ГЛАВА 6. DESIGN COMBINATIONS OF LOADS/FORCES

General

Solving the problem of determining the most dangerous combinations of loads ensures the relationship between the results of calculating the structure for various loads and the design of its elements.

To solve this problem, various approaches are used:

- design combination of loads (DCL);
- design combination of forces (DCF).

The way to determine the DCF is based on finding the elastic potential extrema at any point of the structure from the action of many loads (or many loadings). The use of DCF leads to a limited (much less 2^n, where n is the number of loadings) number of considered combinations, which are the most dangerous. At the same time, designing with the use of DCL involves the study of all possible combinations, in the limiting case, their number reaches 2^n.

The DCF is determined according to the normative formulas SNiP, SP, DBN or EN, and the calculations are performed on the basis of the method described above, taking into account the features of the elastic potential characteristic of the sections of rods, plates, shells and solids. These features make it possible to express the solution of the problem of choosing dangerous combinations in terms of the criterion of extreme stresses at characteristic points of the sections. Due to this, the number of considered combinations is significantly limited.

6.1 PECULIARITIES OF DESIGNING DCF IN THE LOADING STATE EDITOR

Initial data preparation for Design combination of loads is performed in the Loading States Editor. Switching to the mode is carried out using the menu command **Editors and Structural Design ⇨ Loading States Editor** (button  on the toolbar).

In the editor, the data must be specified in accordance with the general rules for the formation of DCF:

- parameters of design combinations are set for each of the load cases of the problem;
- each DCF refers to one of the types of combinations provided for by regulatory documents;
- there are 8 types of load cases, implemented, with the help of which their correct logical interconnection is ensured by software.

6.1.1 DCF in accordance with SNiP 2.01.07-85*, DBN V.1.2-2:2006, SP 20.13330.2011, SP 20.13330.2016

There is a possibility to account for alternating, mutually exclusive and concurrent loadings. Loading types:

- constant;
- long-term;
- short-term;
- crane vertical;
- special;
- instant;
- inactive.

All the DCF generation operations are performed in the load case editor window (Fig. 6.1)

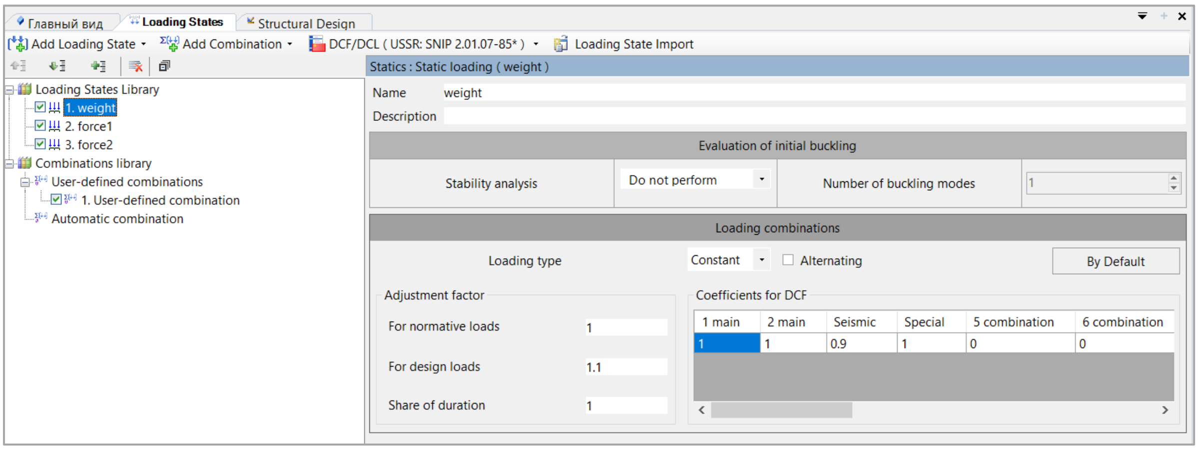

Fig. 6.1. DCF formation

The DCF parameters here include:

- Coefficients to design loads.
- **Share of duration** is a coefficient showing what part of the load in the considered load case is accepted as long-acting.
- Consider the **Alternating** i.e. the set checkbox means that the DCF should take into account the probability of changing the sign of the main force of the combination. Such efforts include, for example, the seismic ones.
- **Concurrent loading** means the loadings (but no more than six overall) that can be considered together with the main loading for this type. For example, if the main load is the vertical crane loading, then the horizontal braking impact loading will be the concurrent load.
- **Mutually exclusive loadings** - this parameter introduces restrictions on those loadings that cannot be included in one combination at the same time. Such, for example, are the load cases **Wind on the right** and **Wind on the left**.

Also, for the formation of the DCF and automatic generation of the DCL in the library of combinations, restrictions are set for cranes and brakes (Fig. 6.2, 1), and also, combination coefficients can be set according to the degree of influence for long-term, short-term and short-term crane loads (Fig. 6.2, 2 and 3). Also, in the window with combinations factors by impact degree, groups of cranes operating conditions are set.

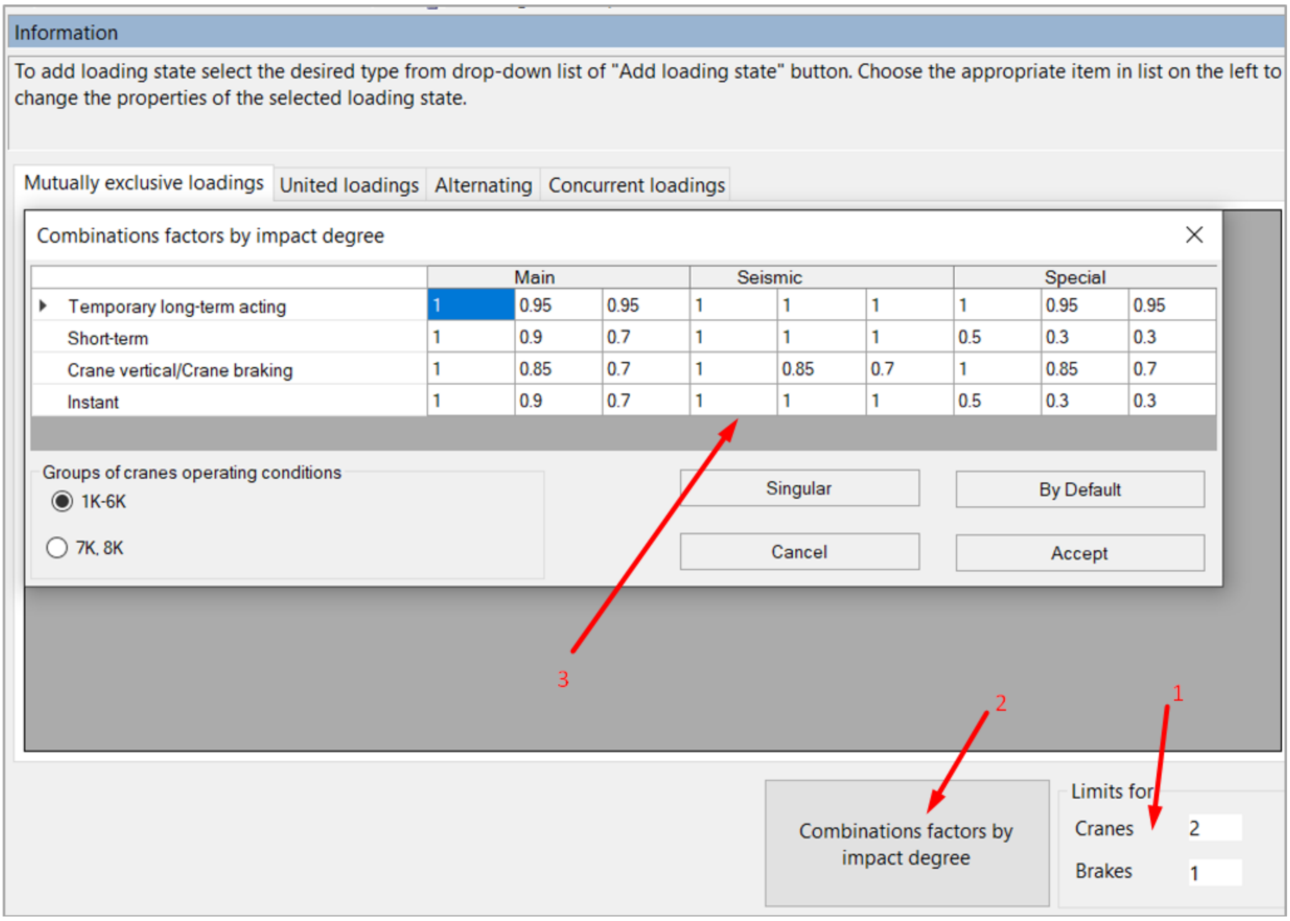

Fig. 6.2. Loadings States Library. Restrictions and coefficients of combinations according to the degree of influence

As a result of the DCF processor operation, 4 groups of combinations are calculated:

- **group A** – design values that take into account only those load cases that have a duration of action; this group includes loadings with constant, long-term and short-term loadings;
- **group B** – design values that take into account all load cases, regardless of the duration of action;
- **group AN** — normative values corresponding to group A;
- **group BN** — normative values corresponding to group B.

Only design values for groups A and B can be printed in the results table, while groups AN and BN with standard values are used by design systems to calculate and check the sections of steel, reinforced concrete and wooden elements.

6.1.2 DCF according to EU regulations (EN 1990:2002)

For DCF according to EN, in the load case parameters, in general, the following can be specified:

- Constant impact with the following types of impact:

- Metal construction;
- Concrete, reinforced concrete, stone, reinforced masonry, wood;

- Insulating, leveling and finishing layers produced at the factory;
- Insulating, leveling and finishing layers produced on the construction sites;
- Soils in natural occurrence;
- Soils on the construction sites;
- Another permanent.

- Temporary impact with the following types of impact:

- Category A: domestic, residential areas;
- Category B: office space;
- Category C: meeting areas;
- Category D: retail space;
- Category E: storage premisis;
- Category F: traffic areas for vehicles ≤30 kN;
- Category G: traffic areas for vehicles weighing from 30 to 160 kN;
- Category H coverings (roofs);
- Snow loads on buildings (see EN1991-1-3)*: Finland, Iceland, Norway, Sweden;
- For areas in other countries members of CEN located at an altitude of H>1000 m above sea level;
- For areas in other countries members of CEN located at an altitude of H≤1000 m above the sea level;
- Ice loads;
- Wind loads;
- Temperature action (excluding fires);
- Other temporary.

- Crane vertical impact with the following types of impact:

- Full vertical loads from bridge and portable cranes;
- Reduced vertical loads from bridge and portable cranes;

- Для сопутствующего статического загружения может дополнительно назначаться **Крановое тормозное** воздействие со следующими видами воздействия:

- Braking along the crane runway.
- Cart’s braking along the bridge crane;
- Crane obliquity when driving along the crane runway beam;
- Buffer forces related to crane’s movement;
- Buffer forces related to cart’s movement along the bridge crane.

- Seismic impact.

- Critical impact (except seismic).

- Pre-tensioning.

- Inactive.

For different types of impact in active columns, in addition, depending on the type of impact, alternating, coefficient to normative loads, coefficients for groups A, B, C to calculated unfavorable (dominant or concurrent to basic) and unfavorable (other concurrent) loads can be set, coefficients ψ_0, ψ_1, ψ_2.

Limits for crane and brakes are set in the Loading States Library (fig. 6.3, 1), and variable action coefficients can also be set (fig. 6.3, 2 and 3). Additionally, in the window with variable action coefficients, the following is set:

- Optional use of formulas 6.10a and 6.10b from EN 1990:2002 for action combinations for permanent or transient design situations.
- Coefficients $\psi_{1,1}$ or $\psi_{2,1}$, that are used in combination of actions for accidental design situations.
- Ultimate limit states:

  - EQU (Group A) — loss of static equilibrium of the structure or any part of it considered as a rigid body, where:

  1) minor variations in the value or the spatial distribution of permanent actions from a single source are significant, and

  2) the strengths of construction materials or ground are generally not governing;

  - STR/GEO (Group B and/or Group C),

  where STR is an internal failure or excessive deformation of the structure or structural members, including footings, piles, basement walls, etc., where the strength of construction materials of the structure governs;

  GEO is a failure or excessive deformation of the ground, where the strengths of soil or rock is significant in providing the resistance.

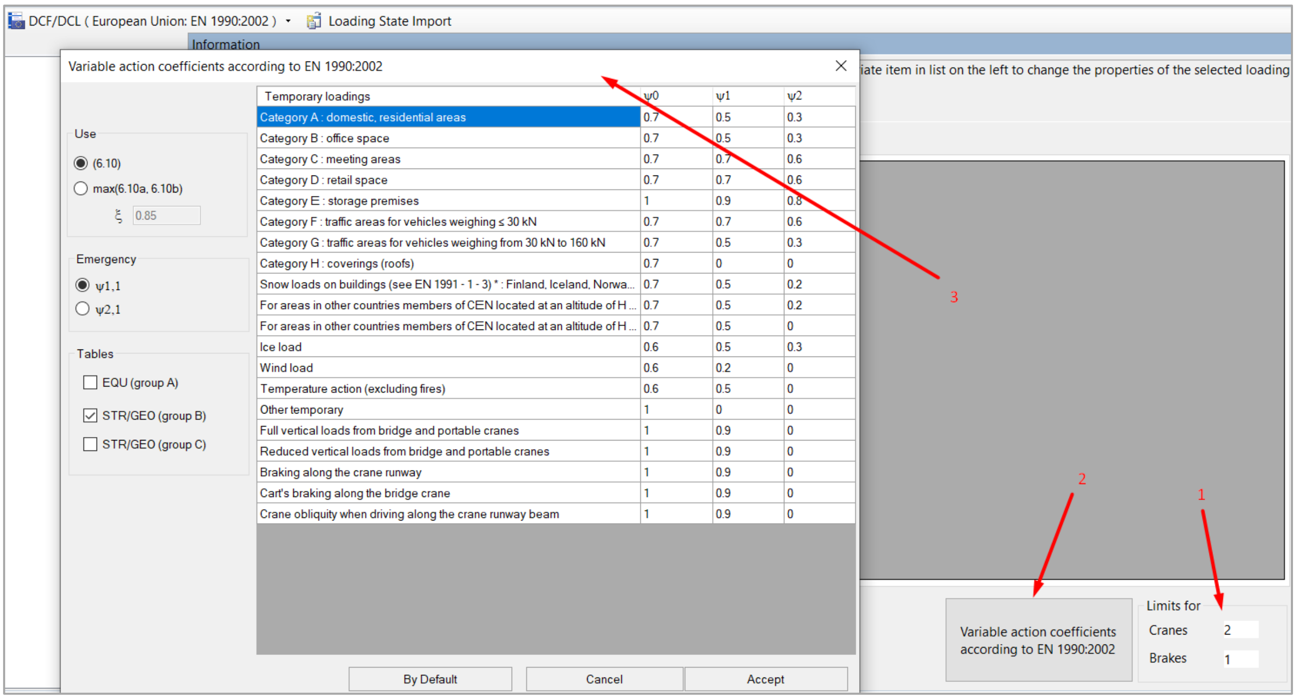

Fig. 6.3. Loading States Library. Limits and variable action coefficients

As a result of the operation of the DCF processor in accordance with EU standards, the following is calculated:

- DCF (design combination of forces): by critical limit state groups (formula numbers from EN 1990:2002 6.10, 6.10a, 6.10b, 6.11b, 6.12b);

- NCF (normative combination of forces): serviceability limit states (formula numbers from EN 1990:2002 6.14b, 6.15b, 6.16b), used in structural calculations of sections of steel, reinforced concrete and timber elements for the 2nd limit state.

In the table of DCF results in accordance with the EU norms, the number of the formula from EN 1990:2002, according to which the combination was obtained, is printed, and there is also a column in which the final coefficients are written for each of the load cases that fell into a certain combination.

6.1.3 Load case relation

When determining the DCF, logical relationships between load cases are taken into account, which reflect the physical meaning of the load cases and the requirements regulated by various regulatory documents. There are three types of loadings:

- independent (dead load, equipment weight, etc.);
- mutually exclusive (wind from the left and wind from the right, seismic, impact along different coordinate axes, etc.);
- concurrent (braking with the vertical crane loads, etc.).

It is also possible to assign alternating load cases with the same modulus of its vector.

Duration of action is taken into account (except for EU norms).

6.2 DCF IN BARS

As a criterion for determining DCF, extreme values of normal and shear stresses at control points of a conditional rectangular section are taken (Fig. 6.4).

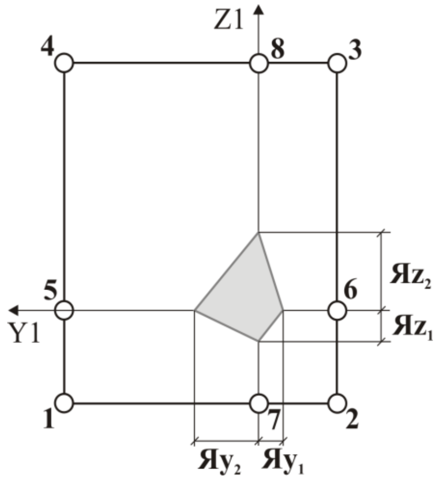

Fig. 6.4. Conditional rectangular section

For normal stresses, the following formula applies:

$$\sigma_k = \frac{N}{F} - \frac{M_y}{J_y} Z_k + \frac{M_z}{J_z} Y_k \,, \tag{6.1}$$

where k — is the point of the rod section $(k = 1 \div 9)$.

This formula is converted as follows at $y = \pm\frac{b}{2}; z = \pm\frac{h}{2}$:

$$\sigma_k F = N \pm \frac{M_y}{Я_{z,i}} \pm \frac{M_z}{Я_{y,i}} \,, \tag{6.2}$$

where $Я_{z,i}$ and $Я_{y,i}$ are core distances in the rod section $(i = 1,2)$.

This approach allows one to determine the extreme normal stresses in a section of any shape, bringing it to a rectangular one.

For shear stresses, the approximate formula is used:

$$\tau_{y,z}F = \frac{Q_{y,z}}{2} \pm \frac{M_{kp}}{2\left(Я_{y_1,z_1} + Я_{y_2,z_2}\right)} \quad (6.3)$$

The formulas for calculating extreme values for each point of the section are given in Table 6.1 (the rule of signs adopted for efforts is used), and the numbering of "criteria" values and their corresponding stresses is given in Table 6.2.

In addition to extreme stresses, extreme values of longitudinal and shear forces are also calculated.

In total, 34 DCF values are selected for the bar section.

Table 6.1. Formulas for calculating the extreme values

№ (section points)	**Principal stresses**	**Section tangential stresses**
1	$\sigma F = N + M_y / Я_{z_2} + M_z / Я_{y_1}$	—
2	$\sigma F = N + M_y / Я_{z_2} - M_z / Я_{y_2}$	—
3	$\sigma F = N - M_y / Я_{z_1} - M_z / Я_{y_2}$	—
4	$\sigma F = N - M_y / Я_{z_1} + M_z / Я_{y_1}$	—
5	$\sigma F = N + M_z / Я_{y_1}$	$\tau F = \frac{Q_z}{2} + \frac{M_{kp}}{2\left(Я_{y_1} + Я_{y_2}\right)}$
6	$\sigma F = M - M_z / Я_{y_2}$	$\tau F = \frac{Q_z}{2} - \frac{M_{kp}}{2\left(Я_{y_1} + Я_{y_2}\right)}$
7	$\sigma F = N + M_y / Я_{z_2}$	$\tau F = \frac{Q_z}{2} + \frac{M_{kp}}{2\left(Я_{z_1} + Я_{z_2}\right)}$
8	$\sigma F = N - M_y / Я_{z_1}$	$\tau F = \frac{Q_z}{2} - \frac{M_{kp}}{2\left(Я_{z_1} + Я_{z_2}\right)}$

Table 6.2. Criteria and their meanings

№№ criteria	1	2	3	4	5	6	7	8	9	10
Value	σ_1 +	σ_1 –	σ_2 +	σ_2 –	σ_3 +	σ_3 –	σ_4 +	σ_4 –	τ_7 +	τ_7 –
№№ criteria	11	12	13	14	15	16	17	18	19	20
Value	τ_8 +	τ_8 –	τ_5 +	τ_5 –	τ_6 +	τ_6 –	N+	N –	σ_7 +	σ_7 –
№№ criteria	21	22	23	24	25	26	27	28	29	30
Value	σ_8 +	σ_8 –	σ_5 +	σ_5 –	σ_6 +	σ_6 –	Q_y+, N+	Q_y–, N+	Q_y+, N–	Q_y–, N–
№№ criteria	31	32	33	34	—	—	—	—	—	—
Value	Q_z+, N+	Q_z–, N+	Q_z+, N–	Q_z–, N–	—	—	—	—	—	—

6.3 DCF IN PLATES

DCF for plane stress state

In the general case, the principal stresses at the same point of the structure for different loadings have different orientations. Therefore, here the DCF is determined from the envelopes of the extreme curves of normal and shear stresses according to the formulas:

$$\sigma_{\alpha_k} = N_x \cos^2 \alpha_k + N_z \sin^2 \alpha_k + T_{xz} \sin 2\alpha_k \ , \tag{6.4}$$

$$\tau_{\alpha_k} = \frac{1}{2}\left(N_z - N_x\right) \sin 2\alpha_k + T_{xz} \cos 2\alpha_k \ , \tag{6.5}$$

where k — is the load number.

The designations are given in fig. 6.5.

Voltages are calculated in the range from 0° до 180°.

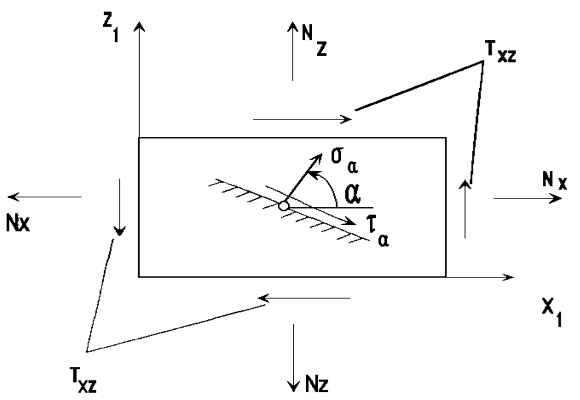

Fig. 6.5. Plane stress state

DCF for plates

Here, an approach similar to that described in the previous paragraph is applied. Bending and torsional moments in the slab make it possible to determine the normal and shear stresses on the upper and lower surfaces of the slab. These stresses are equal in modulus, so formulas (6.4) and (6.5) take the form:

$$M_{\alpha_k} = M_x \cos^2 \alpha_k + M_y \sin^2 \alpha_k + M_{xy} \sin 2\alpha_k \ , \tag{6.6}$$

$$M_{c\alpha_k} = \frac{1}{2}\left(M_y - M_x\right) \sin 2\alpha_k + M_{xy} \cos 2\alpha_k \tag{6.7}$$

Criteria DCF for the shells

A similar approach is applied here as well. Stresses are calculated on the top and bottom surfaces of the shell. In this case, membrane stresses and bending forces are taken into account according to the following dependencies:

$$\sigma_x^{н/в} = N_x \pm \frac{6M_x}{h^2} ; \sigma_y^{н/в} = N_y \pm \frac{6M_y}{h^2} ; \tau^{н/в} = T_{xy} \pm \frac{6M_{xy}}{h^2} \ , \tag{6.8}$$

where:

h — shell thickness;

B and *H* — are indices indicating belonging to the upper and lower surfaces.

6.4 DCF IN SOLID ELEMENTS

The criterion for determining dangerous combinations of stresses in the general case of Stressed Deformed Condition (SDC) is the extreme values of the average stress (hydrostatic pressure) and the main stresses of the deviator. The slope angles of the principal stresses in each element for each load case are determined. The calculations are carried out according to the following formulas:

$$
\begin{aligned}
&\sigma_{\text{™}} = \sigma_x l^2 + \sigma_y m^2 + \sigma_z n^2 + 2\tau_{xy} lm \; + 2\tau_{xz} ln + 2\tau_{yz} mn; \\
&\sigma_{\text{™}} = \sigma_0 + S_{\text{™}}; \\
&S_x = \sigma_x\left(1 - \frac{1}{3l^2}\right); S_y = \sigma_y\left(1 - \frac{1}{3m^2}\right); S_z = \sigma_z\left(1 - \frac{1}{3n^2}\right); \\
&S_{\text{™}} = S_x l^2 + S_y m^2 + S_z n^2 + 2\tau_{xy} lm \; + 2\tau_{xz} ln + 2\tau_{yz} mn
\end{aligned}
\tag{6.9}
$$

where:

σ_ϕ — normal stress on the direction with direction cosines *l*, *m*, *n* to the X1, Y1, Z1 axes;

S_ϕ — is the normal stress of the deviator on the same direction;

$\sigma_0 = \frac{(\sigma_x + \sigma_y + \sigma_z)}{3}$ — average stress.

The selection process is organized as follows. For this element, the direction cosines of the main areas are calculated for all load cases. If *n* load cases are specified in the scheme, then *3n* directions will be found. Then the stresses from all loadings on these directions are calculated and the accumulation of positive and negative stress values is performed.

In accordance with this, the criteria are designated as three-digit numbers. The first two digits indicate the ordinal number of the load case, on the on these directions of which the stresses from all load cases are calculated. The third digit can take values from 1 to 6, which are given the following meaning:

- 1 —total positive value of stresses on the first main direction;
- 2 — total negative value of stresses on the first main direction;
- 3 and 4 — the same on the second main direction;
- 5 and 6 — the same on the third main direction.

So, for example, criterion 143 means that the largest positive stress was obtained on the second main direction of the 14th load case. Criterion 076 means that on the third main direction of the 7th load case, the greatest negative stress was obtained.

The criteria corresponding to the highest and lowest values of the average stress are defined by the numbers 7 and 8, respectively.

6.5 DCF IN SPECIAL ELEMENTS

The criterion for determining dangerous combinations in special (single-noded FE 56 and two-node FE 55) elements is taken to be extreme reaction values.

For FE 55 and 56, the criteria are numbered from 1 to 12, corresponding to the indexing of efforts in this FE.

For peripheral soil elements (FE 53, 54) DCF is not calculated.

6.6 DFC UNIFICATION

Unification in SP LIRA10 means the union of a group of finite elements with identical properties (material parameters and section dimensions) into a single unified element. Unification is carried out on the basis of DCF. From the calculated values of each DCF criterion, the largest is selected and assigned to the unified element. Unification is expedient in the design of elements and allows them to obtain a common design solution.

There are two types of unification implemented:

- **type 1** — a group of elements, having the unified cross section for entire group; at the same time, each rod element in this group has a design section of the same length;
- **type 2 —** a group of elements having the same design sections in ascending order of numbers of design sections, that is, a group of elements has the same first sections, the same second, etc. design sections.

For bar finite elements, both types of unification are applicable. For planar and solid FE, the 1st type is applicable, since these finite elements have a single design section.

The **DCF Unification mode** is called by the  button on the toolbar.

The **DCF Unification mode** panel contains a list of existing groups of unified elements, in which you can change the name of the group and the color of its indication on the screen. Below the list of groups is a list of node numbers that make up the current group.

You can choose the type of unification:

- unified cross section for entire group;
- unification by separate cross sections.

Adding a group of unified elements is performed by pressing the corresponding button, also, if necessary, it is possible to change the group of elements, replenish group with elements and delete the group.

6.7 DCL

Calculation of design combinations of loads (DCL) is carried out by direct summation of the corresponding node displacements and forces (stresses) in the elements.

Formation of DCL tables is possible using **User-defined combination** (Fig. 6.6) or **Automatic combination** (Fig. 6.7). **Automatic combination** is available for SNiP 2.01.07-85*, DBN V.1.2-2:2006, SP 20.13330.2011, SP 20.13330.2016 norms. For **User-defined combination** in the **Coefficient** column, the coefficient depending on the type of combination and type of load must be manually specified.

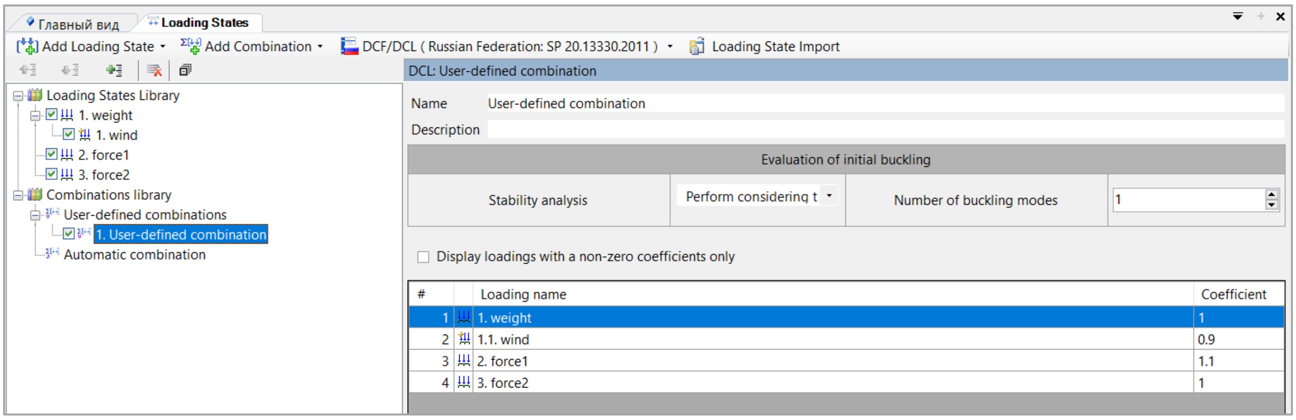

Fig. 6.6. User-defined combination

An automatic combination is created based on the specified initial data for individual load cases. A combination graph will be built, on the basis of which the automatic combinations will be generated using the **Generate combination** button. If the graph has been corrected, you can add combinations that will result from the correction using the **Add new combinations to the list** button.

The display of graph vertices is given in two forms: the full name of the load case or its ordinal number in the library. You can select the type of graph display using the **Names of loading states / only numbers** switches.

If the load cases have been added/removed/disabled in the load library, you need to click on the **Rebuild graph** button in order to get the actual graph.

The list of generated load combinations can be found in the **Combinations** tab. By selecting a line with a combination of load cases and calling the context menu, you can copy this combination to a custom combination of load cases.

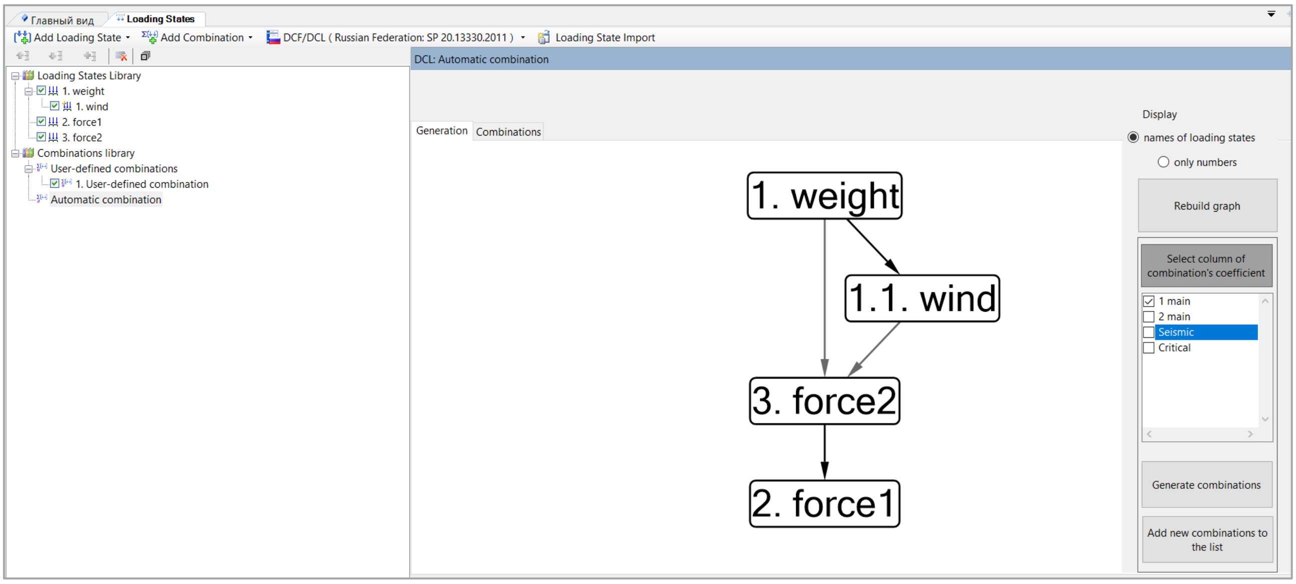

Fig. 6.7. Automatic loads combinations