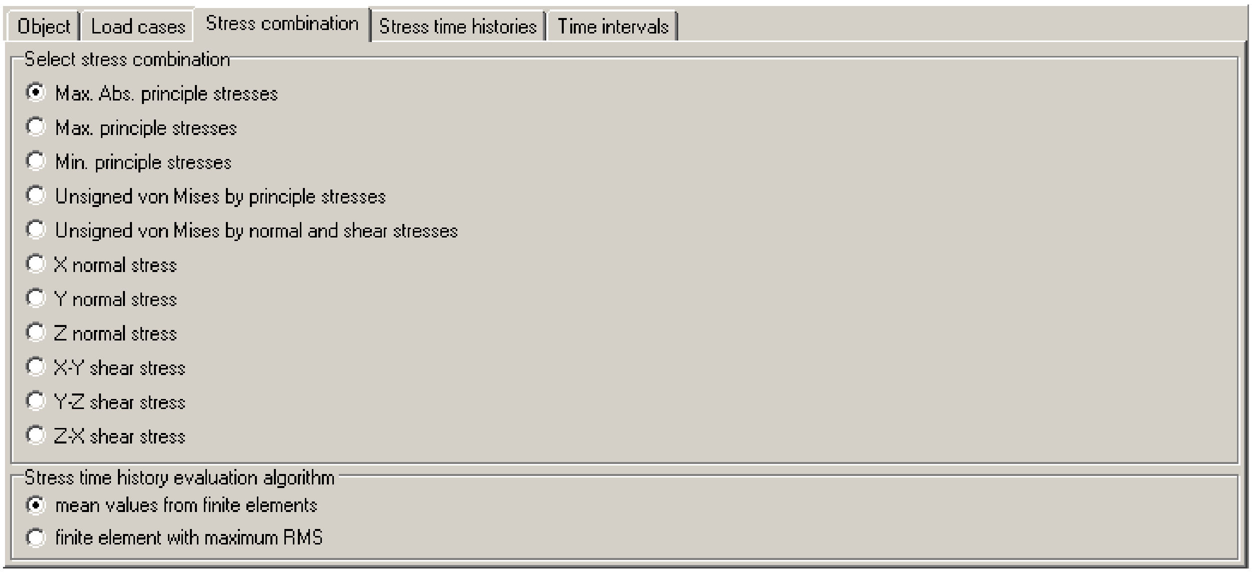



Figure 13.7. Choice of stress combination

The user can assign the following values for the stress combination:

*Max. Abs. principle stresses (signed)*

$$\sigma_{work} = \sigma_1, if\ |\sigma_1| \geq |\sigma_3|$$
$$\sigma_{work} = \sigma_3, if\ |\sigma_1| < |\sigma_3|$$

*Max. principle stresses*

$$\sigma_{work} = \sigma_1$$

*Min. principle stresses*

$$\sigma_{work} = \sigma_3$$

*Unsigned von Mises by principle stresses*

$$\sigma_{work} = \sqrt{\frac{1}{2} \cdot [(\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_2)^2]}$$

*Unsigned von Mises by normal and shear stresses*

$$\sigma_{work} = \sqrt{\frac{1}{2} \cdot \left[\left(\sigma_x - \sigma_y\right)^2 + (\sigma_x - \sigma_z)^2 + \left(\sigma_y - \sigma_z\right)^2 + 6 \cdot \left(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{xz}^2\right)\right]}$$

*Component of stress tensor* (f.e., stress $\sigma_x$ in coordinate system of the flexible subsystem)

$$\sigma_{work} = \sigma_x$$

### 13.2.2.3. Stress histories plotting

For visual control of the selected stress combination at FEM nodes for different load cases the user can use the **Stress loading analysis | Source data | Stress time histories** tab, see Figure 13.8.

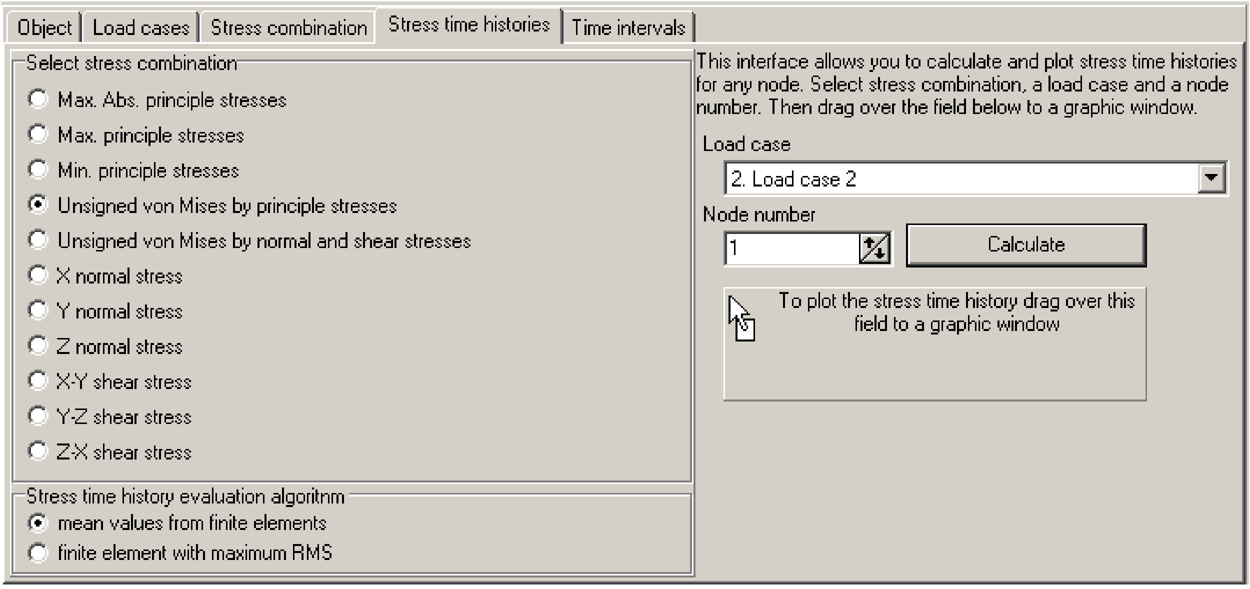
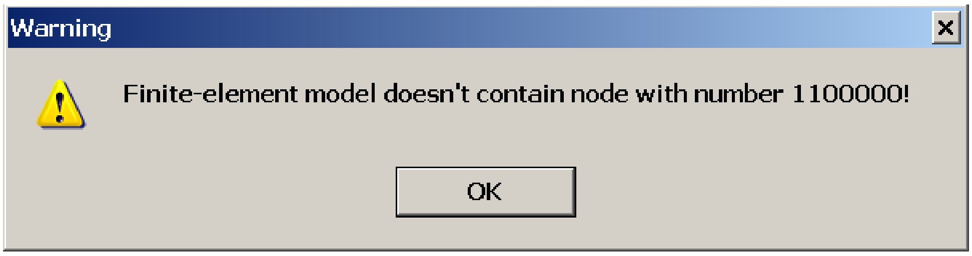


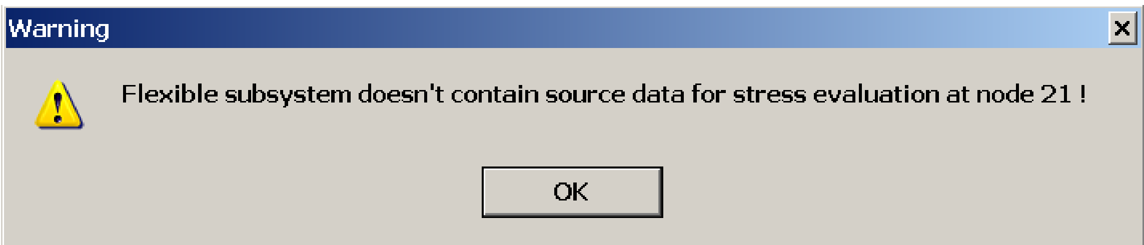

Figure 13.8. Selection of stress history to plot

To plot the stress history the user should select working stress, load case and number of node and click the «**Calculate**» button.

Loading of *.imc file for the selected load case starts. Then evaluating of the stress history at the node is realized.

If the flexible subsystem doesn't contain the node with the selected number or ***.fss** file of the subsystem doesn't contain data for the stress history evaluation at that node the following message is generated.



To plot a stress history it is necessary to open a standard graphic window and drag the  field over it, see Figure 13.9.

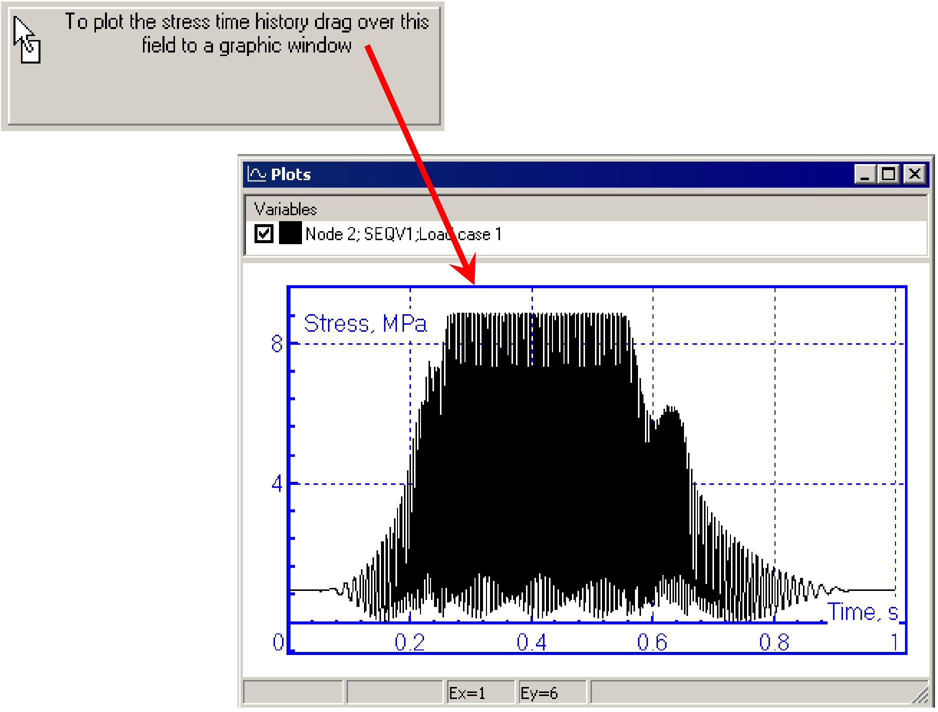



Figure 13.9. Stress histories plotting

The evaluated stress history is a standard graphical variable and can be used for a **Statistics** calculation or for usage in the **Table processor**, see Figure 13.10.

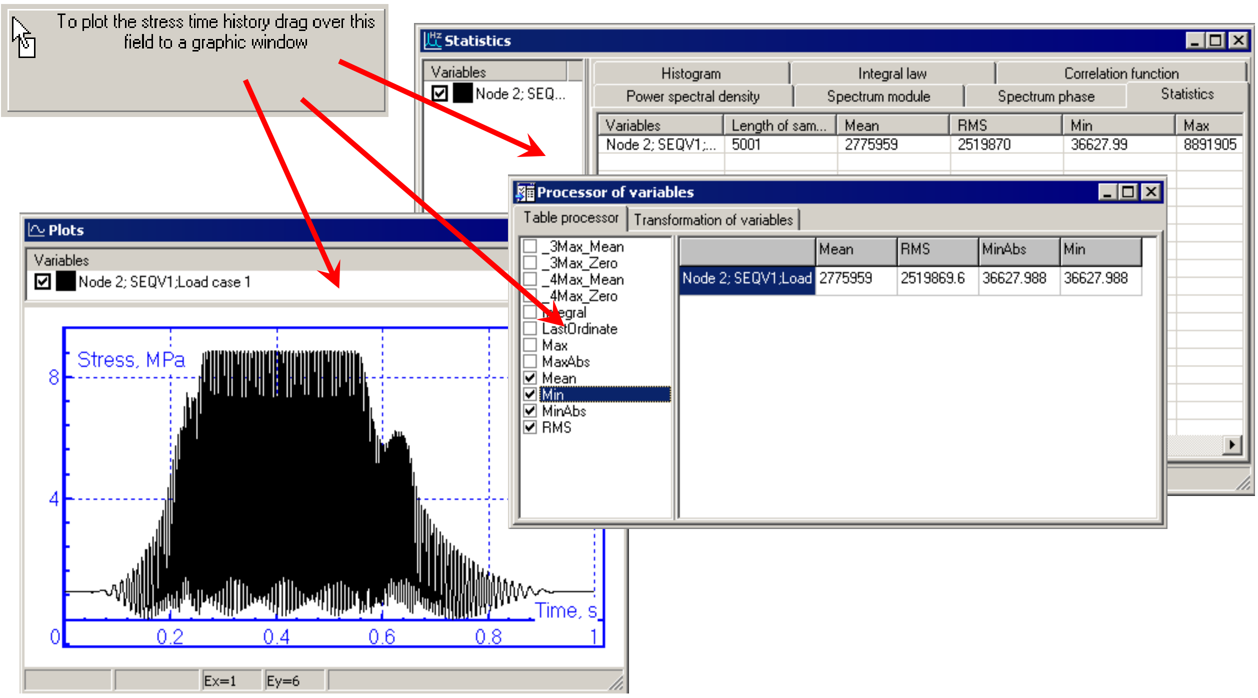



Figure 13.10. Stress history graph usage

### 13.2.2.4. Time intervals of the load cases stress histories setting

**Imc** files contain records of time histories of FEM modal coordinates, generated with user defined time step size. A load case can be presented with the whole stress time history or with the part of it. The part of time history can be defined with two time points: $t_1$ is the start time and $t_2$ is the finish time of the stress history as it shown at Figure 13.11 below.

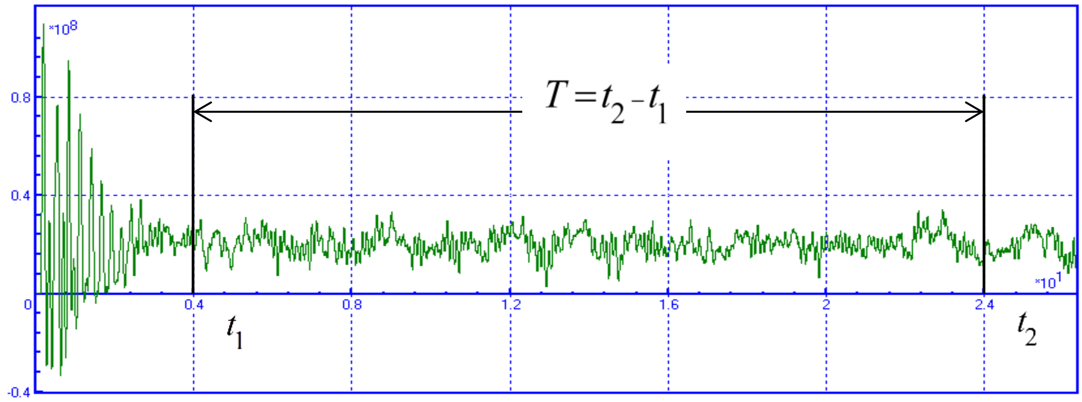


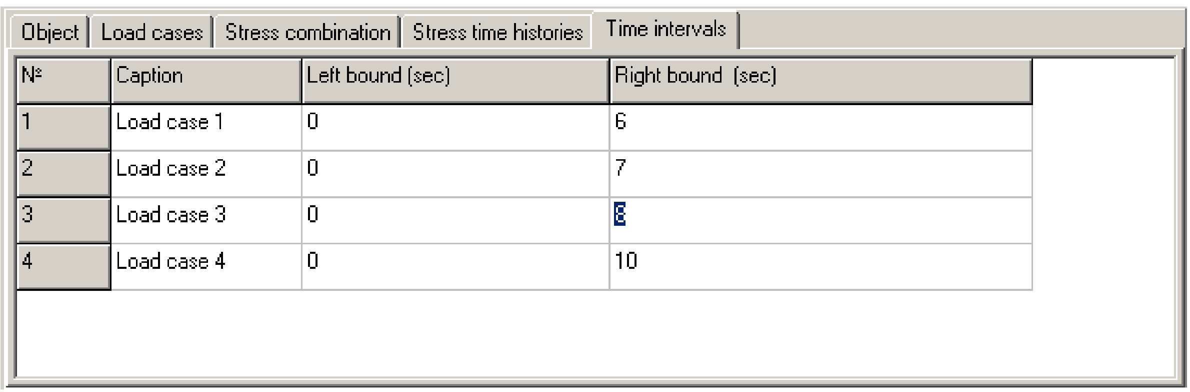

Figure 13.11. Time interval of stress history

For example that option can be used in the following cases:

- cutting of the beginning of time history, which contains transient process if the load case describes a steady-state process;
- cutting of the end of time history, which contains a steady-state process if load case describes a transient process (e.g. starting duty load case), etc.

**Note.** Working stress history time interval $T = t_2 - t_1$ is used for load case cycle count per second value evaluation. This value can have a great influence for durability parameters of the investigated part.

To define the bounds of time histories of the load cases the **Stress loading analysis | Source data | Time intervals** is used, see Figure 13.12.




| № | Caption | Left bound (sec) | Right bound (sec) |
|---|---|---|---|
| 1 | Load case 1 | 0 | 6 |
| 2 | Load case 2 | 0 | 7 |
| 3 | Load case 3 | 0 | 8 |
| 4 | Load case 4 | 0 | 10 |

Figure 13.12. Time intervals setting

Time intervals can be defined by the user at the fields of the table loaded from ***.txt** file or saved to ***.txt** file.

## 13.2.3. Node group initialization

Durability evaluation of a structure requires a preliminary choice of most dangerous zones of the structure and fatigue resistance properties in these zones. Accordingly, a notion of a *group of nodes* is introduced. The group is a set of nodes with equal resistance properties. Preliminarily the choice of node groups is based on the analysis of structural and technological features of the object (often according to regulations).

The **Stress loading analysis | Node groups** tab is used for preliminary setting these data.

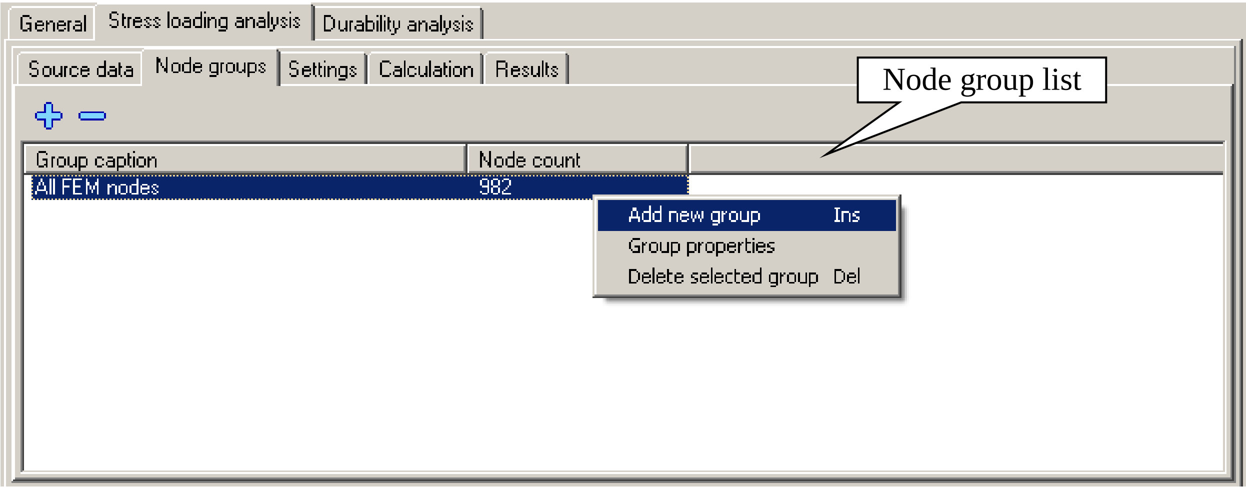



Figure 13.13. Group of nodes

By default all nodes of a FEM model are placed in the **All FEM nodes** group. Use the and buttons as well as commands of the popup menu to add or remove node groups. Group properties are set in the window which can be opened with the help of double click on the selected row of the group.

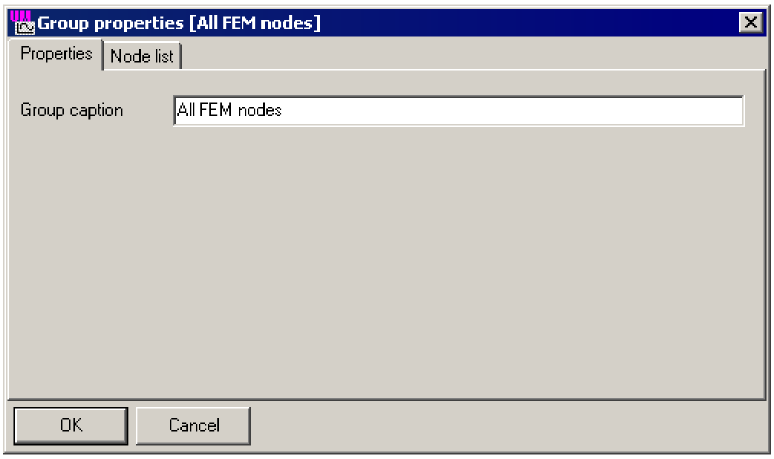



Figure 13.14. Group properties

The window includes **Properties** and **Node list** tabs. The **Properties** tab is used to assign the caption of the group.

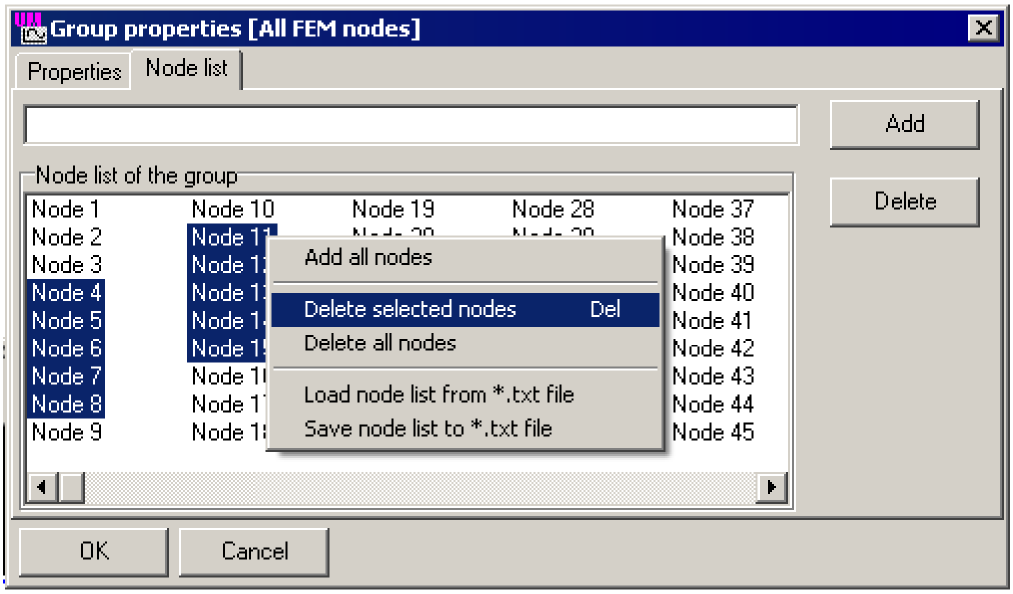
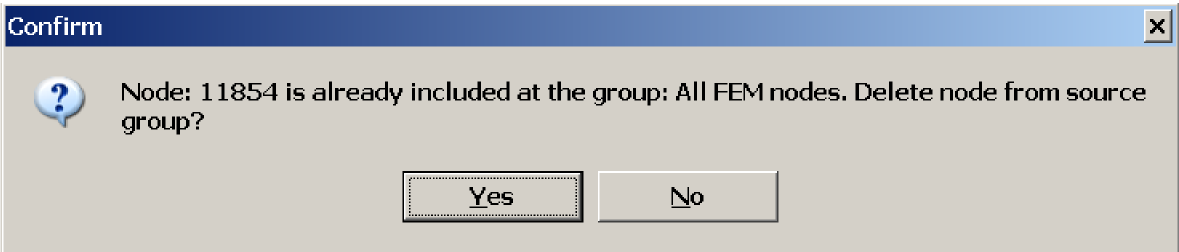



Figure 13.15. Node list of the group

The **Node list** tab contains the list of nodes. The popup menu is used for editing this list.

Each FEM node can be included in one group only. If the user includes a node in more than one list, the message about an error occurs.




**Note.** Choice of nodes for the durability analysis is rather difficult in most cases. Accordingly, the user can modify the node list after stress loading analysis using the **Durability analysis | Fatigue resistance** tab.

## 13.2.4. Stress loading analysis options

The stress loading analysis procedure includes the computation of the stress history statistics and the schematization process for all nodes included in node groups.

According to the computation results depending on the selected options two-parameter loading blocks are calculated for all operating regimes.

Stress loading evaluation parameters are placed at the **Stress loading analysis | Settings** tab.

### 13.2.4.1. General

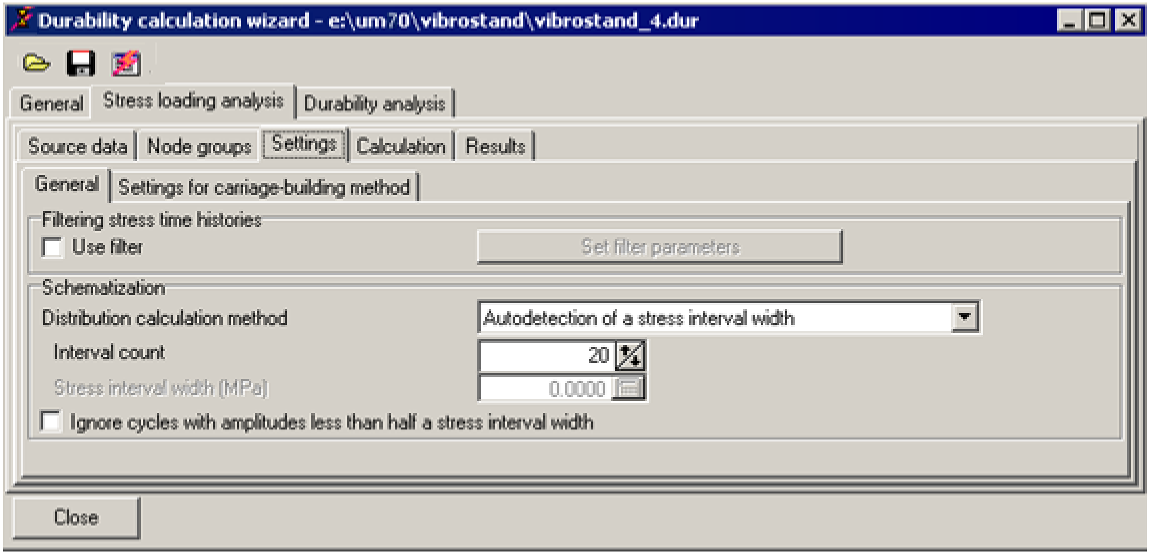



Figure 13.16. General settings of the stress loading analysis

The **stress loading analysis | Settings | General** tab allows you to set the following options of the stress loading evaluation procedure:

- **Filtering stress time histories**

This option allows filtering the stress history process before start of the schematization process. If **Use filter** is on click the **Set filter parameters** button to select the filter type and set its parameters.

**Note.** The procedure that displays stress histories on the Source data | Stress time histories tab uses this filter if the filter is switched on.

- **Schematization**

The **distribution calculation method** combo box allows to choose one of two available methods of the calculation of the stress loading parameters distribution, see Sect. 13.2.2.3. *"Stress histories plotting"*, p. 13-18.

The **interval count** value defines interval count of stress loading parameters distribution. Increasing of this value makes the distribution description more accuracy. According to regularities the interval count value can be set from 14 to 32.

**The stress interval width (MPa)** field allows setting fixed interval width of the stress loading parameters distribution. It is used if the corresponding *distribution calculation method* is selected.

**Ignore cycles with amplitude value less than half of interval width**. This options gives an ability to ignore loading cycles with small amplitudes.

**Note.** Usage of this option is not recommended if the automatic interval width evaluation method is selected.

#### 13.2.4.2. Complementary settings

The **stress loading analysis | Settings** tab contains tabs which allows setting additional stress loading evaluation parameters used in the durability prediction algorithm.

##### 13.2.4.2.1. Stress loading evaluation parameters for carriage-building method

The **stress loading analysis | Settings | Settings for carriage-building method** tab allows to set the central frequency evaluation algorithms. These values are used in the carriage-building method of the durability analysis, see Figure 13.31, Figure 13.17.

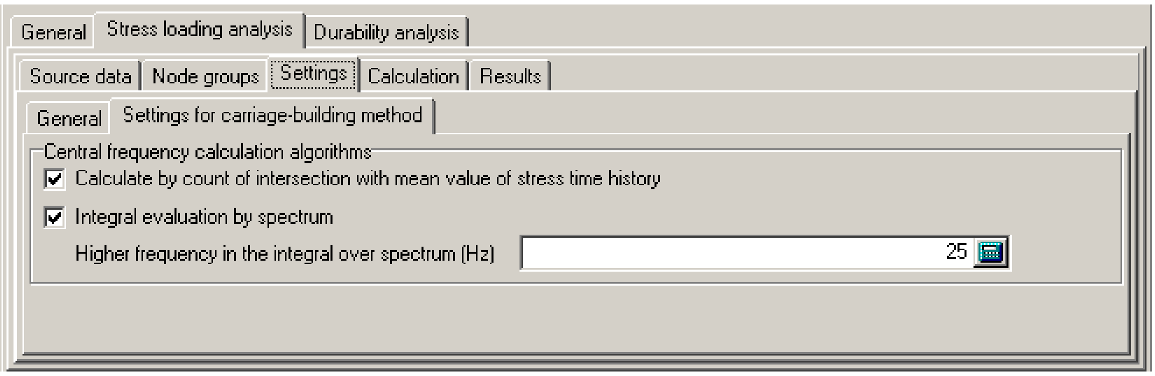



Figure 13.17. Carriage-building method

The following algorithms can be selected:

**Calculate by intersection with mean value of stress count**

$$f_e = \frac{n_m}{2 \cdot T}, \text{ where}$$

$n_m$ is an intersection with mean value count of stress history process;

$T$ is time interval of stress history process.

**Integral evaluation by spectrum**

$$f_e = \sqrt{\int_0^{f_{max}} f^2 \cdot g(f) df}\text{, where}$$

*g(f)* is the normalized spectrum of stress history process;

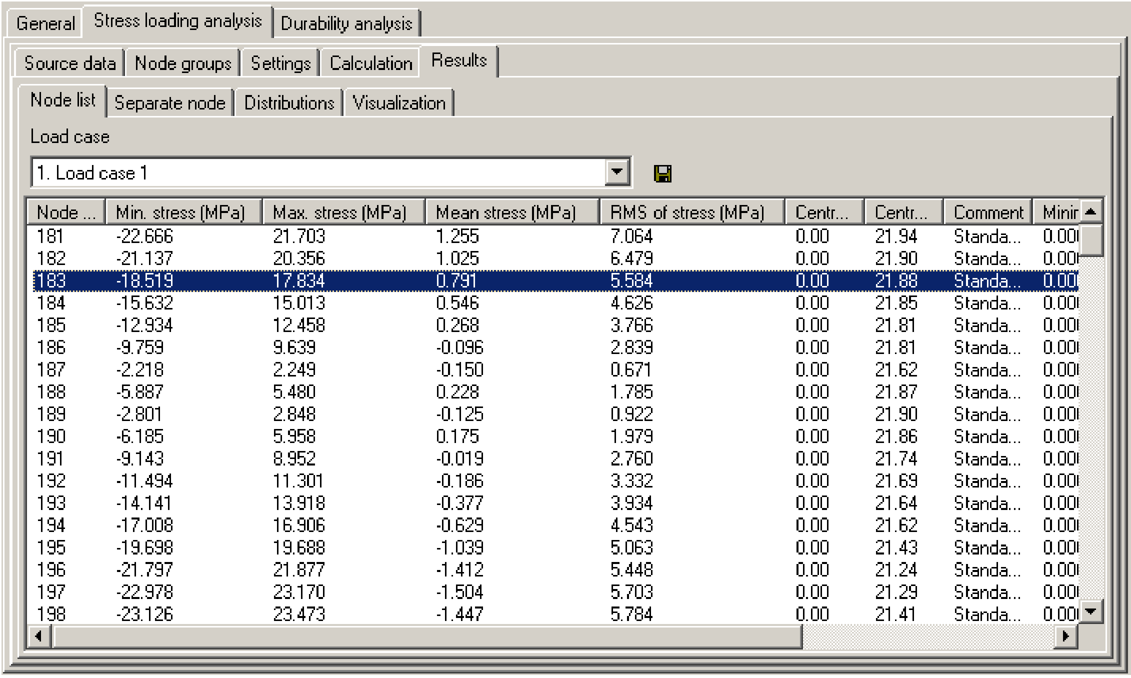
$f^{max}$ is the high bound value of the integral.

## 13.2.5. Stress loading calculation results

Results are presented at the **Stress loading | Results** tab and include statistic parameters of stress history processes and schematization results.

### 13.2.5.1. Node list

**Stress loading | Results | Node list** allows to get information about general loading characteristics at FEM nodes for the load cases.




| Node ... | Min. stress (MPa) | Max. stress (MPa) | Mean stress (MPa) | RMS of stress (MPa) | Centr... | Centr... | Comment | Minir |
|---|---|---|---|---|---|---|---|---|
| 181 | -22.666 | 21.703 | 1.255 | 7.064 | 0.00 | 21.94 | Standa... | 0.00 |
| 182 | -21.137 | 20.356 | 1.025 | 6.479 | 0.00 | 21.90 | Standa... | 0.00 |
| 183 | -18.519 | 17.834 | 0.791 | 5.584 | 0.00 | 21.88 | Standa... | 0.00 |
| 184 | -15.632 | 15.013 | 0.546 | 4.626 | 0.00 | 21.85 | Standa... | 0.00 |
| 185 | -12.934 | 12.458 | 0.268 | 3.766 | 0.00 | 21.81 | Standa... | 0.00 |
| 186 | -9.759 | 9.639 | -0.096 | 2.839 | 0.00 | 21.81 | Standa... | 0.00 |
| 187 | -2.218 | 2.249 | -0.150 | 0.671 | 0.00 | 21.62 | Standa... | 0.00 |
| 188 | -5.887 | 5.480 | 0.228 | 1.785 | 0.00 | 21.87 | Standa... | 0.00 |
| 189 | -2.801 | 2.848 | -0.125 | 0.922 | 0.00 | 21.90 | Standa... | 0.00 |
| 190 | -6.185 | 5.958 | 0.175 | 1.979 | 0.00 | 21.86 | Standa... | 0.00 |
| 191 | -9.143 | 8.952 | -0.019 | 2.760 | 0.00 | 21.74 | Standa... | 0.00 |
| 192 | -11.494 | 11.301 | -0.186 | 3.332 | 0.00 | 21.69 | Standa... | 0.00 |
| 193 | -14.141 | 13.918 | -0.377 | 3.934 | 0.00 | 21.64 | Standa... | 0.00 |
| 194 | -17.008 | 16.906 | -0.629 | 4.543 | 0.00 | 21.62 | Standa... | 0.00 |
| 195 | -19.698 | 19.688 | -1.039 | 5.063 | 0.00 | 21.43 | Standa... | 0.00 |
| 196 | -21.797 | 21.877 | -1.412 | 5.448 | 0.00 | 21.24 | Standa... | 0.00 |
| 197 | -22.978 | 23.170 | -1.504 | 5.703 | 0.00 | 21.29 | Standa... | 0.00 |
| 198 | -23.126 | 23.473 | -1.447 | 5.784 | 0.00 | 21.41 | Standa... | 0.00 |

Figure 13.18. Stress loading: results

Each row of the table corresponds to stress loading parameters of a FEM node. The following data are displayed for the selected load case:

<u>Stress time history (STH) process statistics</u>

- Minimum stress
- Mean stress
- Maximum stress
- RMS value of the process
- Central frequency of the process

<u>STH schematization results</u>

- Load block comment (distribution type, see Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10)
- Minimum cycle amplitude value
- Maximum cycle amplitude value
- Minimum cycle mean value

- Maximum cycle mean value
- Cycle count, detailed from the STH

To sort the table data by one of these parameters just click the corresponding column header.

The popup menu allows selecting columns for displaying at the table. It gives a possibility to export a table to a text file.

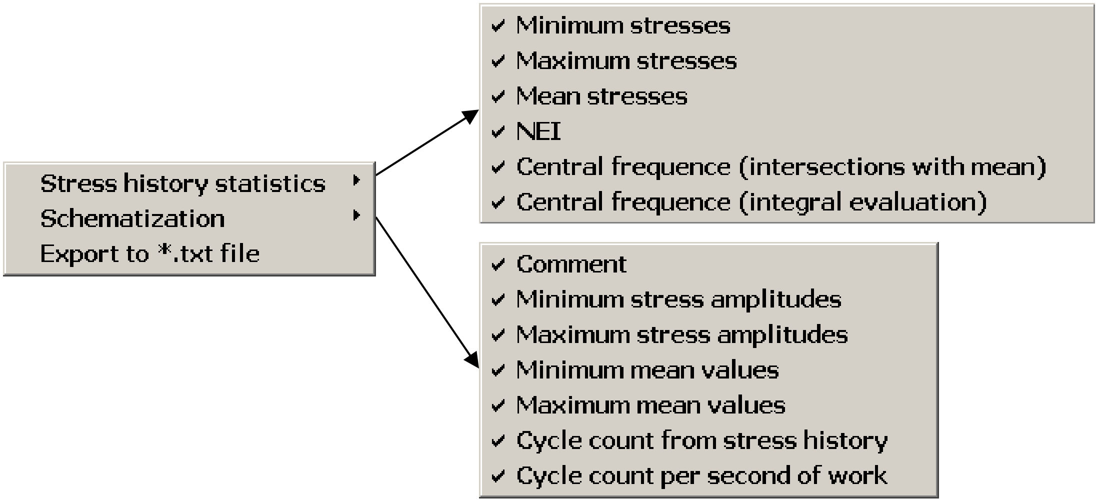



Figure 13.19. Stress loading: results

### 13.2.5.2. Stress loading data for a FEM node

**Stress loading analysis| Results | Separate node** shows results of stress loading evaluation for any particular FEM node and allows relative comparison of the load cases parameters. The list of displayed parameters is equal to the parameter list defined at table **Stress loading analysis | Results | Node list**, see Figure 13.18.

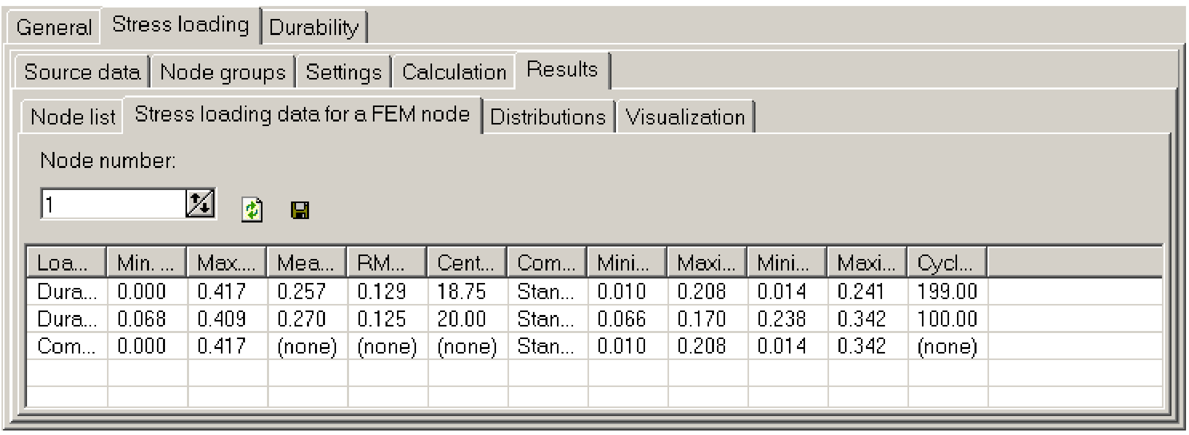



Figure 13.20. Results for particular node

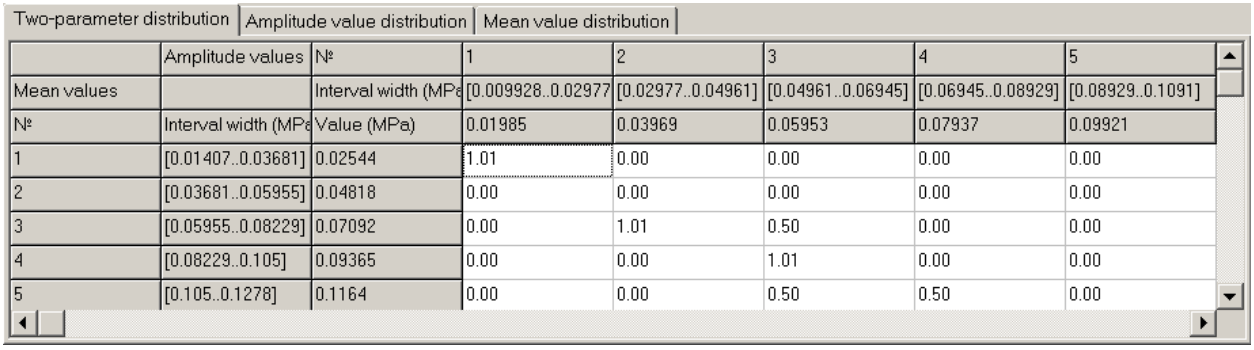
### 13.2.5.3. Distributions

The **stress loading analysis | Results | Distributions** tab is used to represent the information about the stress loading parameters distribution at FEM nodes for the defined load cases in tabular and graphical forms.

#### 13.2.5.3.1. Tabular performance

- **Stress loading analysis | Results | Distributions | Two-parameter distribution**

Table shows the distribution of cycle mean and amplitude values. Cells of the table enclose relative count of cycle which correspond to mean and amplitude value intervals of cells.

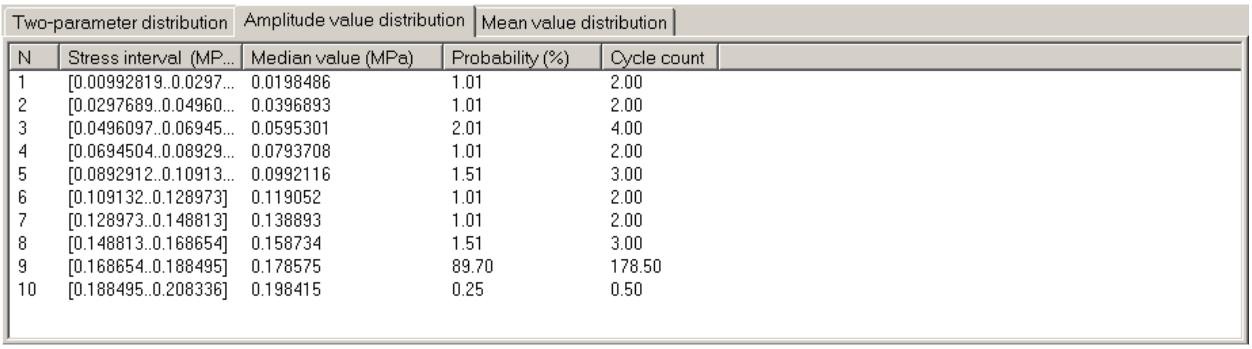



| | Amplitude values | № | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| Mean values | | Interval width (MPa | [0.009928..0.02977 | [0.02977..0.04961] | [0.04961..0.06945] | [0.06945..0.08929] | [0.08929..0.1091] |
| № | Interval width (MPa | Value (MPa) | 0.01985 | 0.03969 | 0.05953 | 0.07937 | 0.09921 |
| 1 | [0.01407..0.03681] | 0.02544 | 1.01 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | [0.03681..0.05955] | 0.04818 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | [0.05955..0.08229] | 0.07092 | 0.00 | 1.01 | 0.50 | 0.00 | 0.00 |
| 4 | [0.08229..0.105] | 0.09365 | 0.00 | 0.00 | 1.01 | 0.00 | 0.00 |
| 5 | [0.105..0.1278] | 0.1164 | 0.00 | 0.00 | 0.50 | 0.50 | 0.00 |

Figure 13.21. Two-parameter distribution

- **Stress loading analysis | Results | Distributions | Amplitude value distribution**

Table presents the distribution of cycle amplitudes calculated from the two-parameter distribution of stress loading parameters.




| N | Stress interval (MP... | Median value (MPa) | Probability (%) | Cycle count |
|---|---|---|---|---|
| 1 | [0.00992819..0.0297... | 0.0198486 | 1.01 | 2.00 |
| 2 | [0.0297689..0.04960... | 0.0396893 | 1.01 | 2.00 |
| 3 | [0.0496097..0.06945... | 0.0595301 | 2.01 | 4.00 |
| 4 | [0.0694504..0.08929... | 0.0793708 | 1.01 | 2.00 |
| 5 | [0.0892912..0.10913... | 0.0992116 | 1.51 | 3.00 |
| 6 | [0.109132..0.128973] | 0.119052 | 1.01 | 2.00 |
| 7 | [0.128973..0.148813] | 0.138893 | 1.01 | 2.00 |
| 8 | [0.148813..0.168654] | 0.158734 | 1.51 | 3.00 |
| 9 | [0.168654..0.188495] | 0.178575 | 89.70 | 178.50 |
| 10 | [0.188495..0.208336] | 0.198415 | 0.25 | 0.50 |

Figure 13.22. Amplitude value distribution

- **Stress loading analysis | Results | Distributions | Mean value distribution**

Table shows the distribution of cycle mean values calculated from the two-parameter distribution of stress loading parameters.

Two-parameter distribution | Amplitude value distribution | Mean value distribution

| N | Stress interval (MPa) | Median value (MPa) | Probability (%) | Cycle count |
|---|---|---|---|---|
| 1 | [0.0140709..0.03680... | 0.02544 | 1.01 | 2.00 |
| 2 | [0.0368092..0.05954... | 0.0481783 | 0.00 | 0.00 |
| 3 | [0.0595474..0.08228... | 0.0709166 | 1.51 | 3.00 |
| 4 | [0.0822857..0.10502... | 0.0936548 | 1.01 | 2.00 |
| 5 | [0.105024..0.127762] | 0.116393 | 1.01 | 2.00 |
| 6 | [0.127762..0.1505] | 0.139131 | 1.01 | 2.00 |
| 7 | [0.1505..0.173239] | 0.16187 | 1.01 | 2.00 |
| 8 | [0.173239..0.195977] | 0.184608 | 1.01 | 2.00 |
| 9 | [0.195977..0.218715] | 0.207346 | 1.26 | 2.50 |
| 10 | [0.218715..0.241454] | 0.230084 | 91.21 | 181.50 |

Figure 13.23. Mean value distribution

#### 13.2.5.3.2. Display of stress loading parameters distributions for a FEM node

To make a plot of the stress loading parameters distribution for different load cases the following steps are necessary:

- select the **Stress loading analysis | Results | Distributions** tab or the **Durability analysis | Results | Distributions** page;
- select a FEM node number and a load case;
- click the  button at the top panel of the tab or select the **«Show as histogram»** option from the popup menu.

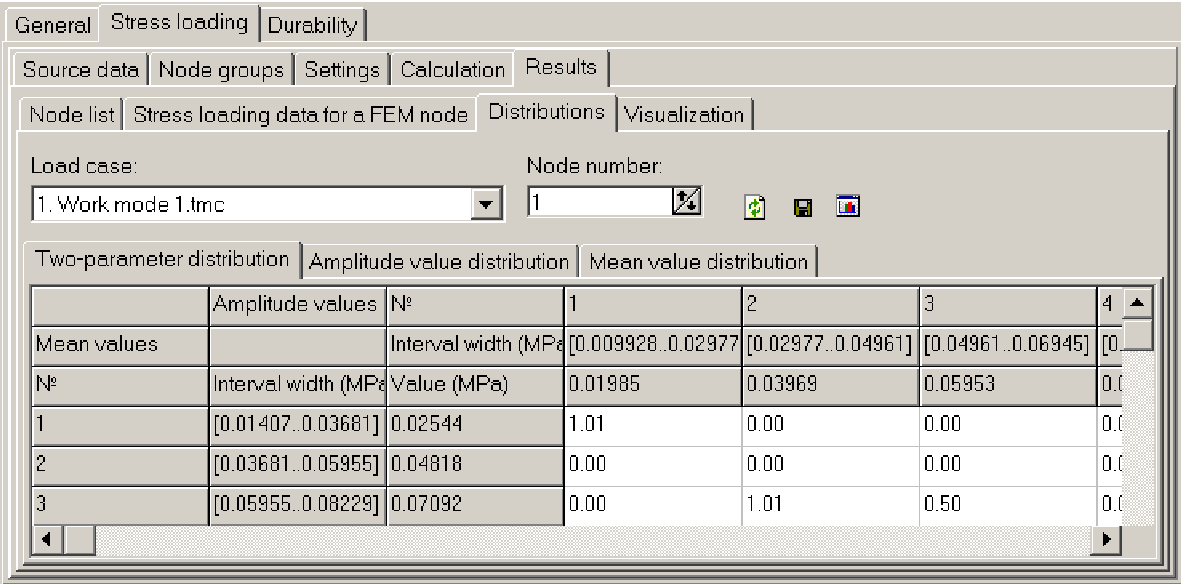



Figure 13.24. Mean value distribution

The following window is used for plotting stress loading parameters distributions. This window contains the following tabs:

- **Two-parameter distribution** tab

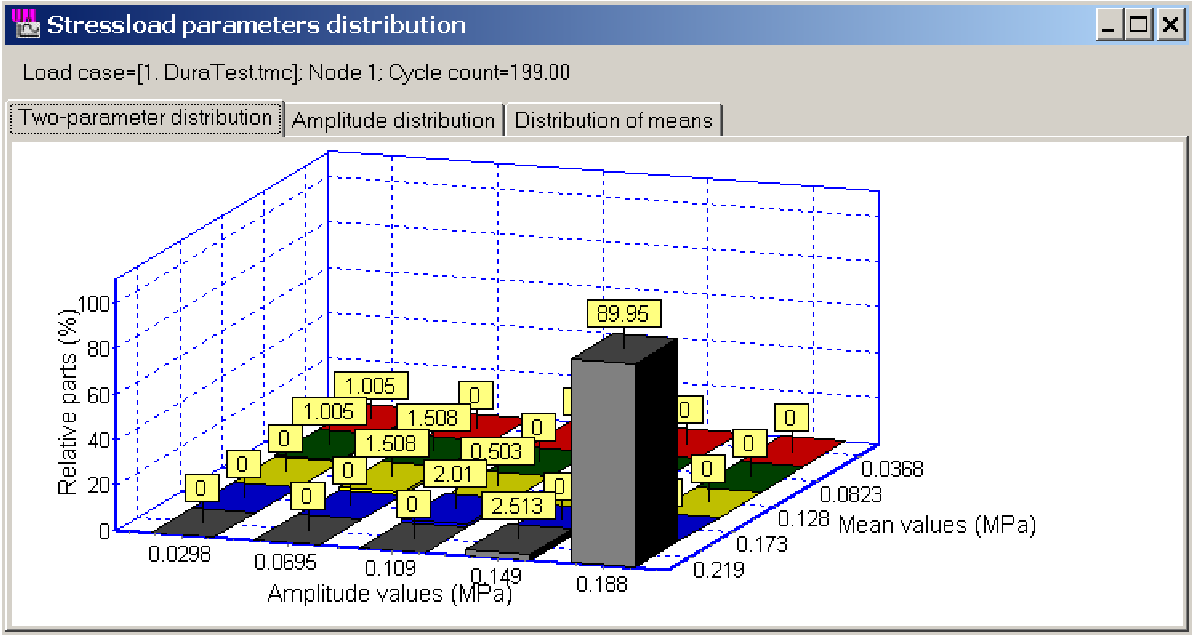



Figure 13.25. Two-parameter distribution

- **Amplitude distribution, Distribution of means** and **Reduced amplitude distribution** (this tab is enabled if the window was opened from the durability results tab).

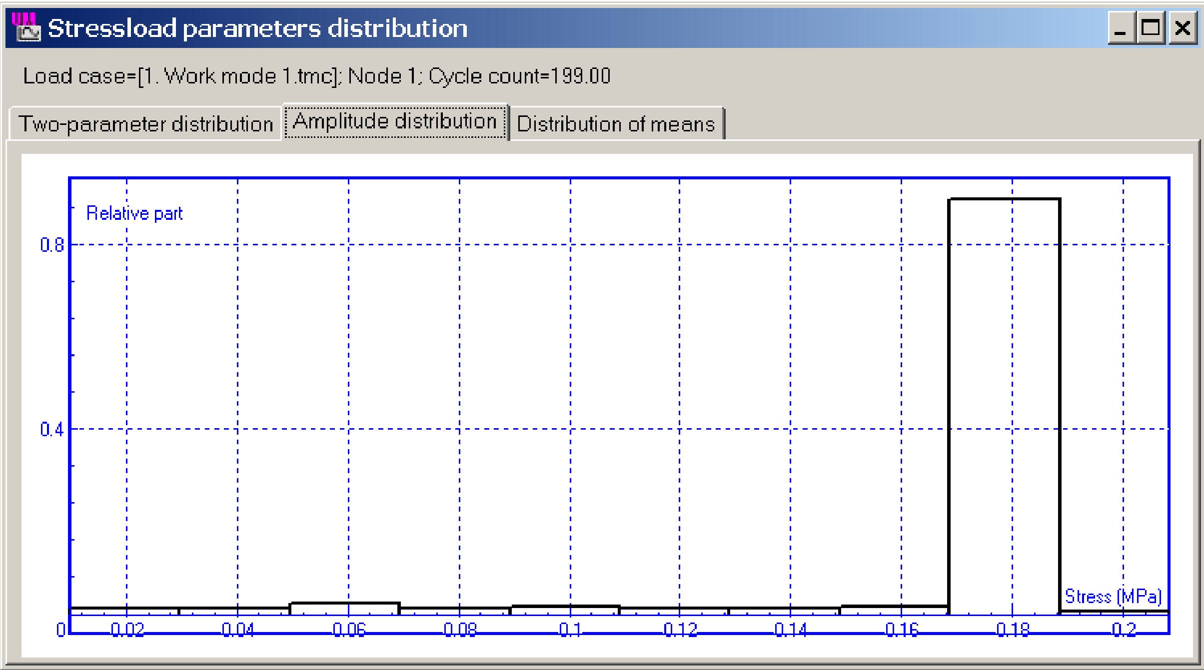



Figure 13.26. Amplitude distribution

### 13.2.5.3.3. Display of stress loading parameters for the FEM

Using the **Stress loading | Results | Visualization** tab you can visualize stress loading parameters values at FEM nodes and select node lists for the further durability analysis.

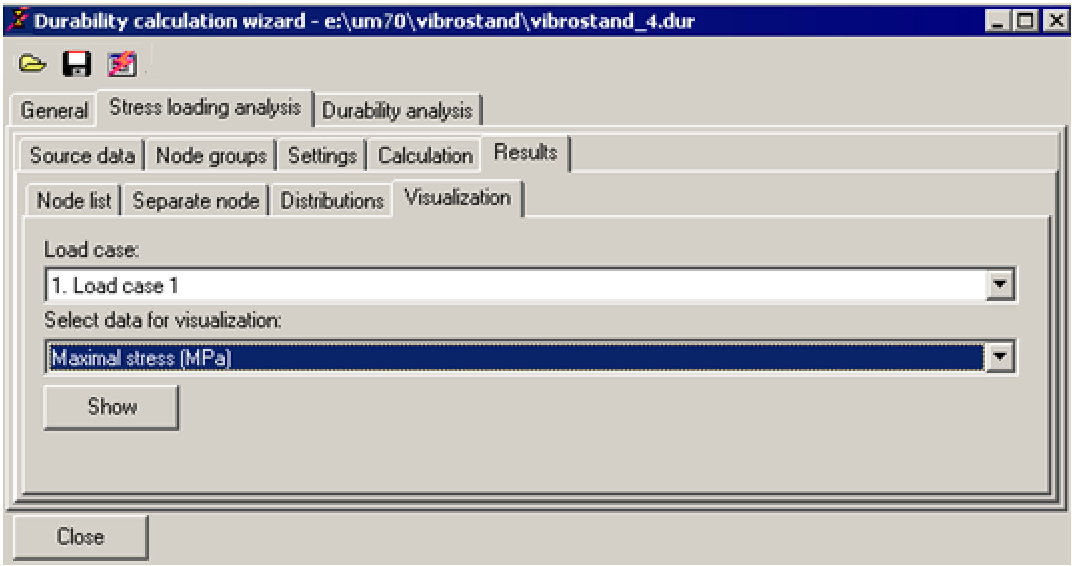



Figure 13.27. Visualization of results of stress loading

The user can select a load case and data for visualization from the corresponding combo boxes, see Figure 13.27.

The animation window is used for displaying. The color scheme corresponds to values of the selected stress loading parameter. Figure 13.28 shows the distribution of maximum values of equivalent stresses at FEM nodes.

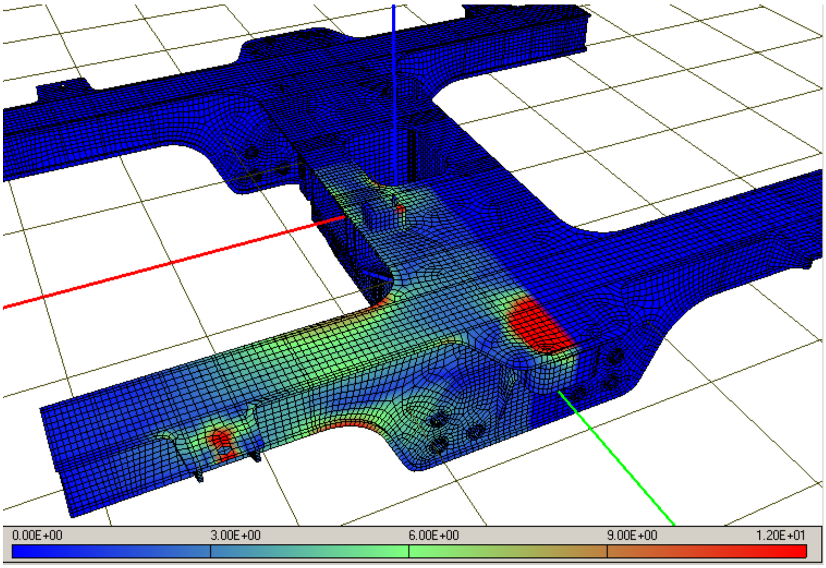
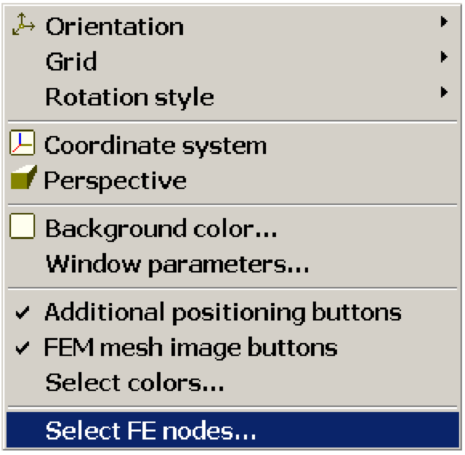



Figure 13.28. Maximal stress distribution

The user can change display options with the help of the popup menu of the animation window.




The popup menu contains additional options for the following operations:

- **«Select colors…»**

This option can be used for the selection of the color scheme. The user can define colors for different values of the displayable parameter.

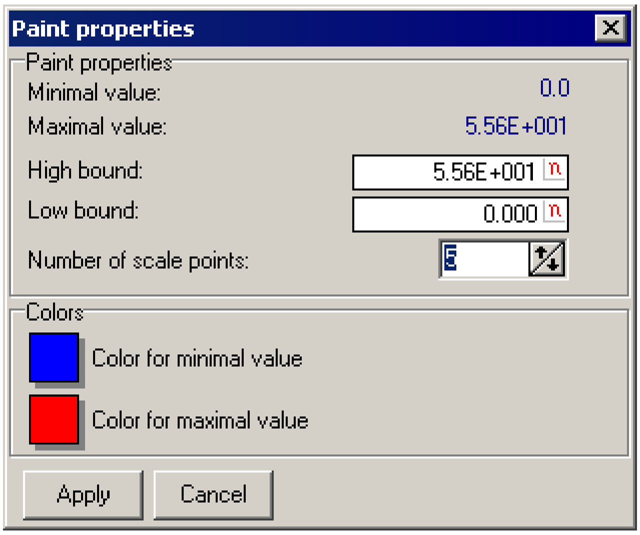



Figure 13.29. Maximal stress distribution

- **«Select FE nodes…»**

This command is used for defining and marking out nodes in the node list. A node can be selected by mouse, by coordinates or by node number. A new window appears.

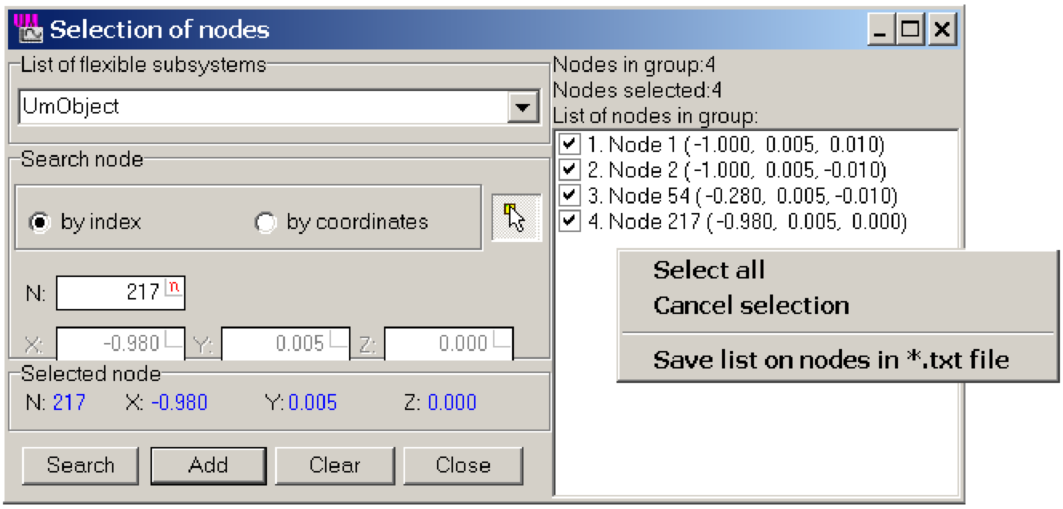



Figure 13.30. Node selection for marking

The selection of a node can be made:

- by the node number (input the node number at the field «N:»);
- by the node coordinates (input the node coordinates at the flexible subsystem CS at the fields «X:», «Y:», «Z:»);
- by mouse (if  button is pressed).

After the search criterion is defined click the **Search** button and add the obtained node to the list by clicking the **Add** button. To mark out the added node the user should select it from the right list, see Figure 13.30 (nodes 1, 2, 54, 217 are checked and will be displayed).

The popup menu of the node list allows the following actions:

- **Select all**
- **Cancel selection**
- **Save node list in *.txt file**

The node list can be saved in text file for the later usage in the initialization of node groups, see Sect. 13.2.3. *"Node group initialization"*, p. 13-22.

**Note.** Node groups can include a great number of FE nodes at the preliminary stage of investigation. With the help of this option the user can correct initially defined node lists for the later durability analysis.

# 13.3. Durability analysis in UM Durability

UM Durability enables the S-N analysis in compliance with the following methods.

- Carriage-building method
- S-N Simple method

This chapter includes description of the general sequence of the calculation.

## 13.3.1. Durability analysis procedure

In the Figure 13.31 below, the basic stages of the durability analysis are depicted.

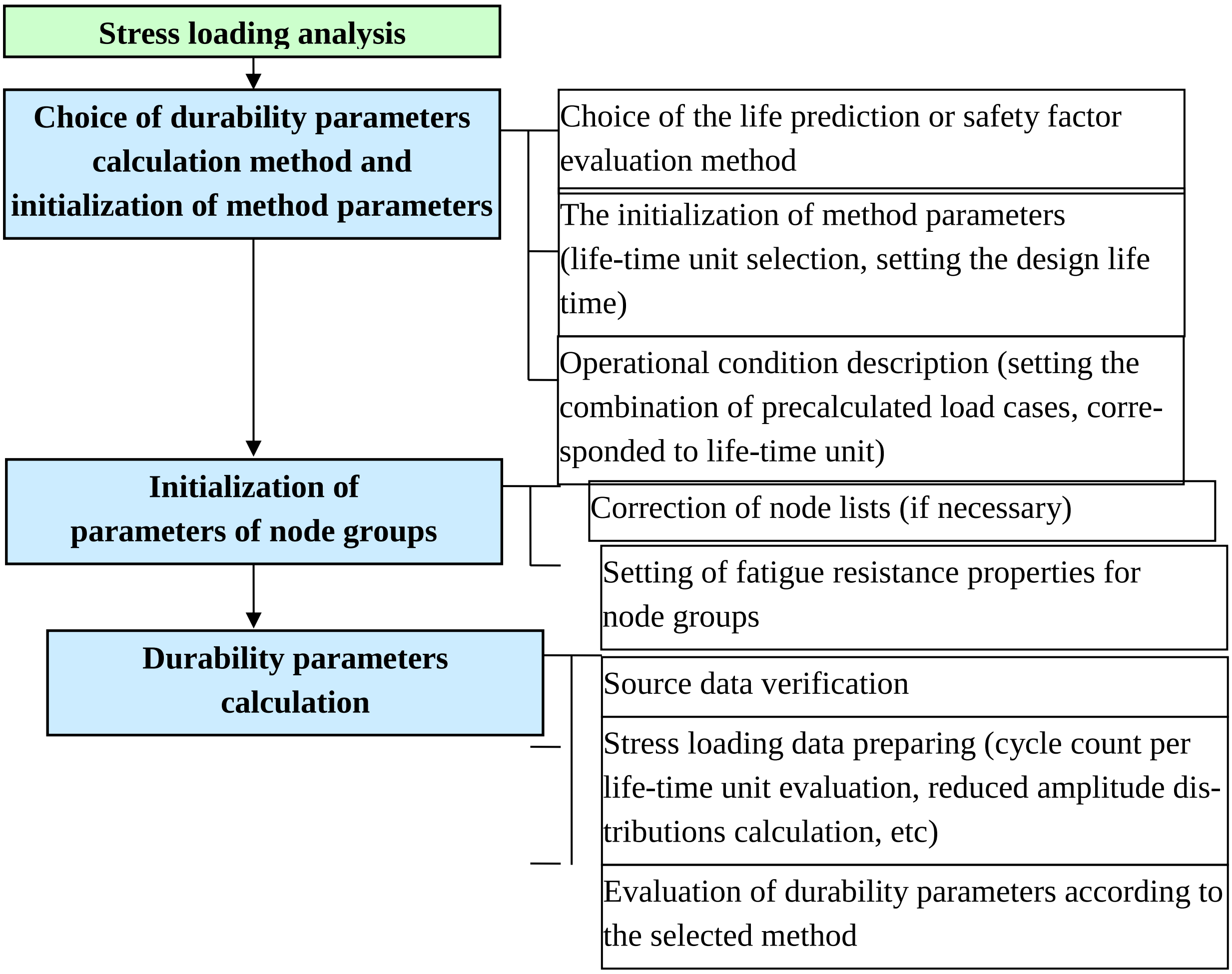



Figure 13.31. Stages of durability analysis

The durability analysis procedure includes several stages. UM Durability suggests the following order of operations:

- Stress loading analysis

The stress loading data analysis is carried out according to the sequencing described at Sect. 13.2. *"Stress loading analysis in UM Durability"*, p. 13-5.

- Choice of durability analysis method and initialization of method parameters

The calculation method is usually predefined by investigation demands. The user should also define a life-time unit and set data for load cases to the life-time unit reduction.

- Correction of node groups and fatigue resistance properties for them

The durability parameters calculation is based on the results of stress loading analysis for selected nodes. The user can regroup nodes for the durability analysis or exclude some of them from the list.

- Durability parameters calculation

Various methods of durability evaluation might be used to get estimation of various durability parameters, for example safety factors, life-time, path length, etc.

### 13.3.1.1. Choice of durability analysis method and initialization of method parameters

Each of durability calculation methods realized at the UM Durability program module has its own characters. Selection of the method is usually based on demands to object characters and investigation results.

The **Durability analysis | Evaluation method** tab is used to select method and assign method parameters, see Figure 13.32.

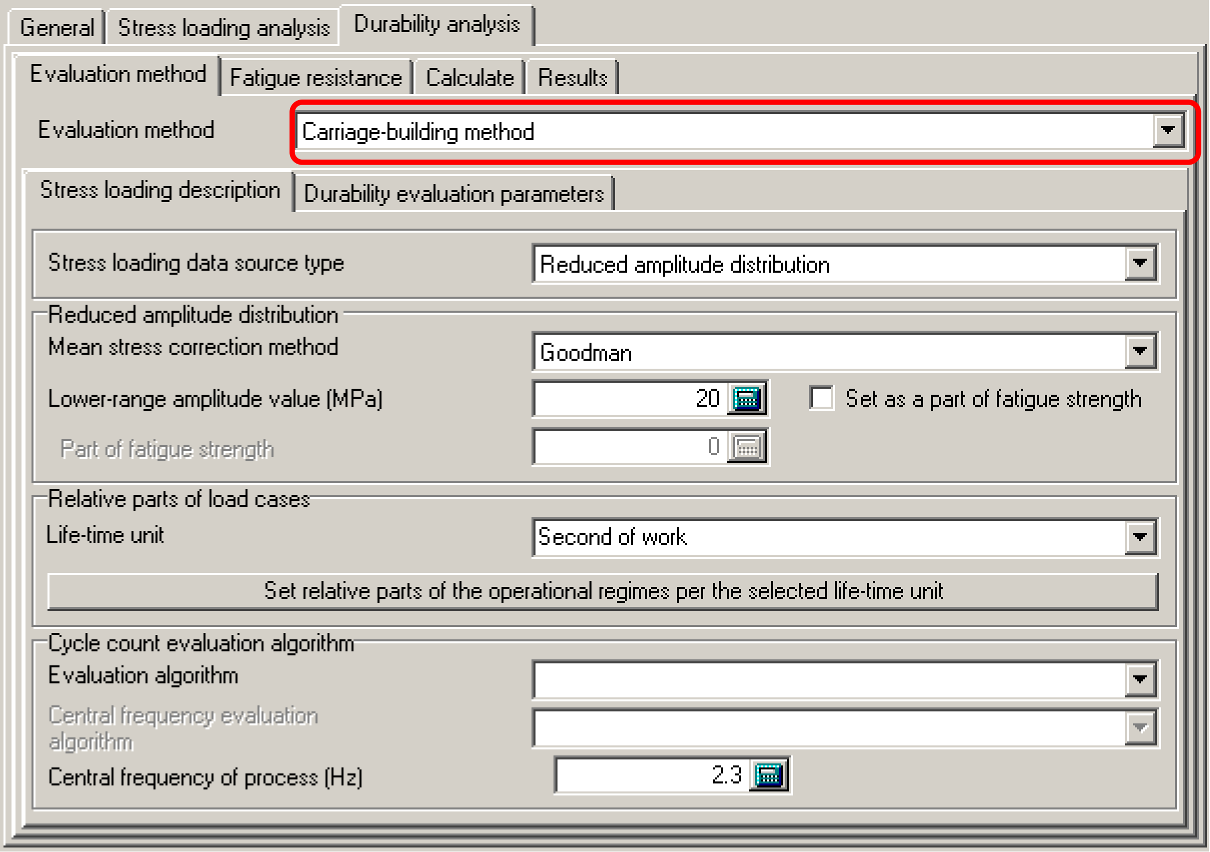



Figure 13.32. Durability analysis method selection

### 13.3.1.2. Life time unit features

In general, all the methods demand the stress loading description. Data for the selected nodes for the load cases (operational regimes) were calculated at the stage of stress loading analysis

To evaluate durability parameters the user should select life-time unit and define the relative part of each of the load cases per this unit. Further analysis is based on these data.

UM Durability allows using several kinds of life-time units. Each of them has its own features.

<u>Second of work life-time unit</u>

If this life-time unit is selected the user should define relative parts of operational regimes represented with load cases in working time of the object.

Let $n_{real}^{<k>}$ be the number of stress load cycles evaluated from the stress time history (STH) which presents the **k** load case.

Cycle count per second of work for the **k** load case is calculated according to the following equation

$$n_{sec}^{<k>} = \frac{n_{real}^{<k>}}{t_2^{<k>} - t_1^{<k>}}, \text{ where}$$

$t_1^{<k>}, t_2^{<k>}$ are initial and end time points of **k** load case STH, see Sect. 13.2.2.4. *"Time intervals of the load cases stress histories setting"*, p. 13-20.

Cycle count per second of work $n_{sec}^{<CLB>}$ is evaluated according to the following equation

$$n_{sec}^{<CLB>} = \sum_k C^{<k>} \cdot n_{sec}^{<k>}, \text{where}$$

$C^{<k>}$ is a **k**-load case relative part.

Relative parts of the load cases per operation time of the object can be defined in the following window (**Set relative parts…** button), see Figure 13.33.

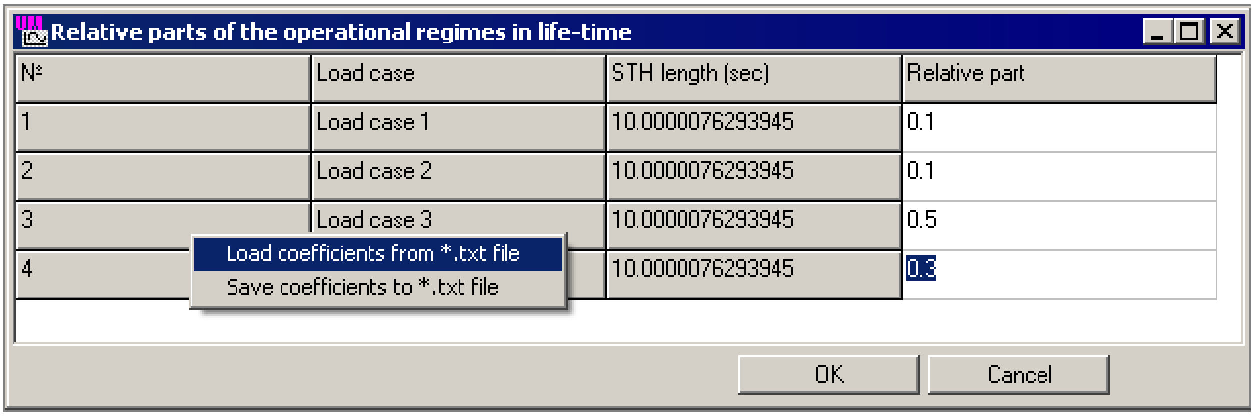



Figure 13.33. Setting relative parts of load cases per operation time. Second of work life-time unit.

The STH time interval value is evaluated according to STH bounds defined at the stage of load case description, see Sect. 13.2.2.4. *"Time intervals of the load cases stress histories setting"*, p. 13-20. These values cannot be changed in this window.

Relative parts can be set manually in the rows of the table or loaded from a text file with the help of the popup menu, see Figure 13.33.

Path length life-time unit

Cycle count per kilometer of path length in **k** operational regime $n_{km}^{<k>}$ is calculated according to the following equation

$$n_{km}^{<k>} = \frac{n_{real}^{<k>}}{L^{<k>} \cdot 10^{-3}}, \text{where}$$

$L^{<k>}$ is a path length (in meters) corresponds to the stress time history (STH) which presents the **k** load case.

Cycle count per kilometer of path length $n_{km}^{<CLB>}$ is evaluated according to the following equation

$$n_{km}^{<CLB>} = \sum_k C^{<k>} \cdot n_{km}^{<k>}$$

The length values $L^{<k>}$ and the relative parts of the load cases per operation path length $C^{<k>}$ can be defined in the following window, see Figure 13.34.

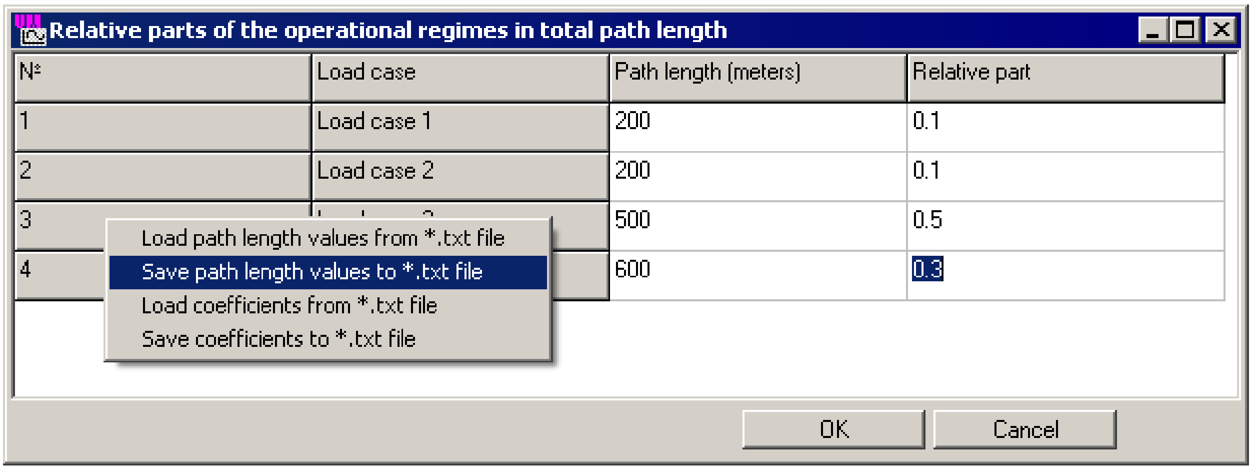



Figure 13.34. Setting relative parts of load cases per operation time. Path length life-time unit.

User defined life-time unit

The user can define a life-time unit (only if the S-N Simple durability calculation method is used).

In this case the user should define a repeat count of the load cases STH per the life-unit.

Cycle count per user defined unit in **k** operational regime $n_R^{<k>}$ is calculated according to the following equation

$$n_R^{<k>} = R^{<k>} \cdot n_{real}^{<k>}.$$

Cycle count per life-time unit $n_R^{<CLB>}$ is evaluated according to the following equation

$$n_R^{<CLB>} = \sum_k R^{<k>} \cdot n_{real}^{<k>}, \text{where}$$

$R^{<k>}$ is the repetition number of the **k**-load case STH per life-time unit. These values can be defined in the following window, see Figure 13.35.

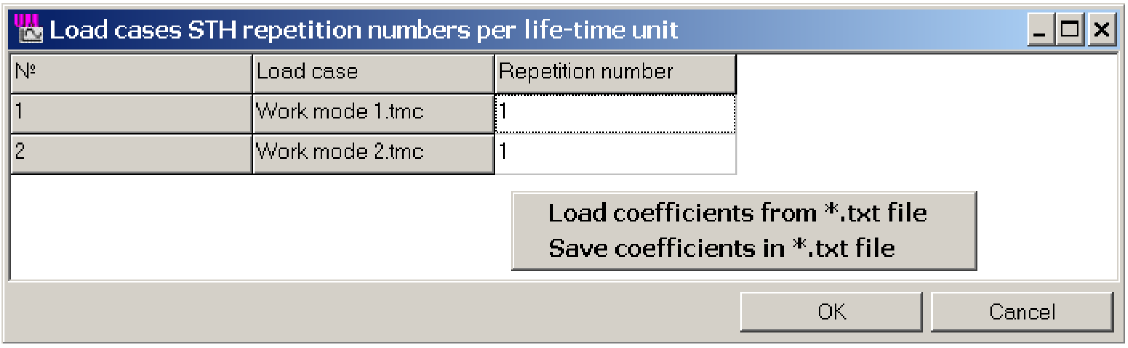



Figure 13.35. Setting relative parts of load cases per operation time. User defined life-time unit.

### 13.3.1.3. Fatigue resistance properties initialization for node groups

Node groups are preliminary defined at the stage of stress loading data analysis, see Sect. 13.2.3. *"Node group initialization"*, p. 13-22. To evaluate durability parameters fatigue resistance properties for nodes must be defined.

Fatigue resistance properties depend on several factors such as material properties, loading type, position of the control node (the control node is used for durability estimate in dangerous zone), etc.

The **Durability analysis | Fatigue resistance** tab is used for operations with node groups, see Figure 13.36.

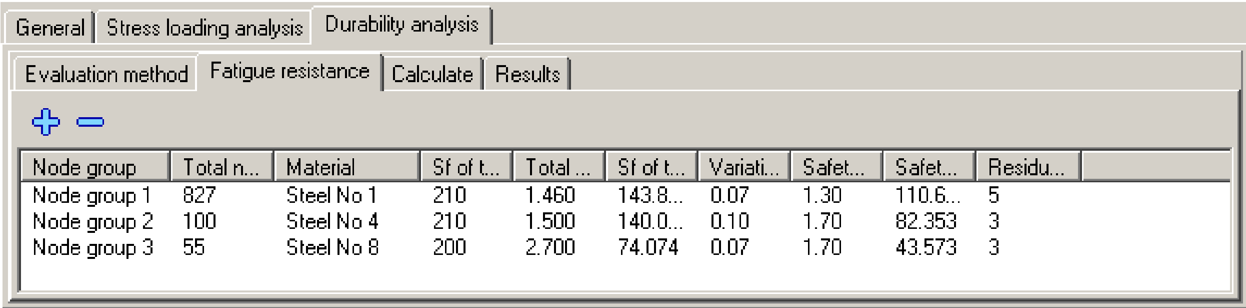



Figure 13.36. Setting fatigue resistance properties of node groups

Use left mouse button double-click at the node group row from the list to set the group data.

Select the **Properties** tab of the **Group properties window** to define the fatigue resistance of the group, see Figure 13.37.

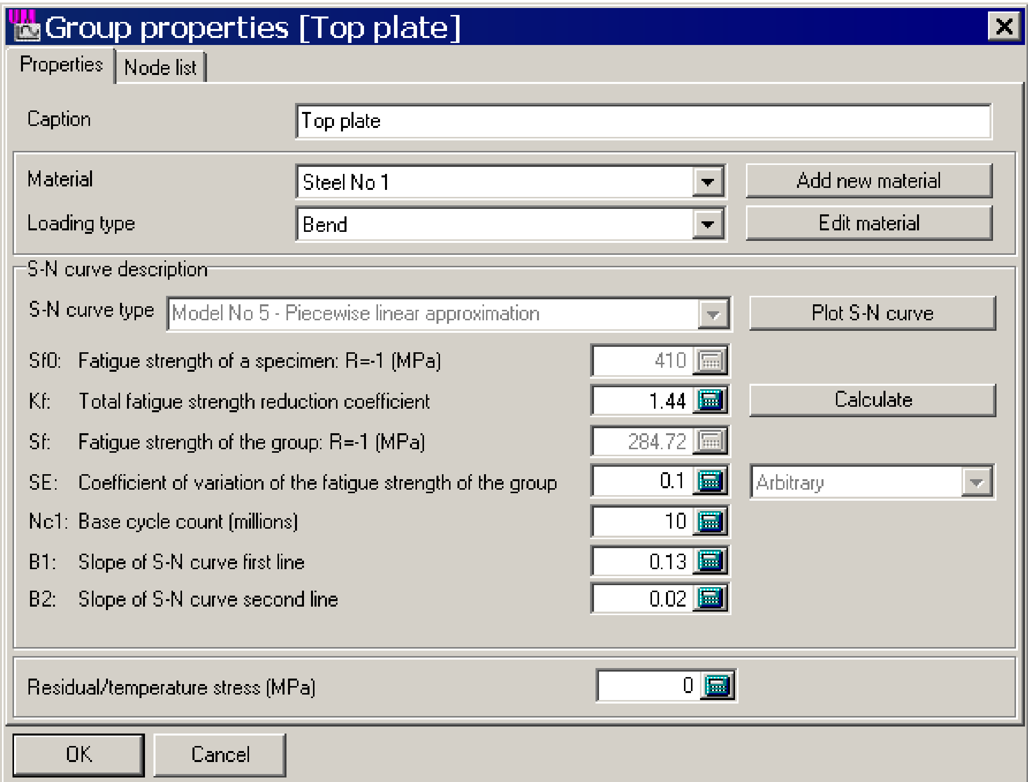



Figure 13.37. Setting fatigue resistance properties of node group

The user should select material from the **Material database** (see Sect. 13.3.1.3.1. *"Material database"*, p. 13-44) with the help of the **Material** combo box or define a new one with the **Add new material** button. To control or edit the material properties one can click **Edit material** button.

The S-**N curve type** is set according to the selected durability analysis method.

The fatigue strength of the material defined in the database is shown at the **Fatigue strength of a specimen** field.

The **Total fatigue strength reduction coefficient** shows the ratio between the fatigue strength of the material and the fatigue strength of the group.

If properties which are defined in the database correspond to the investigation of a standard specimen the user can correct these properties by a set of coefficients. The coefficient list depends on the selected method and can include size factor, surface treatment factor, surface finish factor, material heterogeneity factor, etc. Click **Calculate** to define values of these coefficients.

**Fatigue strength of the group** is evaluated from the fatigue strength of the material and total fatigue strength reduction coefficient values.

**Coefficient of variation of the fatigue strength of the group** value is used for the probability of no-failure effect consideration.

Select the **Node list** tab of the **Group properties window** to correct node lists of the previously defined groups. The user can also add  or delete  some of these groups, see Sect. 13.2.3. *"Node group initialization"*, p. 13-22.

**Note.** Durability parameters can be evaluated only for nodes, which have been included in any node groups at the stage of the stress loading analysis.

#### 13.3.1.3.1. Material database

The database is intended to keep the user-defined library of characteristics of materials that you often use. By default, the database is empty.

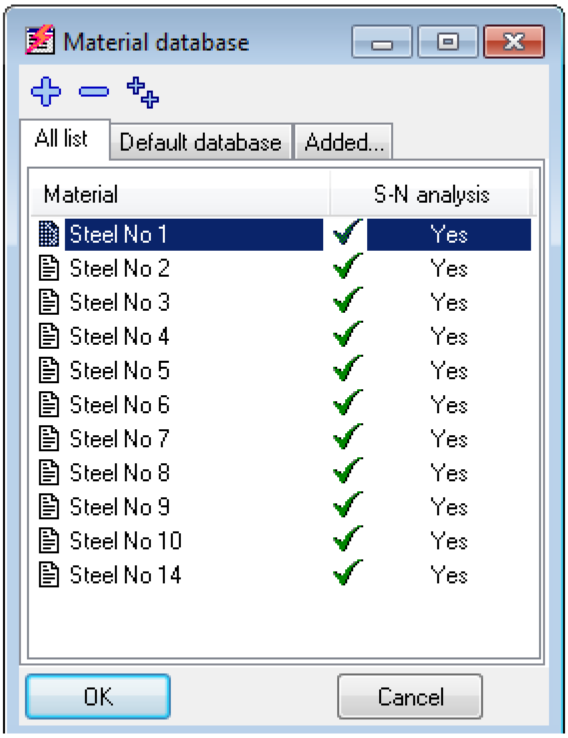



Figure 13.38. Material database window

Use buttons from the top tool panel to create (), delete () or copy () material properties records.

Double-click at any row opens **Material properties** window.

Mechanical properties defined by uniaxial tension test can be set at the **Common properties** tab.

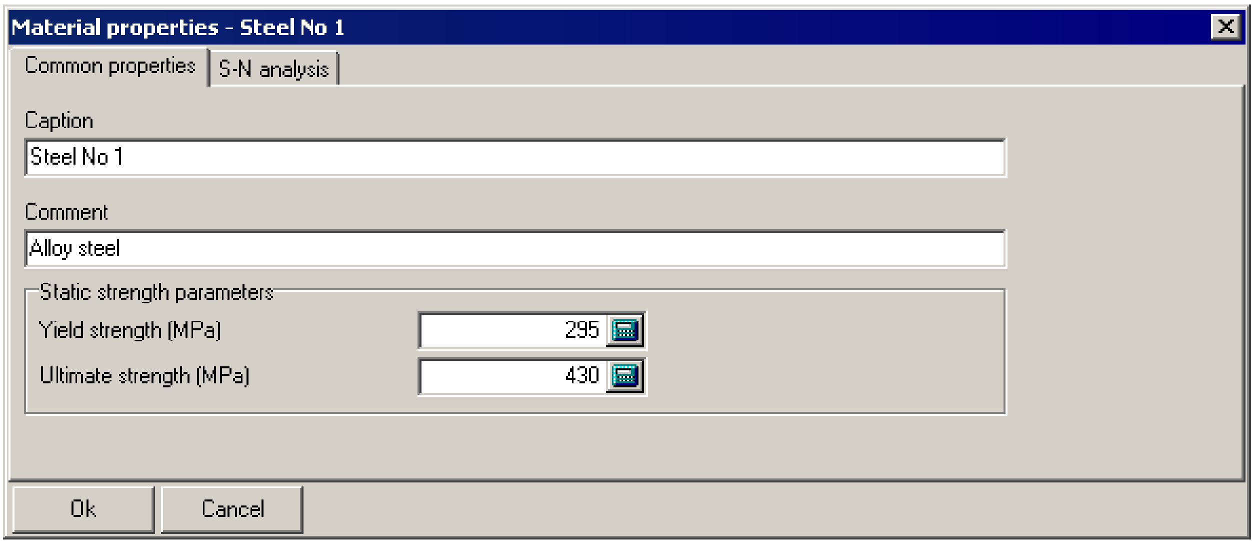



Figure 13.39. Material properties window

For the description of S-N fatigue resistance properties S-N curves are used. S-N curves set functional dependence between regular stress loading parameters (cycle range, cycle amplitude) and destruction cycle count.

These dependences are the results of experimental investigations which are usually carried out with polish standard specimens in different load conditions. The user can define S-N curves described material fatigue resistance properties for **Bend, Stress/strain** and **Torsion** loading.

#### 13.3.1.3.2. S-N curve mathematical models

There is a great variety of S-N curve mathematical models based on different ways of statistical approximation of experimental data. Durability evaluation methods defined at UM Durability use the following S-N curve models.

Model No1 – Straight line in logarithmic scale

This model is used in the carriage-building method and can be described with the following functional dependence:

$$\sigma^m \cdot N = const, \text{where}$$

$\sigma$ is the cycle amplitude value of regular stress loading process;

$N$ is the loading cycle count led to the destruction of a specimen or the crack size increasing to predefined value;

$m$ is S-N curve inclination index.

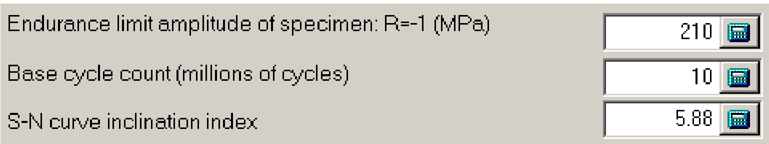
The cycle count which leads to the destruction ($N$) can be evaluated from the loading amplitude value ($\sigma$) according to the following equation:

$$N = N_0 \cdot \left(\frac{\sigma_{-1}}{\sigma}\right)^m, \text{where}$$

$N_0$ is a basic cycle count;

$\sigma_{-1}$ is endurance limit (fatigue strength) of a specimen.

These parameters can be defined in the following form fields:




Model No2 – Piecewise linear approximation

This model is used in the common machine-building method and can be described with the following functional dependence:

$$N = \begin{cases} N_0 \cdot \left(\frac{\sigma_{-1}}{\sigma}\right)^{m_1}, \text{при } \sigma \geq \sigma_{-1} \\ N_0 \cdot \left(\frac{\sigma_{-1}}{\sigma}\right)^{m_2}, \text{при } \sigma < \sigma_{-1} \end{cases}, \text{where}$$

*N* is the loading cycle count led to the destruction of specimen or the crack size increasing to predefined value;

$\sigma_{-1}$ is the cycle amplitude value of regular stress loading process;

$N_0$ is the basic cycle count;

$m_1$, $m_2$ are S-N curve inclination indices.

These parameters can be defined at the following form fields

| | |
|---|---|
| Endurance limit amplitude of specimen: R=-1 (MPa) | 210 |
| Base cycle count (millions) | 10 |
| S-N curve inclination index: first line | 6 |
| S-N curve inclination index: second line | 20 |

<u>Model No3 – Hyperbolic approximation</u>

This model is used in the locomotive-building method and can be described with the following functional dependence:

$$N = \beta \cdot \frac{\sigma_u - \sigma}{\sigma - \sigma_{-1}}, \text{where}$$

$N$ is the loading cycle count led to the destruction of specimen or crack size increasing to predefined value;

$\sigma_{-1}$ is the cycle amplitude value of regular stress loading process;

$\sigma_u$ is ultimate strength of material;

$\beta$ is specimen constant.

These parameters can be defined at the following form fields

| | |
|---|---|
| Endurance limit amplitude of specimen: R=-1 (MPa) | 210 |
| S-N curve constant of specimen (1e5) | 0.56 |

<u>Model No 5 – Piecewise linear approximation</u>

This model is similar to *Model 2*. Values $\sigma_{-1}$, $m_1$, $m_2$ are replaced with the following:

SAI1 is the virtual stress amplitude intercept:

$$SAI1 = S_f \cdot N_0^{b_1}$$

$b_1$, $b_2$ are slopes of S-N curve lines in the logarithmic scale:

$$b_1 = {}^1\!/_{m_1}, \quad b_2 = {}^1\!/_{m_2}$$

These parameters can be defined at the following fields.

| | |
|---|---|
| SAI: Stress amplitude intercept (MPa) | 3 082.38 |
| B1: Slope of S-N curve: first line | 0.17 |
| Nc1: Fatigue transition point (millions of cycles) | 10 |
| B2: Slope of S-N curve: second line | 0.05 |
| Sf: Endurance limit amplitude of specimen: R=-1 (MPa) | 210 |

#### 13.3.1.4. Reduced amplitude distribution calculation

Fatigue resistance properties of standard specimens are usually investigated for regular symmetric stress cycle. In these cases, S-N curves describe dependences between amplitude of the symmetric stress cycle loading and the life-time of the specimens. At the same time stress loading of the most of construction elements is not symmetrical.

Two methods are usually used to consider the asymmetry of stress cycles.

- The first method is used in the case of regular stress loading. Fatigue strength characteristics are determined using the Haigh diagram, and loading is defined with the help of amplitude distribution.
- The second method bases on the one-parameter *reduced amplitude distribution* forming. Reduced amplitude of the asymmetric stress cycle is the amplitude value of symmetrical cycle led to the damage which equals to the damage from the asymmetric stress cycle. This reduction procedure is used if mean value of stress cycle is positive. It supposes that compressive stresses have not influence on the fatigue strength of the structure. This method is implemented in UM Durability.

UM Durability uses the following methods of mean stress effect evaluation:

- *Kinasoshvili*

Kinasoshvili's model uses the following formula for mean stress correction:

$$\sigma_{a\_r} = \sigma_a + \psi \cdot \sigma_m, \text{where}$$

$\psi$ is the coefficient of sensitivity to cycles asymmetry.

- *Soderberg*

$$\sigma_{a\_r} = \frac{\sigma_a}{\left(1 - \left(\frac{\sigma_m}{\sigma_y}\right)\right)}, \text{where}$$

$\sigma_y$ is the tensile yield point.

- *Gerber*

$$\sigma_{a\_r} = \frac{\sigma_a}{\left(1 - \left(\frac{\sigma_m}{\sigma_u}\right)^2\right)}, \text{where}$$

$\sigma_u$ is the ultimate tensile strength.

*Goodman*

$$\sigma_{a\_r} = \frac{\sigma_a}{\left(1 - \left(\frac{\sigma_m}{\sigma_u}\right)\right)}$$

The *distribution of reduced amplitudes* is formed based on the correlation table and mean values according to the following algorithms.

- For each cell of the correlation table with non-zero value the central values of median and amplitude intervals are calculated.
- Then the mean stress correction procedure is executed that gives us reduced amplitudes as a result. Then the distribution of reduced amplitudes is formed.

Values of temper or temperature stresses are considered. In this case their values are added to medians of intervals.

If the low limit of damaging amplitude $\sigma_a^{lim}$ is used then all amplitudes which are less than this limit are not considered during forming the distribution.

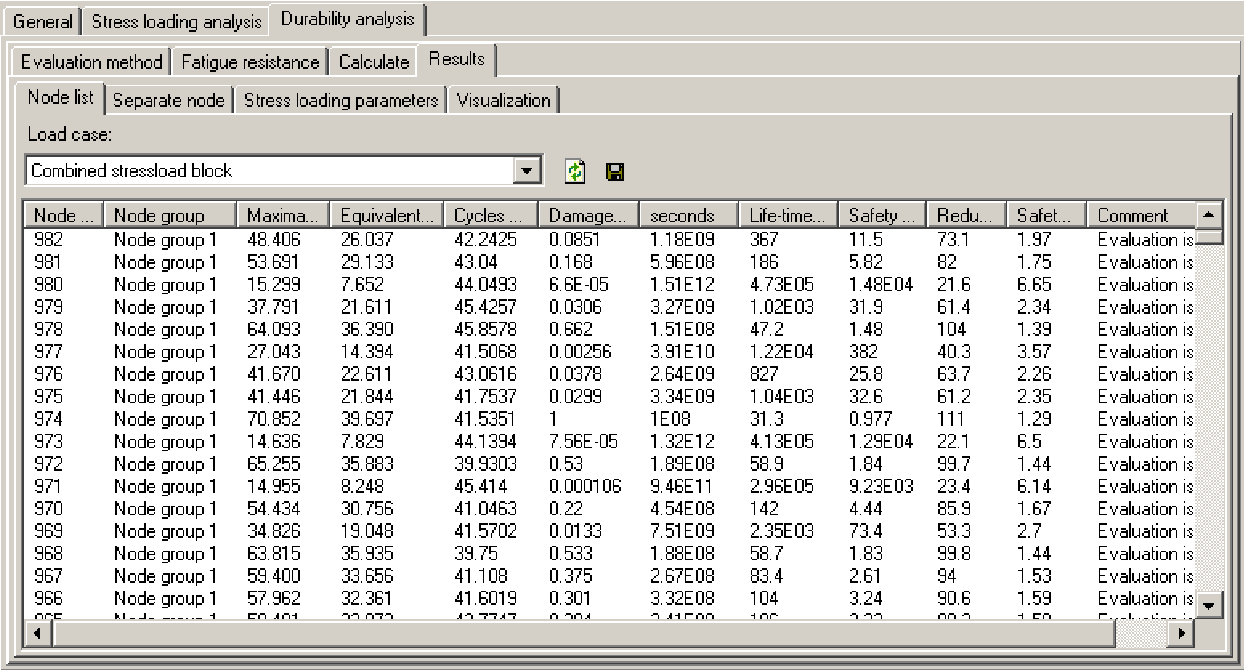
### 13.3.1.5. Durability analysis results performance

The user can display durability parameters calculated for the FEM nodes included in the groups for the operational conditions described with the combination of the load cases. The user can also display the results, evaluated for the particular operational modes.

Results are presented in the **Durability analysis | Results** tab.

### 13.3.1.6. Node list

**Durability analysis | Results | Node list** allows to get information about general loading characteristics and durability parameters at the FEM nodes for the selected particular operational regime or for the **Combined stressload block**, see Figure 13.40.




| Node ... | Node group | Maxima... | Equivalent... | Cycles ... | Damage... | seconds | Life-time... | Safety ... | Redu... | Safet... | Comment |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 982 | Node group 1 | 48.406 | 26.037 | 42.2425 | 0.0851 | 1.18E09 | 367 | 11.5 | 73.1 | 1.97 | Evaluation is |
| 981 | Node group 1 | 53.691 | 29.133 | 43.04 | 0.168 | 5.96E08 | 186 | 5.82 | 82 | 1.75 | Evaluation is |
| 980 | Node group 1 | 15.299 | 7.652 | 44.0493 | 6.6E-05 | 1.51E12 | 4.73E05 | 1.48E04 | 21.6 | 6.65 | Evaluation is |
| 979 | Node group 1 | 37.791 | 21.611 | 45.4257 | 0.0306 | 3.27E09 | 1.02E03 | 31.9 | 61.4 | 2.34 | Evaluation is |
| 978 | Node group 1 | 64.093 | 36.390 | 45.8578 | 0.662 | 1.51E08 | 47.2 | 1.48 | 104 | 1.39 | Evaluation is |
| 977 | Node group 1 | 27.043 | 14.394 | 41.5068 | 0.00256 | 3.91E10 | 1.22E04 | 382 | 40.3 | 3.57 | Evaluation is |
| 976 | Node group 1 | 41.670 | 22.611 | 43.0616 | 0.0378 | 2.64E09 | 827 | 25.8 | 63.7 | 2.26 | Evaluation is |
| 975 | Node group 1 | 41.446 | 21.844 | 41.7537 | 0.0299 | 3.34E09 | 1.04E03 | 32.6 | 61.2 | 2.35 | Evaluation is |
| 974 | Node group 1 | 70.852 | 39.697 | 41.5351 | 1 | 1E08 | 31.3 | 0.977 | 111 | 1.29 | Evaluation is |
| 973 | Node group 1 | 14.636 | 7.829 | 44.1394 | 7.56E-05 | 1.32E12 | 4.13E05 | 1.29E04 | 22.1 | 6.5 | Evaluation is |
| 972 | Node group 1 | 65.255 | 35.883 | 39.9303 | 0.53 | 1.89E08 | 58.9 | 1.84 | 99.7 | 1.44 | Evaluation is |
| 971 | Node group 1 | 14.955 | 8.248 | 45.414 | 0.000106 | 9.46E11 | 2.96E05 | 9.23E03 | 23.4 | 6.14 | Evaluation is |
| 970 | Node group 1 | 54.434 | 30.756 | 41.0463 | 0.22 | 4.54E08 | 142 | 4.44 | 85.9 | 1.67 | Evaluation is |
| 969 | Node group 1 | 34.826 | 19.048 | 41.5702 | 0.0133 | 7.51E09 | 2.35E03 | 73.4 | 53.3 | 2.7 | Evaluation is |
| 968 | Node group 1 | 63.815 | 35.935 | 39.75 | 0.533 | 1.88E08 | 58.7 | 1.83 | 99.8 | 1.44 | Evaluation is |
| 967 | Node group 1 | 59.400 | 33.656 | 41.108 | 0.375 | 2.67E08 | 83.4 | 2.61 | 94 | 1.53 | Evaluation is |
| 966 | Node group 1 | 57.962 | 32.361 | 41.6019 | 0.301 | 3.32E08 | 104 | 3.24 | 90.6 | 1.59 | Evaluation is |

Figure 13.40. Durability evaluation results. Node list.

- Maximum stress (MPa)

Right bound of the reduced amplitude distribution evaluated from the selected load case stress time history

- Equivalent amplitude of the reduced amplitude distribution (MPa)

The amplitude of regular loading led to the damage which equals to the damage resulted from irregular loading described with the reduced amplitude distribution (the cycle count of regular loading is equal to the cycle count of irregular loading).

- Cycle count per life-time unit
- Damage accumulated per life-time unit
- Life time (in terms of the life-time unit)

- Life time (years)
- Safety factors
- Reduced equivalent amplitude (MPa)

These parameters are evaluated according to the selected analysis method, see Sect. 13.3. *"Durability analysis in UM Durability"*, p. 13-36.

- Comment

If the durability parameters evaluation at the node is successful then **comment** is «Evaluation is successful»

### 13.3.1.7. Durability parameters for a particular node

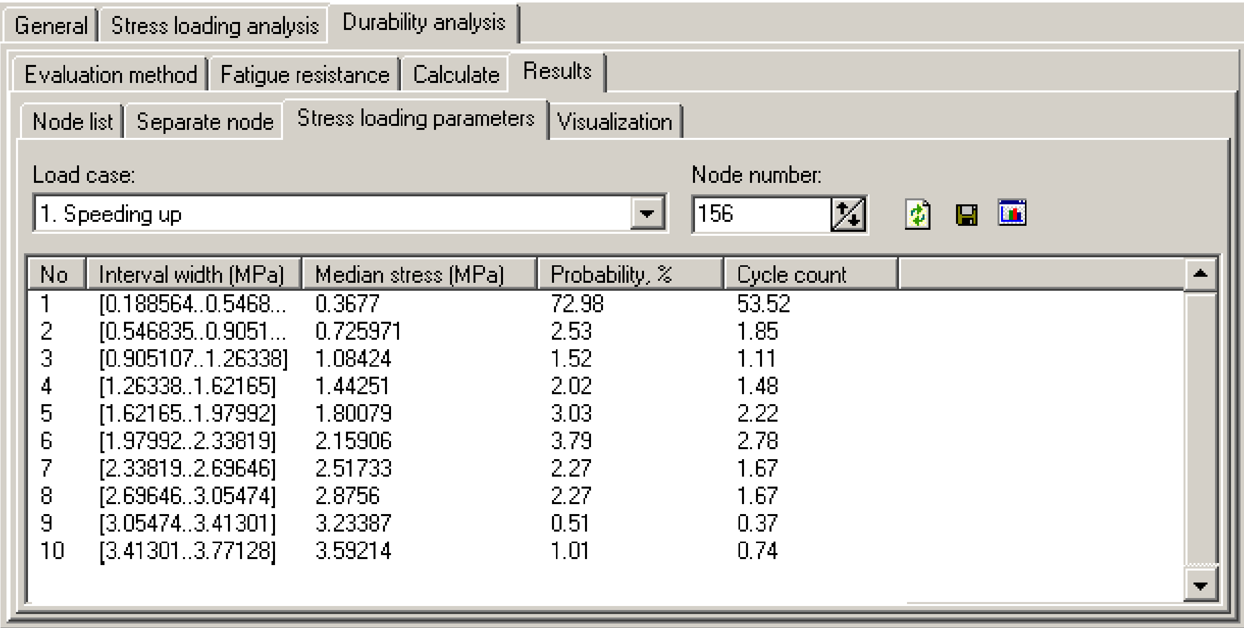
The **Particular node** tab allows to display results of the durability parameters evaluation at the selected FEM node. The parameter list is equal to the parameter list, defined at table **Durability | Results | Node list**, see above.

### 13.3.1.8. Stress loading parameters

The **Durability analysis | Results | Stress loading parameters** page allows to get tabular and graphical information about the reduced amplitude distribution (see Sect. 13.3.1.4. *"Reduced amplitude distribution calculation"*, p. 13-48) at the particular node for the defined load cases.

### 13.3.1.8.1. Tabular performance

The table shows the distribution of reduced amplitudes calculated from the two-parameter distribution of stress loading parameters according to the selected mean stress effect evaluation method, see Figure 13.41.




| No | Interval width (MPa) | Median stress (MPa) | Probability, % | Cycle count |
|---|---|---|---|---|
| 1 | [0.188564..0.5468... | 0.3677 | 72.98 | 53.52 |
| 2 | [0.546835..0.9051... | 0.725971 | 2.53 | 1.85 |
| 3 | [0.905107..1.26338] | 1.08424 | 1.52 | 1.11 |
| 4 | [1.26338..1.62165] | 1.44251 | 2.02 | 1.48 |
| 5 | [1.62165..1.97992] | 1.80079 | 3.03 | 2.22 |
| 6 | [1.97992..2.33819] | 2.15906 | 3.79 | 2.78 |
| 7 | [2.33819..2.69646] | 2.51733 | 2.27 | 1.67 |
| 8 | [2.69646..3.05474] | 2.8756 | 2.27 | 1.67 |
| 9 | [3.05474..3.41301] | 3.23387 | 0.51 | 0.37 |
| 10 | [3.41301..3.77128] | 3.59214 | 1.01 | 0.74 |

Figure 13.41. Durability evaluation results. Stress loading parameters.

### 13.3.1.8.2. Reduced amplitude distribution for a FEM node performance

To plot the reduced amplitude distribution for a FEM node for the particular load cases the following steps are necessary:

- select the **Durability analysis | Results | Stress loading parameters** page;
- select the FEM node number and the load case (to plot the distribution for the combination of the load cases select the **Combined stress loading block** item);
- click  button at the top panel of the page or select the «**Show as bar chart**» option from the popup menu.

The following window will be opened automatically, see Figure 13.42.

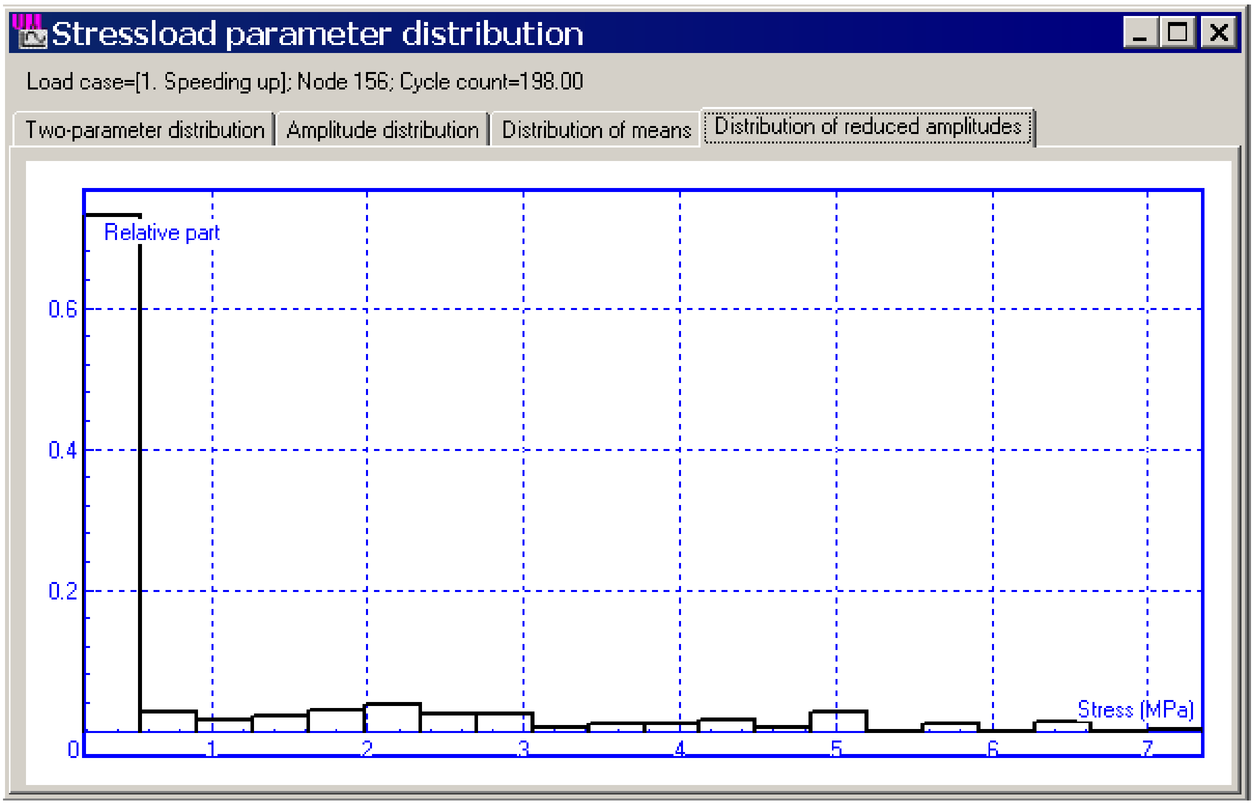



Figure 13.42. Durability evaluation results. Distribution of reduced amplitudes

This window is also used for the displaying the stress loading parameters distributions, see Sect. 13.2.5.3.2. *"Display of stress loading parameters distributions for a FEM node"*, p. 13-31.

#### 13.3.1.9. Durability parameters visualization for the FEM

Use the **Durability analysis | Results | Visualization** tab to get the visual representation of the durability parameters values at the FEM nodes included in the groups, see Figure 13.43.

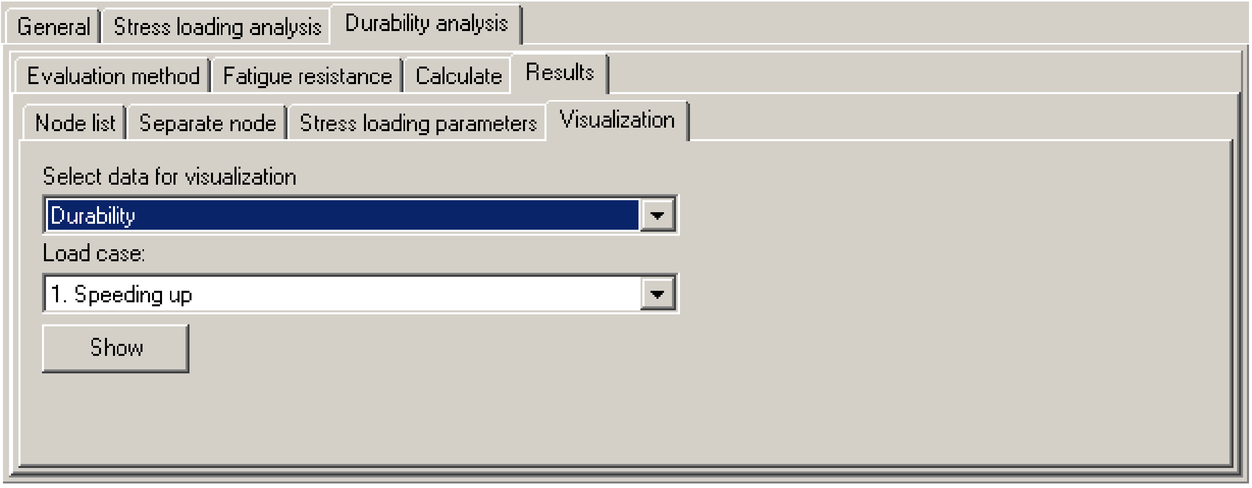



Figure 13.43. Durability evaluation results. Visualization.

Select data for visualization and the load case from the corresponding combo boxes and click the **Show** button.

The animation window is used for the displaying. Color scheme corresponds to values of the selected durability parameter. The user can change display options or select a list of nodes with the help of the popup menu of the animation window, see Sect. 13.2.5.3.3. *"Display of stress loading parameters for the FEM"*, p. 13-33.

# 13.4. Durability evaluation methods

## 13.4.1. Carriage-building method

This method is based on the Russian carriage-building regulations. It also includes several additional evaluation algorithms.

Characteristic parameters of the method are the following:

- Stress loading can be described with an amplitude distribution or with a spectral characteristic of the loading process (RMS value of the process).
- The durability evaluation is based on the linear damage accumulation Palmgren-Miner rule.
- S-N curve describes with a single line in double logarithmic scale (Model No1, see Sect. 13.3.1.3.2. *"S-N curve mathematical models"*, p. 13-45).
- The results of the analysis are the reduced equivalent amplitude, the life-time or the life-path length.

This issue includes controls descriptions, design parameters and evaluation algorithms.

### 13.4.1.1. Stress loading description

The Stress loading description is based on the results of stress loading analysis, see Sect. 13.2. *"Stress loading analysis in UM Durability"*, p. 13-5.

The **Durability analysis | Evaluation method | Stress loading description** tab is used for the description.

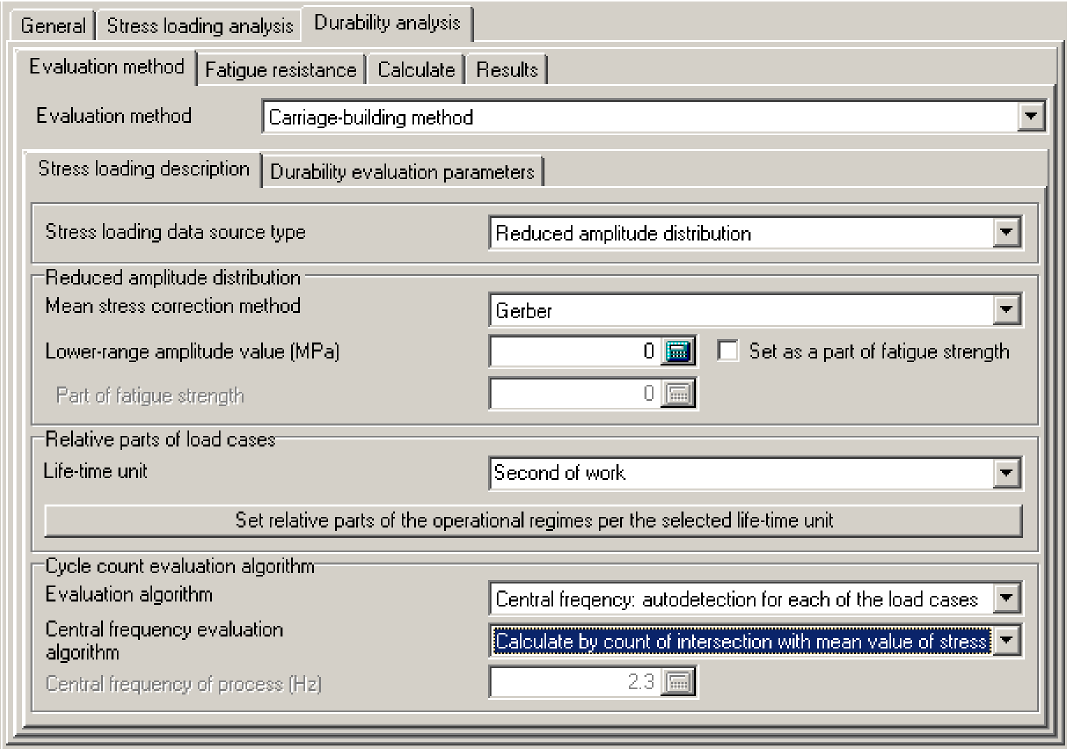



Figure 13.44. Stress loading description

**Stress loading data source type**

The carriage-building method suggests two types of stress loading data description.

In the first case, stress loading data are described with *reduced amplitude distribution*. The second variant of the description is based on the spectral characteristic of loading process (*RMS value of loading process*).

**Note.** Russian regulations prescribe to use spectral characteristics only for narrow-band loading process with normal distribution of stress values. Otherwise we should use amplitude distribution.
Durability evaluation in terms of kilometers of path is available only for the first variant of stress loading data description.

**Mean stress effect calculation method**[2]

The user can select one of the mean stress effect calculation algorithms, see Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10.

**Lower-range amplitude value (MPa)***

This value is used at the procedure of the reduced amplitude distribution evaluation, see Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10.

The lower-range amplitude value can be set as defined value or as a part from fatigue strength of the group (check box **Set as a part from fatigue strength**).

**Life-time unit**

The user can select second of work or kilometer of path length as a life-time unit.

To describe operational conditions the user should click the button **Set relative parts of the operational regimes per the life-time unit** and set the corresponding values in the window.

**Cycle count evaluation algorithm**

The carriage-building method suggests second of work or kilometer of path length as a design unit. Accordingly, the durability evaluation algorithm should define cycle count per second of work or per kilometer of path length.

There are several ways of cycle count per second value definition. We can use the central frequency of the process evaluated from stress histories on one of the three available methods, see Sect. 13.2.4.2.1. *"Stress loading evaluation parameters for carriage-building method"*, p. 13-25, or directly define this at the field **Central frequency of the work process**.

---

[2] This option is available only for stress loading data description in the form of reduced amplitudes distribution, see **Stress loading source data type**

**Note.** The evaluation of central frequency values takes place during the stress loading analysis procedure. Consequently, corresponding controls of the preliminary stress loading analysis should be selected, see Sect. 13.2.4.2.1. *"Stress loading evaluation parameters for carriage-building method"*, p. 13-25.

Alternatively, cycle count per second or cycle count per kilometer value can be evaluated on the base of stress history schematization results.

#### 13.4.1.2. Durability evaluation algorithm parameters

**Durability analysis | Evaluation method | Durability evaluation parameters** tab is used for setting controls of the durability prediction algorithm.

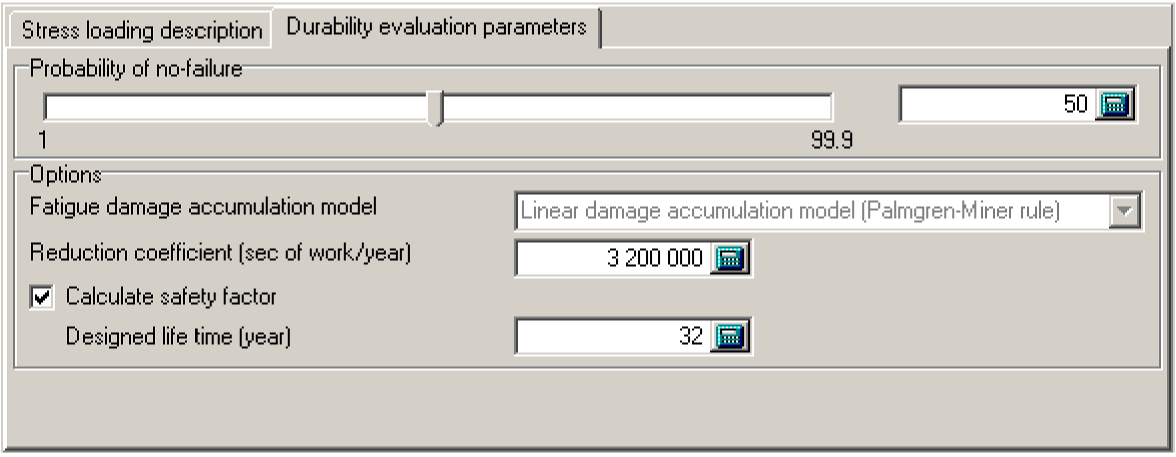



Figure 13.45. Durability evaluation parameters

**Probability of no-failure**

This parameter defines the fatigue strength value. The fatigue strength of the group has normal distribution with mean value $\overline{S}_f$ and coefficient of variation $\upsilon_{sf}$. These values are defined for each of node groups (see Sect. 13.4.1.3. *"Fatigue resistance properties"*, p. 13-57) and used for the fatigue strength evaluation:

$$S_f = \overline{S}_f \cdot \left(1 - Z_p \cdot \upsilon_{S_f}\right), \text{where}$$

$Z_p$ is a normal distribution quantile for probability P.

**Reduction coefficient**

This value is used for the conversion of the selected life-time unit to a year of work.

If the result unit is a path length, this coefficient is equal to *kilometer of path length per year* value.

If the result unit is a second of work, this coefficient is equal to *seconds of work per year* value.

Russian regularities suggest the following equation for *seconds of work per year* value ($B$) evaluation:

$$B = 365 \cdot \frac{10^3 \cdot \Im_c}{\overline{V}}, \text{where}$$

$\overline{\Im_c}$ is design average daily path length, km/day;

$\overline{V}$ is average speed of carriage motion, m/s.

**Designed life time (year)**

The carriage-building durability analysis method permits to evaluate reduced equivalent amplitude and object usage safety factor, see Sect. 13.4.1.4. *"Evaluation procedure"*, p. 13-58.

To make these evaluations available the user should click **Calculate safety factor** check box and set the **Design life-time value**.

### 13.4.1.3. Fatigue resistance properties

The carriage-building method uses *Model №1* of S-N curve description, see Sect. 13.3.1.3.2. *"S-N curve mathematical models"*, p. 13-45.

Fatigue resistance properties for node groups can be defined on the **Durability | Fatigue resistance** tab, see Sect. 13.3.1.3. *"Fatigue resistance properties initialization for node groups"*, p. 13-42.

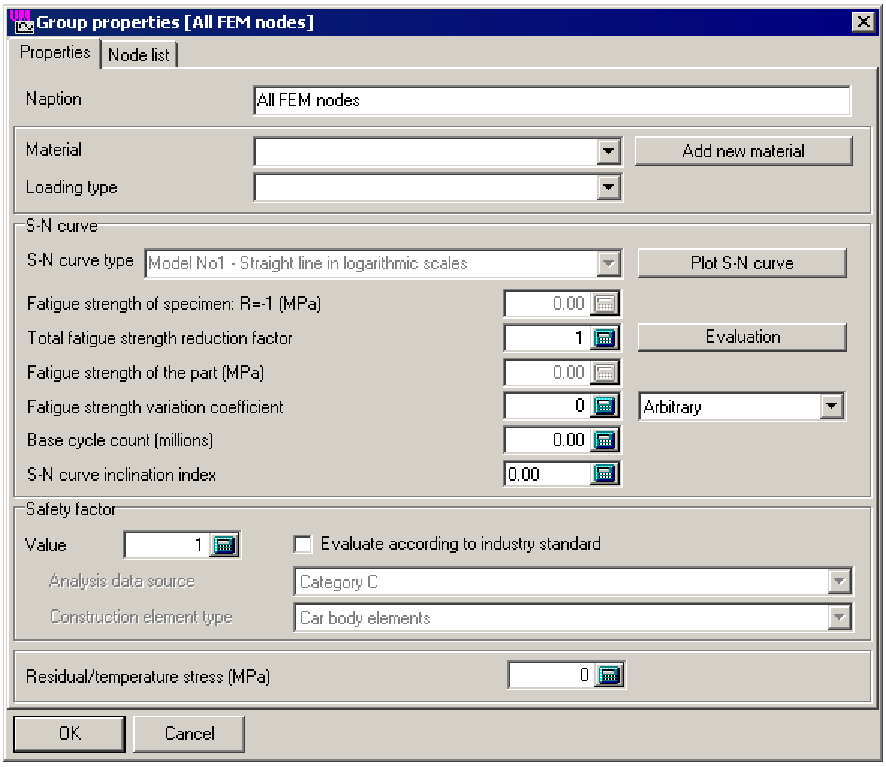



Figure 13.46. Group properties

The **group properties** window (Figure 13.46) lets the user select material of the group from material database, make correction of the fatigue strength value and variation coefficient, set permissible value of safety factor and define temper value for the group nodes.

Fields **Fatigue strength of material specimen, Base cycle count** and **S-N curve incline index** are filled in automatically according to values defined for material of the group at the material database, see Sect. 13.3.1.3.1. *"Material database"*, p. 13-44.

**Total fatigue strength reduction factor** (Figure 13.47) $C_f$ can be defined as a value or calculated with the following equation:

$$C_f = \overline{C_\sigma} \cdot \frac{C_{heterogeneity} \cdot C_{treatment}}{C_{size} \cdot C_{finish}} \cdot M, \text{where}$$

$\overline{C_\sigma}$ is efficient stress concentration factor which considers decreasing of fatigue resistance properties owing to local geometry features;

$C_{heterogeneity}$ is material heterogeneity factor;

$C_{treatment}$ is surface treatment factor;

$C_{size}$ is size factor;

$C_{finish}$ is surface finish factor;

$M$ is additional multiplier used for other factors description.

To define all these factors the user should click the **Calculate** button and fill in fields of the following window.

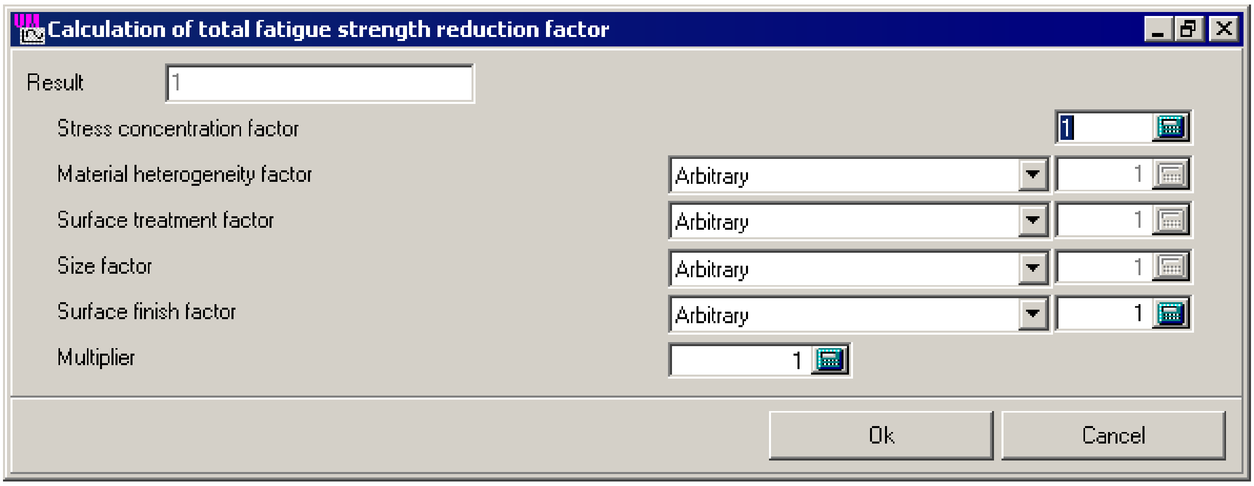



Figure 13.47. Total fatigue strength reduction factor

### 13.4.1.4. Evaluation procedure

This section is dedicated to the description of durability parameters evaluation algorithms and results of the carriage-building method.

**Note.** The method uses *linear Palmgren-Miner damage accumulation rule*. Fatigue resistance properties of the material are described with the *Model №1* S-N curve, see Sect. 13.3.1.3.2. *"S-N curve mathematical models"*, p. 13-45.

Let us consider the main stages of the evaluation procedure. Let the stress loading data is described with the reduced amplitude distribution:

- *Reduced amplitude distribution* evaluation for all node groups. This evaluation (see. Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10) uses the preliminary evaluated *distributions of stress loading parameters. Reduced amplitude values* are evaluated according to the selected *mean stress effect calculation algorithm* (see Sect. 13.4.2.1. *"Stress loading description"*, p. 13-62) and pre-defined *residual stress* values (see Sect. 13.4.2.3. *"Fatigue resistance properties"*, p. 13-65). *Lower-range amplitude value* is also taken into account (see Sect. 13.4.2.1. *"Stress loading description"*, p. 13-62).

Equivalent amplitudes $\sigma_{a,э}^{<k>}$ evaluation. *Equivalent amplitude* ($\sigma_{a,э}^{<k>}$) is an amplitude of a regular loading resulted in damage, equals to the damage, resulted from the **k**-load case irregular loading.

$$\sigma_{a,э}^{<k>} = \sqrt[m]{\sum_i t_i^{<k>} \cdot \sigma_i^{<k>}}, \text{where}$$

1. $\sigma_i^{<k>}$ is characteristic value of the **i**-interval of the reduced amplitude distribution which performs the k-load case;
2. $t_i^{<k>}$ is a relative part of cycles evaluated from the **k** load case STH which parameter values allow to relate them to the **i** interval;
3. *m* is the *Model No1* S-N curve parameter.

- *Damage per the life-time unit* $D_{unit}^{<k>}$ for the load cases evaluation.

Two estimates are used:

1. value, calculated on the base of fatigue strength value, evaluated without safety factor (used for *reduced equivalent amplitudes* evaluation)

$$D_{unit}^{<k>} = \frac{n_{unit}^{<k>}}{N_0} \cdot \left(\frac{\sigma_{a,e}^{<k>}}{\sigma_{-1}}\right)^m$$

2. value, calculated on the base of fatigue strength value, evaluated with safety factor (used for *durability* evaluation)

$$D_{unit[n]}^{<k>} = \frac{n_{unit}^{<k>}}{N_0} \cdot \left(\frac{\sigma_{a,e}^{<k>}}{\sigma_{-1}} \cdot [n]\right)^m, \text{where}$$

1. $n_{unit}^{<k>}$ is a cycle count per the life-time unit;
2. $\sigma_{-1}$ is a fatigue strength;
3. $N_0$ is a base cycle count;
4. [*n*] is a reserve coefficient, see Sect. 13.4.1.3. *"Fatigue resistance properties"*, p. 13-57.

- *Damage per life-time unit* evaluation

$$D_{unit}^{<CLB>} = \sum_k C^{<k>} \cdot D_{unit}^{<k>},\;\; D_{unit[n]}^{<CLB>} = \sum_k C^{<k>} \cdot D_{unit\,[n]}^{<k>}, \text{where}$$

$C^{<k>}$ is a relative part of the **k**-load case operation time or operation path length.

- *Cycle count per life-time unit* evaluation

$$n_{unit}^{<CLB>} = \sum_k C^{<k>} \cdot n_{unit}^{<k>}$$

- Reduced equivalent amplitude evaluation. *Reduced equivalent amplitude* is amplitude of regular loading with the cycle count which equals to the base cycle count resulted in damage which is equal to the value, which can be accounted in case of design life-time non-regular loading, described with the combination of the load cases.

$$\sigma_{R,e} = \sqrt[m]{B \cdot [T_c] \cdot D_{unit}^{<CLB>}} \cdot \sigma_{-1} = \sqrt[m]{B \cdot [T_c] \sum_k C^{<k>} \cdot D_{unit}^{<k>}} \cdot \sigma_{-1} =$$

$$= \sqrt[m]{\frac{B \cdot [T_c]}{N_0} \sum_k C^{<k>} \cdot n_{unit}^{<k>} \cdot \sum_i t_i^{<k>} \cdot \left(\sigma_i^{<k>}\right)^m}, \text{where}$$

  - $B$ is life-time units per year (e.g. seconds per year);
  - $[T_c]$ is the design calendar life-time of the object, see Sect. 13.4.1.2. *"Durability evaluation algorithm parameters"*, p. 13-56.

- *Safety factor of reduced amplitude value*

$$n_{R,e} = \frac{\sigma_{-1}}{\sigma_{R,e}}$$

- *Durability evaluation (in terms of life-time units)*

$$T_{sec} = \frac{1}{D_{\mathrm{sec}[n]}^{<CLB>}} = \frac{\left(\frac{\sigma_{-1}}{[n]}\right)^m \cdot N_0}{\sum_k C^{<k>} \cdot n_{sec}^{<k>} \cdot \sum_i t_i^{<k>} \cdot \left(\sigma_i^{<k>}\right)^m},$$

$$L_{km} = \frac{1}{D_{km\,[n]}^{<CLB>}} = \frac{\left(\frac{\sigma_{-1}}{[n]}\right)^m \cdot N_0}{\sum_k C^{<k>} \cdot n_{km}^{<k>} \cdot \sum_i t_i^{<k>} \cdot \left(\sigma_i^{<k>}\right)^m}$$

- *Calendar life-time*

$$T_c = \frac{T_{sec}}{B_{sec/year}},\;\; T_c = \frac{L_{km}}{B_{km/year}}$$

- *Safety factor of design life time*

$$n_T = \frac{T_c}{[T_c]}$$

Let us consider the main stages of the evaluation procedure if RMS values for the stress loading description are used:

- *Reduced equivalent amplitude evaluation.*

$$\sigma_{R,e} = \sqrt[m]{\frac{B \cdot [T_c]}{N_0} \cdot A \cdot \sum_k C^{<k>} \cdot n_{unit}^{<k>} \cdot (S_\sigma^{<k>})^m}\text{, where}$$

$A = 2^{\frac{m}{2}} * \Gamma(\frac{m+2}{2})$ is function of m;

$S_\sigma^{<k>}$ is RMS value of STH, which presents the k-load case.

- *Safety factor of reduced amplitude*

$$n_{R,e} = \frac{\sigma_{-1}}{\sigma_{R,e}}$$

- *Durability (in seconds of work)*

$$T_{\text{сек}} = \frac{\left(\frac{\sigma_{-1}}{[n]}\right)^m \cdot N_0}{A \cdot \sum_k C^{<k>} \cdot n_{\text{сек}}^{<k>} \cdot (S_\sigma^{<k>})^m}$$

- *Calendar life-time*

$$T_c = \frac{T_{sec}}{B_{sec/year}}$$

- *Safety factor of design life time*

$$n_T = \frac{T_c}{[T_c]}$$

## 13.4.2. S-N method

The S-N method has the following features:

- Stress loading data are described with stress loading amplitude distributions.
- Durability evaluation is based on the linear damage accumulation rule of Palmgren-Miner.
- The S-N curve is described with two straight lines in double logarithmic scale.
- Life-time in terms of seconds of work or kilometers of path length or user defined unit is the result of the calculation.

This issue includes controls descriptions, design parameters and evaluation algorithms.

### 13.4.2.1. Stress loading description

Stress loading description is based on the results of stress loading analysis, see Sect. 13.2. *"Stress loading analysis in UM Durability"*, p. 13-5, and has the following properties.

The **Durability analysis | Method | Stress loading description** tab is used for the description.

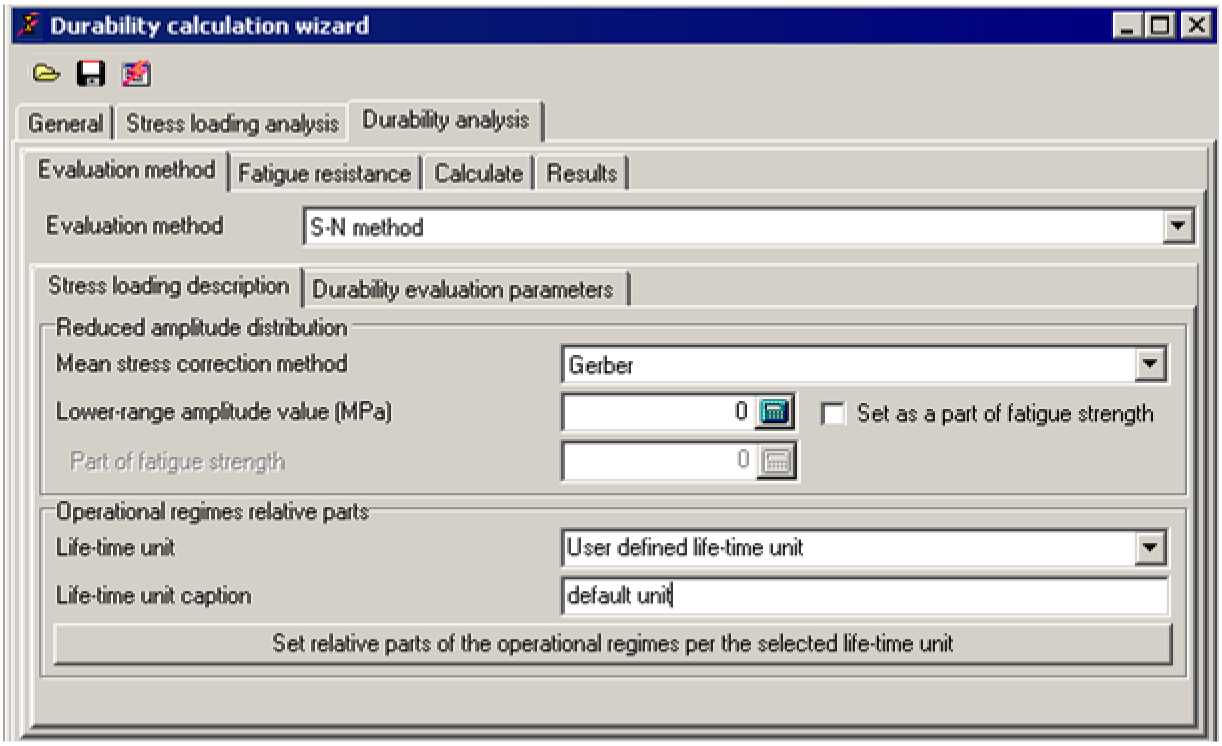



Figure 13.48. S-N method

**Mean stress correction method**

The user can select one of the mean stress correction algorithms, see Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10.

**Lower-range amplitude value**

This value is used for the evaluation of loading reduced amplitude distribution, see Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10.

Lower-range amplitude value can be set as a defined value or as a part from fatigue strength of the group (check box **Set as a part from fatigue strength**).

**Life-time unit**

The user can select seconds of work or kilometers of path length as a standard life-time unit or define his own one.

In the **Life-time unit caption** box you can specify your own life-time unit caption.

To describe operational conditions the user should click the **Set relative parts of the operational regimes per the life-time unit** button and set the corresponding values in the appeared window.

### 13.4.2.2. Durability evaluation algorithm parameters

The **Durability | Method | Durability evaluation parameters** tab is used for setting parameters of the durability prediction algorithm.

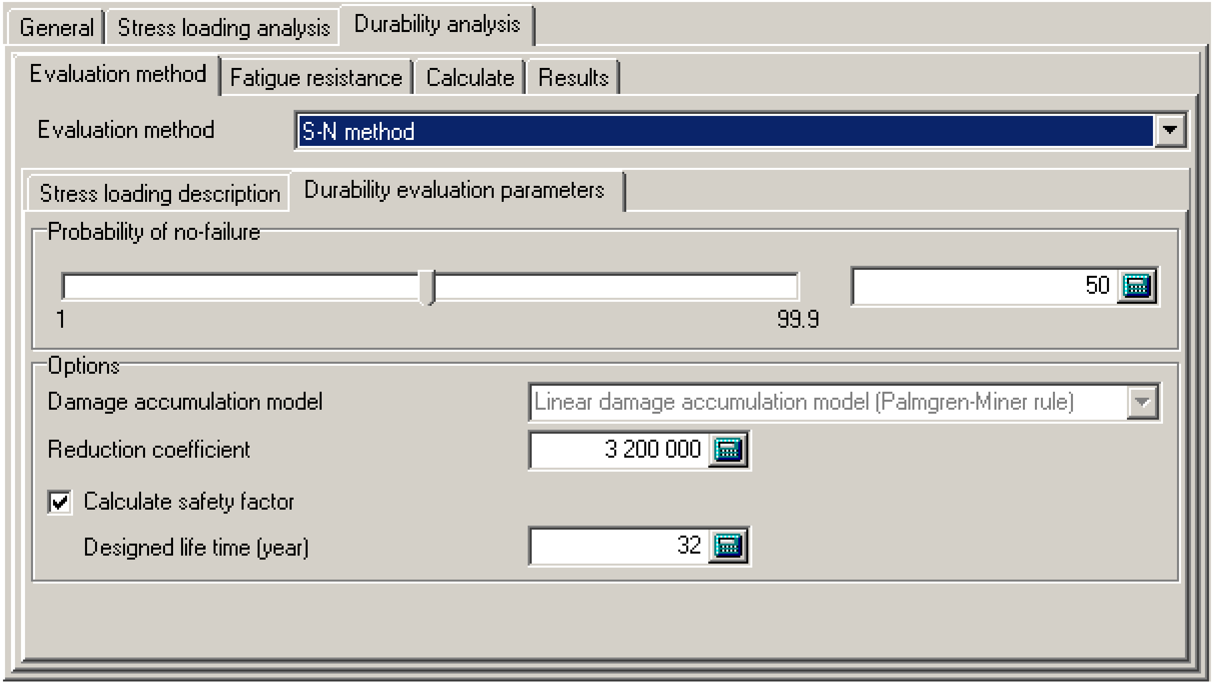



Figure 13.49. Durability evaluation parameters

**Probability of no-failure**

This parameter defines fatigue strength value. Let the fatigue strength of the group has the normal distribution with a mean value $\overline{S_f}$ and a coefficient of variation $\upsilon_{sf}$. These values are defined for each of node groups (see Sect. 13.4.1.3. *"Fatigue resistance properties"*, p. 13-57) and used for the fatigue strength evaluation:

$$S_f = \overline{S_f} \cdot \left(1 - Z_p \cdot \upsilon_{S_f}\right), \text{where}$$

$Z_p$ is normal distribution quantile for probability *P*.

**Fatigue damage accumulation model**

Carriage-building method uses linear Palmgren-Miner damage accumulation rule.

**Reduction coefficient**

This value is used to convert design units to calendar time. If the result unit is path length, this coefficient is equal to *kilometer of path length per year* value.

If the result unit is second of work, this coefficient is equal to *seconds of work per year* value.

Russian regularities suggest the following equation for the evaluation of *seconds of work per year* value *B*:

$$B = 365 \cdot \frac{10^3 \cdot \overline{\mathfrak{I}_c}}{\bar{V}}, \text{where}$$

$\overline{\mathfrak{I}_c}$ is design daily average path length, km/day;

$\overline{V}$ is average speed of carriage motion, m/sec.

**Safety factor evaluation**

For the evaluation of safety factor, the design life-time value is necessary. This value along with the reduction coefficient lets the program evaluate the design life-time in terms of design units.

The definition of this value makes available the calculation of reduced equivalent amplitude. For the description of the evaluation algorithm see Sect. 13.4.1.4. *"Evaluation procedure"*, p. 13-58.

### 13.4.2.3. Fatigue resistance properties

The S-N method uses Model №5 of the S-N curve description, see Sect. 13.3.1.3.2. *"S-N curve mathematical models"*, p. 13-45.

Fatigue resistance properties for node groups can be defined on the **Durability | Fatigue resistance** page, see Sect. 13.3.1.3. *"Fatigue resistance properties initialization for node groups"*, p. 13-42.

The **Group properties** window lets the user select material of the group from material database, make correction of the fatigue strength value and variation coefficient, set permissible value of safety factor and define temper value for the group nodes.

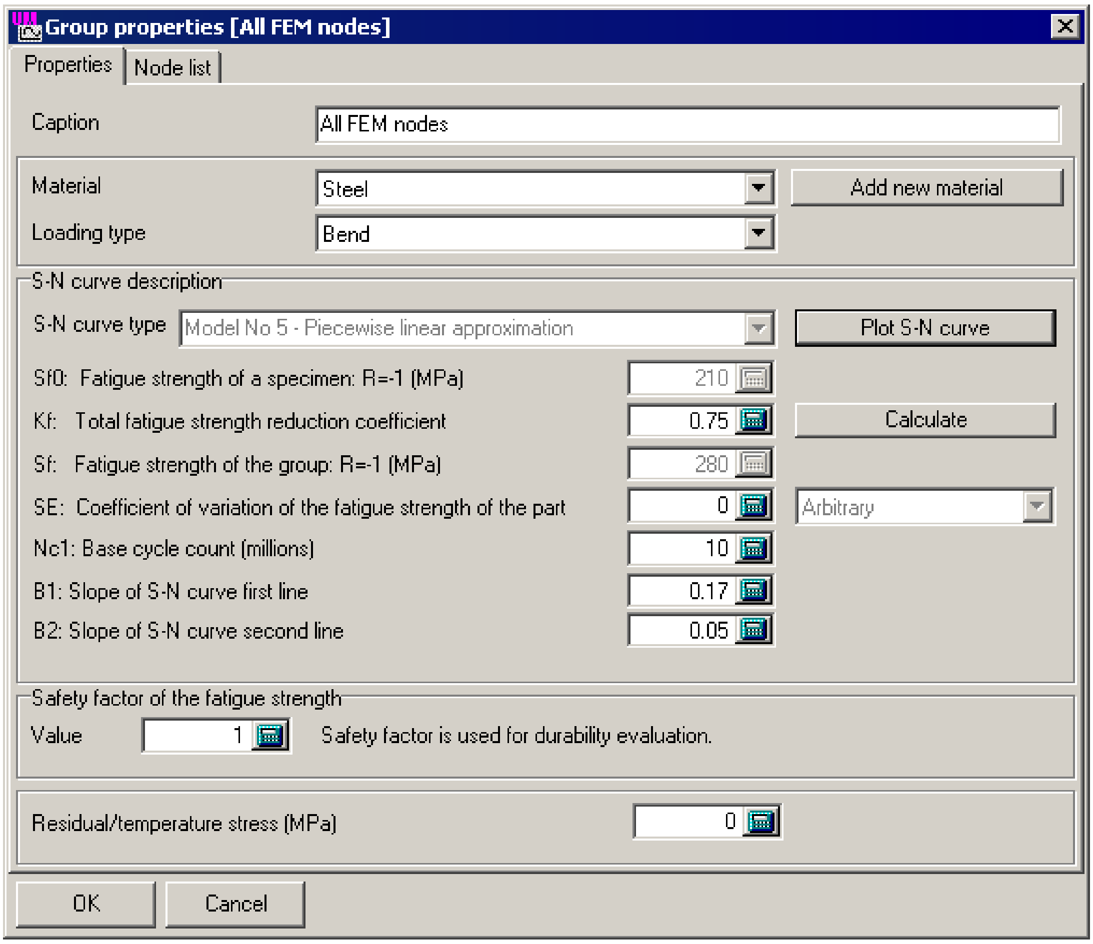



Figure 13.50. Durability evaluation parameters

Fields **Fatigue strength of material specimen, Base cycle count, S-N curve incline index** are filled in automatically according to the values defined for material of the group at the material database, see Sect. 13.3.1.3.1. *"Material database"*, p. 13-44.

**Total fatigue strength reduction factor** can be defined as a value or calculated with the following equation:

$$K_f = \overline{K_\sigma} \cdot \frac{K_y}{K_{\text{м}} \cdot K_{\text{пов}}} \cdot M, \text{where}$$

$\overline{K_\sigma}$ is efficient stress concentration factor which considers decreasing of fatigue resistance properties owing to local geometry features;

$K_{\text{у}}$ is surface treatment factor;

$K_{\text{м}}$ is size factor;

$K_{\text{пов}}$ is surface finish factor;

$M$ is additional multiplier used for other factors description.

To define all these factors, the user should click the **Calculate** button and fill in the fields of the following window.

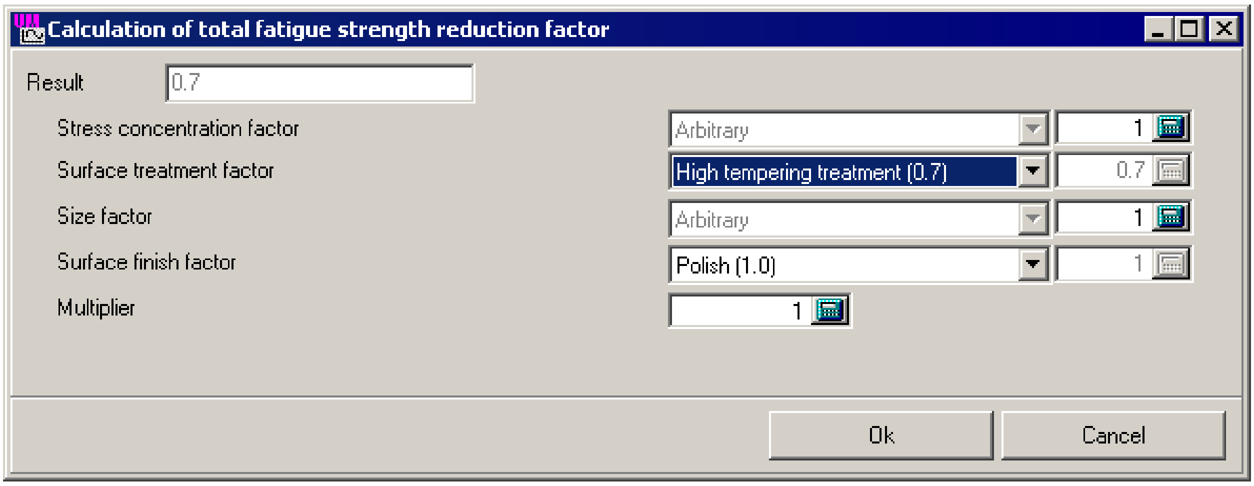



Figure 13.51. Durability evaluation parameters

**Permissible value of safety factor** can be defined manually at the following field.

The value, defined at the field **«Residual/temperature stress»**, is taken into account at the evaluation of reduced amplitude distribution, see Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10.

### 13.4.2.4. Evaluation procedure

This section is dedicated to the description of durability parameters evaluation algorithms and results of the S-N method.

**Note.** The method uses *linear Palmgren-Miner damage accumulation rule*. Fatigue resistance properties of the material are described with the S-N curve in the *Model №5* form, see Sect. 13.3.1.3.2. *"S-N curve mathematical models"*, p. 13-45.

Let us consider the main stages of the evaluation procedure with the user defined life-time unit:

- *Reduced amplitude distribution* calculation for all nodes of all groups is based on the preliminary evaluated *distribution of stress loading parameters* (see. Sect. 13.2.1.3. *"Stress loading parameters distributions"*, p. 13-10), according to the selected *mean stress effect calculation algorithm* (see Sect. 13.4.2.1. *"Stress loading description"*, p. 13-62) and defined *residual/thermal stress* values (see Sect. 13.4.2.3. *"Fatigue resistance properties"*, p. 13-65). *Lower-range amplitude value* is also taken into account (see Sect. 13.4.2.1. *"Stress loading description"*, p. 13-62).
- *Damage per life-time unit* for the particular work modes.

$$D_{unit}^{<k>} = \sum_i \frac{n_{unit}^{<k>} \cdot t_i^{<k>}}{N\left(\sigma_i^{<k>}\right)}, \text{where}$$

a) $n_{unit}^{<k>}$ is cycle count per life-time unit;

b) $\sigma_i^{<k>}$ is characteristic value of the i-interval of the reduced amplitude distribution which performs the k-load case;

c) $t_i^{<k>}$ is the relative part of cycle count of the k load case, which parameter values allow them to relate to the i interval;

d) *N(σ)* is the cycle count of regular loading with *σ* amplitude, which results in destruction of the detail. This value is calculated according to Model №5 S-N curve description, see Sect. 13.3.1.3.2. *"S-N curve mathematical models"*, p. 13-45.

- Equivalent amplitudes $\sigma_{a,э}^{<k>}$ evaluation. *Equivalent amplitude* ($\sigma_{a,э}^{<k>}$)is an amplitude of a regular loading resulted in damage, equals to the damage, resulted from the **k**-load case irregular loading.

$$D_{unit}^{<k>} = \frac{n_{unit}^{<k>}}{N\left(\sigma_{a,e}^{<k>}\right)} = \sum_i \frac{n_{unit}^{<k>} \cdot t_i^{<k>}}{N\left(\sigma_i^{<k>}\right)}$$

Accordingly,

$$\sigma_{a,e}^{<k>} = \sigma\left(N\left(\sigma_{a,e}^{<k>}\right)\right) = \sigma\left(\left(\sum_i \frac{t_i^{<k>}}{N\left(\sigma_i^{<k>}\right)}\right)^{-1}\right)$$

- *Damage per design unit.*

$$D_{unit}^{<CLB>} = \sum_k D_{unit}^{<k>},$$

- *Cycle count per design unit for work condition.*

$$n_{unit}^{<CLB>} = \sum_k n_{unit}^{<k>}, \text{where}$$

- *Durability (in terms of life-time units)*

$$T = \frac{1}{D_{unit}^{<CLB>}}$$

- *Calendar life-time.*

$$T_c = \frac{T}{B}$$

- *Safety factor of life-time.*

$$n_T = \frac{T_c}{[T_c]}$$