Panels With Complex Perforation Patterns:

Analysis of Mechanical Behaviour Under External Loads

Perforated panels, broadly used in civil and building engineering, must satisfy a number of requirements, one of them being able to withstand, without destruction, a variety of mechanical loads, such as wind pressure. A mechanical load leads to internal stresses to appear in the panel, and if the maximum stresses exceed the material yield strength, the panel will develop plastic deformations. With further increase of the mechanical loads, fractures may occur. The result could be a partial or complete loss of the panel integrity.

A variety of perforation patterns are commonly used in panels manufactured on industrial scale. Perforations may have circular, slotted, rectangular, and hexagonal and some other shapes; they can be placed at different distances from each other, and also may have different geometrical dimensions.

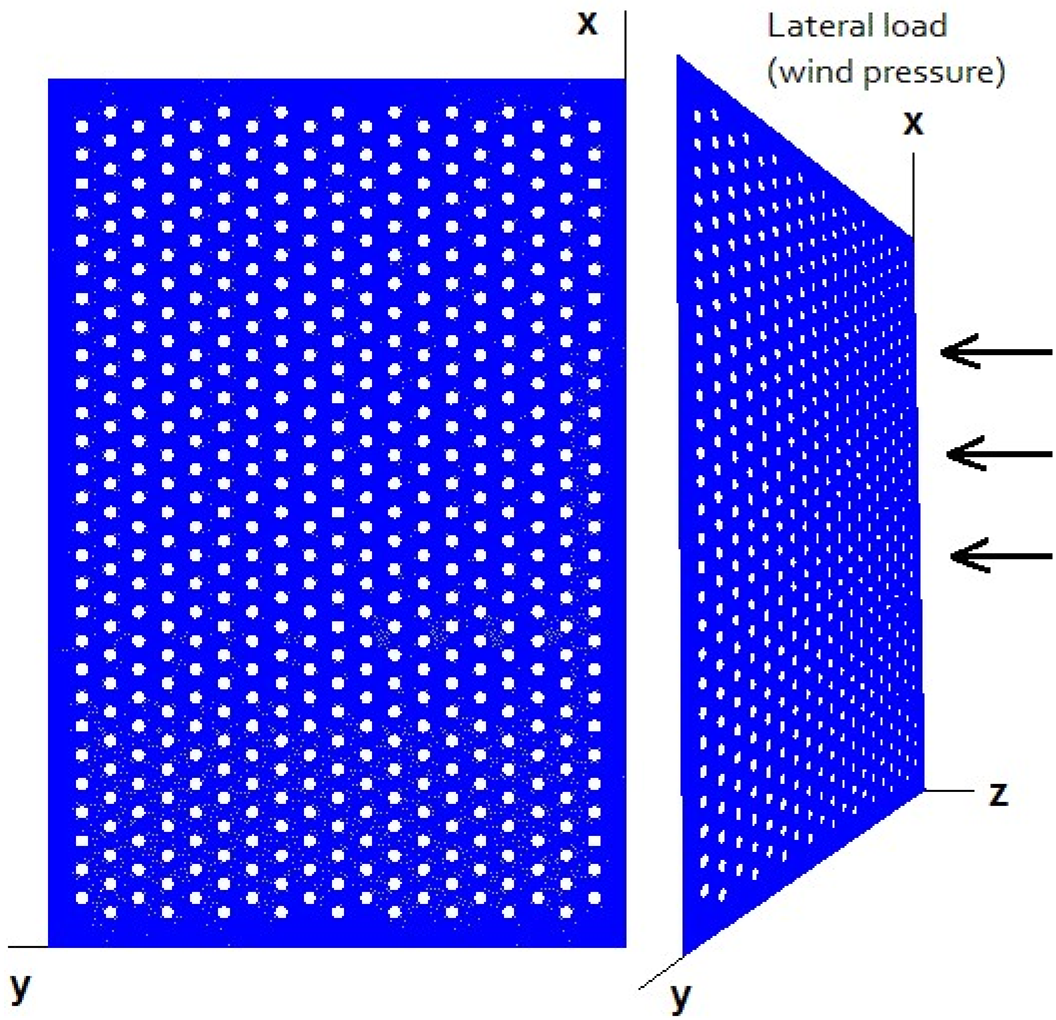
In this White Paper, we investigate the influence of differences in perforations' shapes and sizes on the *stress distribution* inside the panels, in order to accurately *predict the values of maximum stresses*, as well as *their locations*, with the ultimate goal: to exclude all uncertainties regarding the structural integrity of the panels with different perforation patterns, and therefore to ensure that for all cases (different geometrical dimensions, different materials used, different thickness, different loading conditions) quality numerical analysis and predictions can be made, thus giving the engineers and designers a powerful tool providing reliable stress and deflections evaluation results.

Accurate mathematical analysis of perforated panels is required for determining the correct deflections, bending and twisting moments, shear forces and stresses.

We consider a number of examples: with circular, slotted and hexagonal openings, and demonstrate where the mechanical properties of the panels are similar, and where they differ from each other.

As a first example, consider deformation of a **2** by **3** meters perforated aluminium panel with staggered pattern of circular holes. The panel is *simply-supported* on all four edges and is subjected to lateral wind load. We assume that the panel is made of some aluminium alloy, which would allow us to select specific values of the material constants. The list of the model parameters is as follows:

- the Young's modulus **E = 71 GPa**
- Poisson ratio **v = 0.34**
- material thickness **h = 3 mm**
- lateral pressure **p = 375 Pa** (which corresponds to wind speed of 25 meters per second)



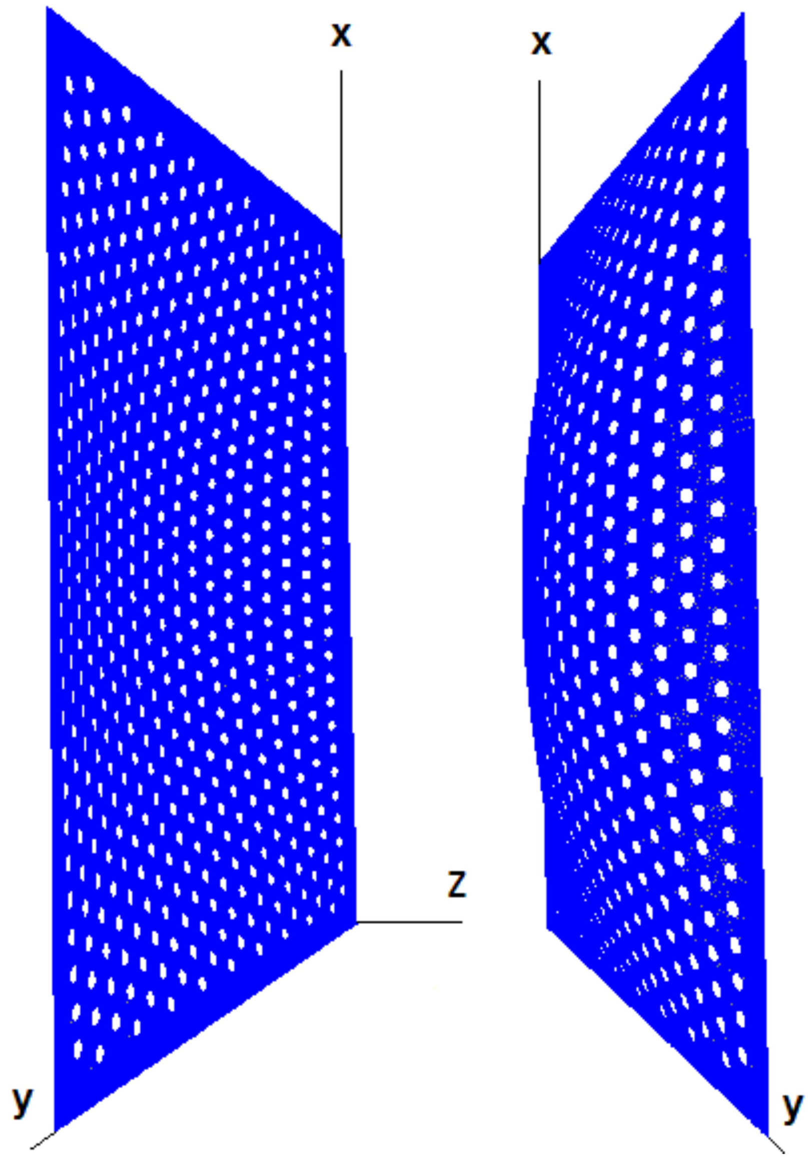
On the next several pages we present and discuss:

- the panel deformed state,
- distribution of bending moments **Mx**, **My** and twisting moments **Mxy** over the whole panel,
- distribution of shear forces **Qx** and **Qy** in the vicinity of one of the panel corners, and
- von Mises stress contours.

In order to obtain the results, we used Finite Element Analysis software

designed specifically to process plates with large number of perforations.

First, we discuss the deformed state of the panel. As expected, the panel manifests deflection in the directon *opposite to the positive direction* of the Z-axis, i.e. in accordance with the wind load. It should be noted that in this example we deliberately assumed rather "loose" boundary conditions along the panel edges: the edges are supposed to be fixed so they cannot move in the Z-direction, but at the same time angular rotation around the edges is allowed. Whereas a more realistic boundary condition would be a complete restraint of the edges, we deliberately consider a *simply supported* panel first, in order to demonstrate *how drastically the distribution of stresses, as well as their values, depend on the quality of the attachment of the panel edges to the supporting rails.*

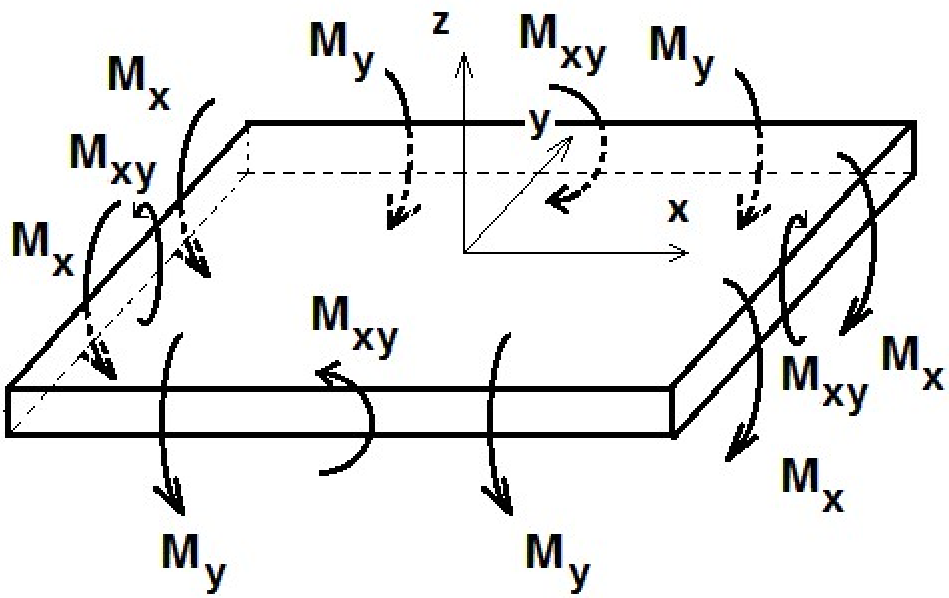


Now we turn to analysis of internal stresses in the panel. A usual ("pre-computer era") approach, which models the perforated panel as a continuous plate with reduced stiffness, would work for approximate analysis of deflections only. However, it is unsuitable for stress analysis, since the stresses are expected to manifest higher values precisely due to the presense of perforations, and in close vicinity of the latter. Therefore, the Finite Element Analysis becomes the only viable option.

Ultimately, our goal is to examine *whether the panel has sufficient strength to withstand maximum possible mechanical loads* without plastic deformations and/or without destruction. The stress parameter we are looking for is the *von Mises stress*. Comparing it with the material yield

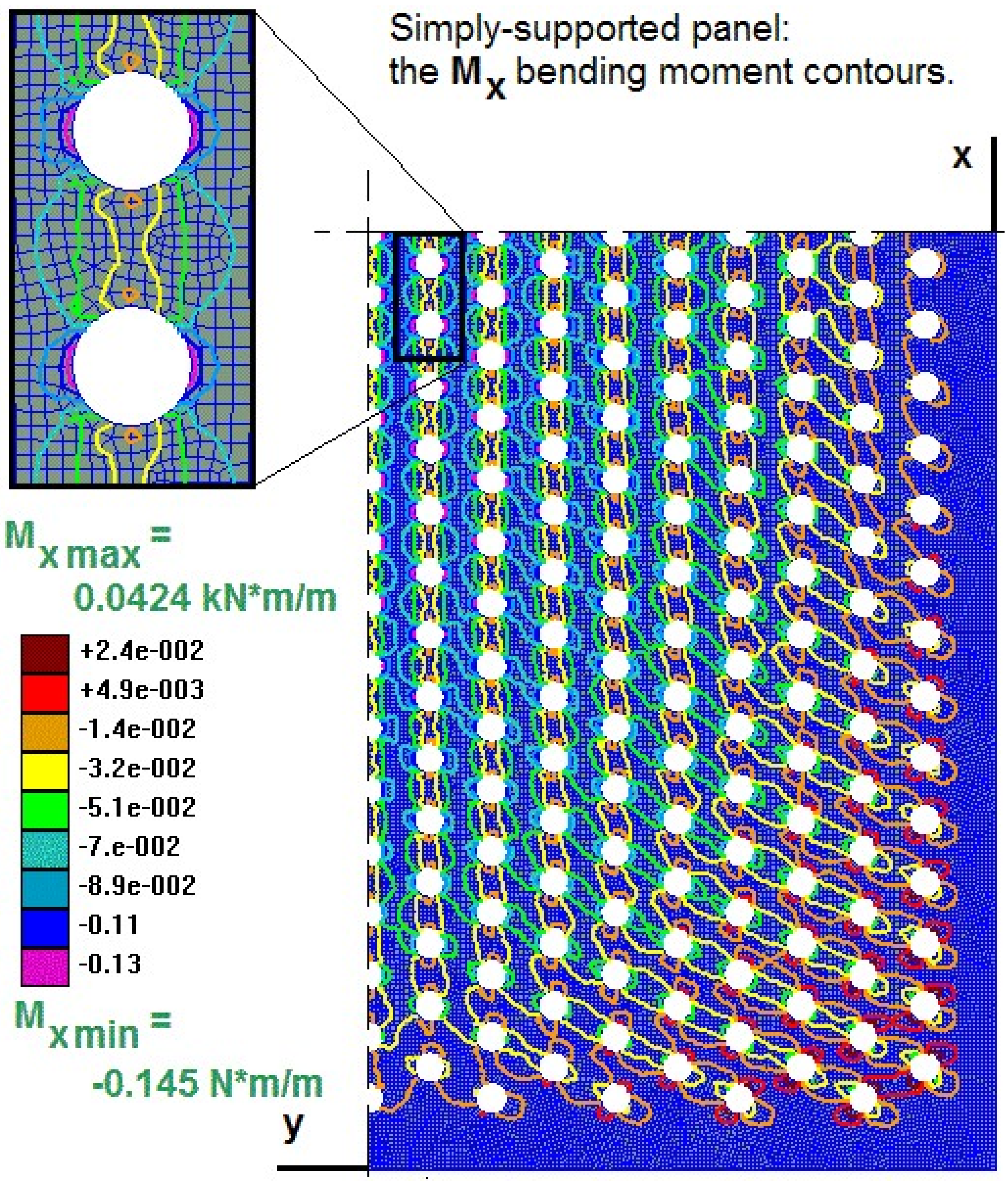
strength would allow us to predict whether the material would experience plastic deformations or not.

In turn, finding the von Mises stresses in the panel is based on evaluation of several parameters listed above, namely: the bending moments, twisting moments, and shear forces. We present several images containing contours of the moments and forces, which would allow us to make several important conclusions. We assume the standard approach to the definition of internal moments and forces, as shown in the image below.



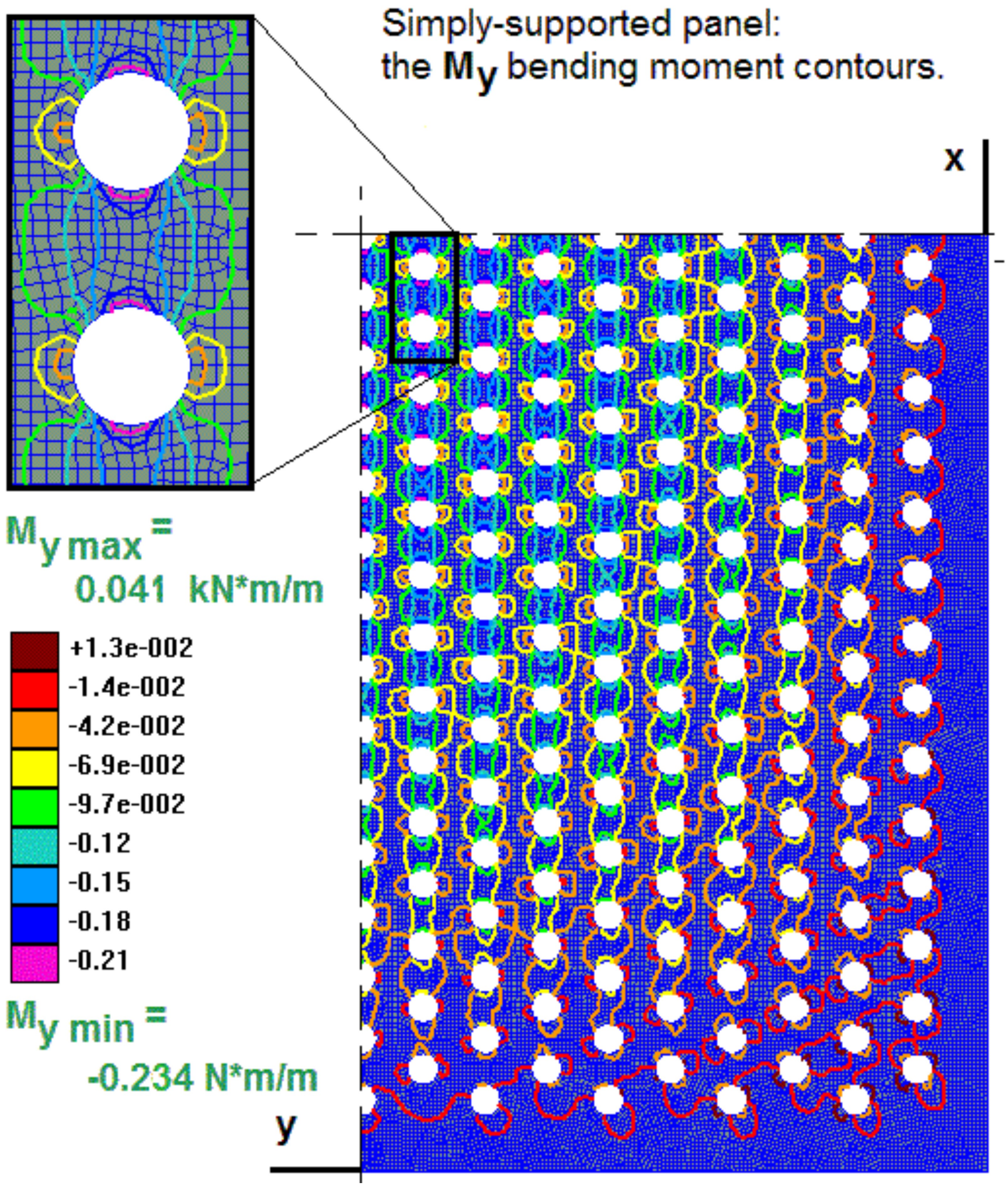
Bending and twisting moments (positive directions shown)

In particular, we observe that the standard definition of bending moments assumes the latter being *positive* if the upper fibres of the panel are in the state of *tension*; conversely, the moments are negative if the upper fibres are *compressed.* The latter is the case for all our examples, since the lateral (wind) load is applied in the direction opposite to the Z-axis, so the fibres in the upper layer of the panel are compressed.



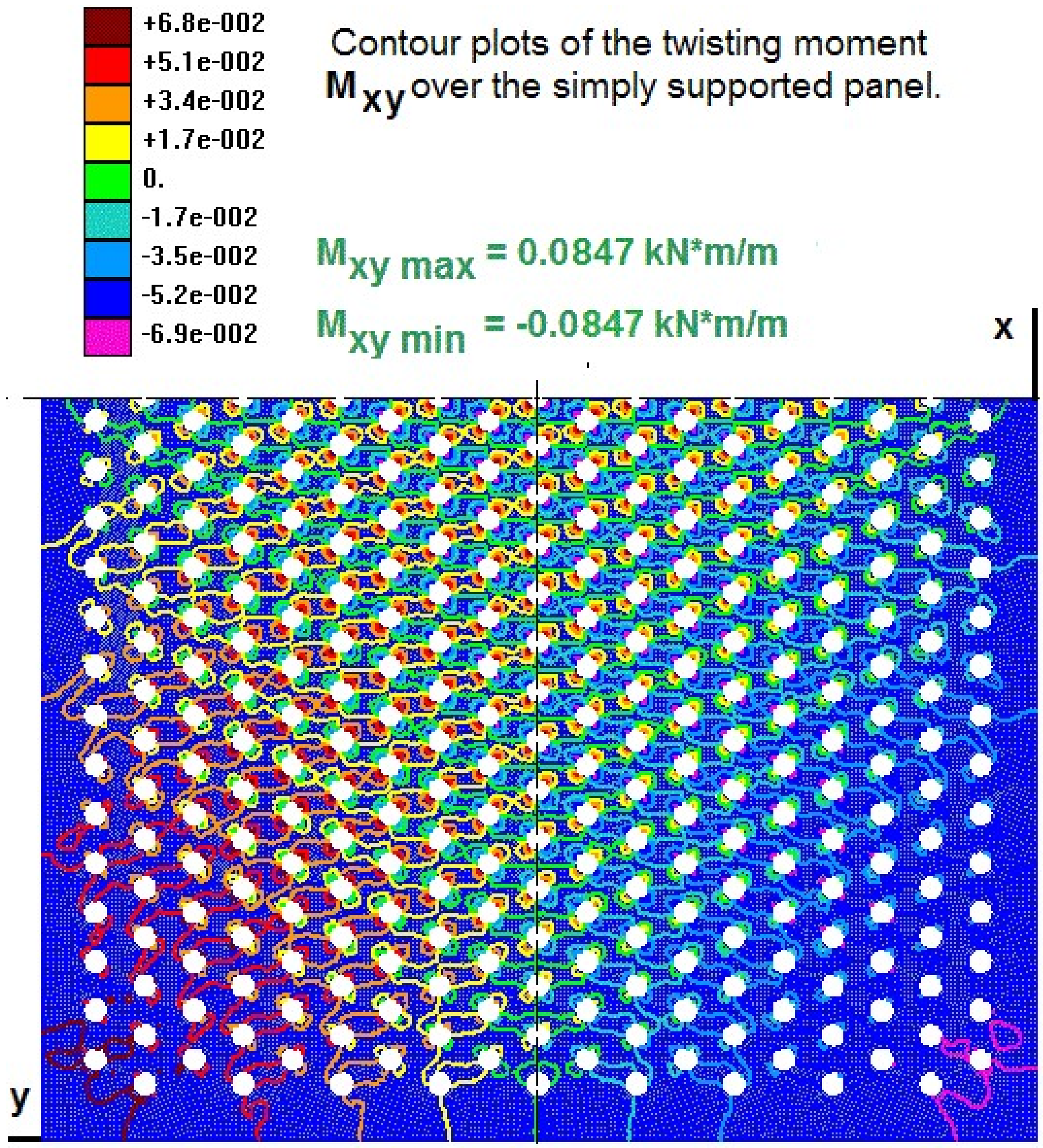
Since each of the **Mx** and **My** contours manifests complete symmetry with respect to both axes of symmetry of the panel itself (i.e. the axes drawn through the geometrical center of the panel), we provide pictures for just a quarter of the panel, for better scaling and clarity.

The maximum (by absolute value) bending moments are observed in the vicinity of the openings located in the central part of the panel. This statement is correct to both **Mx** and **My** bending moments.

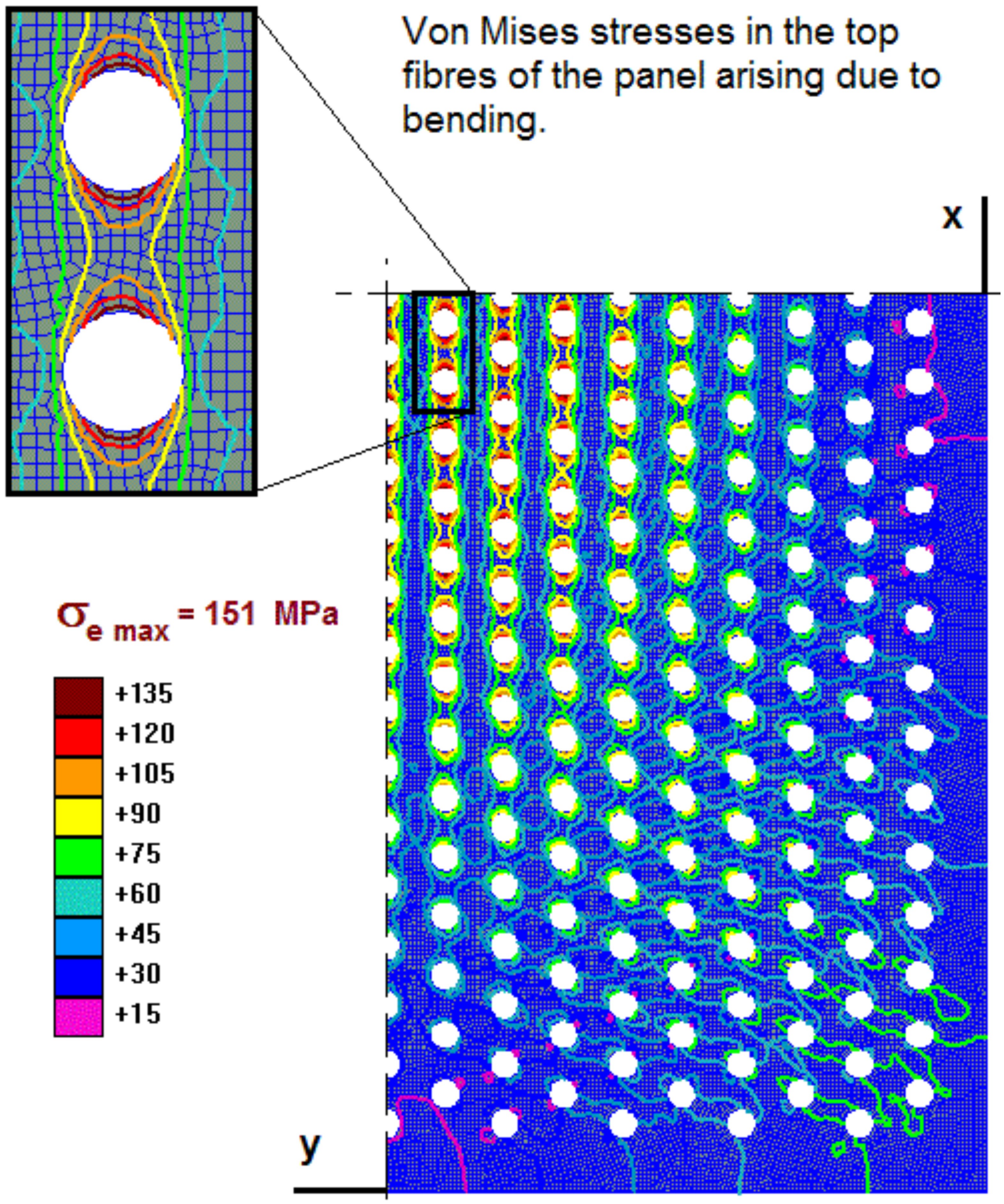


However, the twisting moments' contours (presented on the next page) are symmetrical not with respect to the axes of symmetry of the panel, but with respect to the center point of the panel. We provide the picture of the

contours for one (the lower) half of the panel; contours on the upper part can be obtained by rotating the picture around the center point by 180 degrees.



The twisting moments manifest relatively uneven distribution; however, their absolute values are significantly smaller than those of the bending moments, and therefore they do not make any significant contribution to the von Mises stresses.

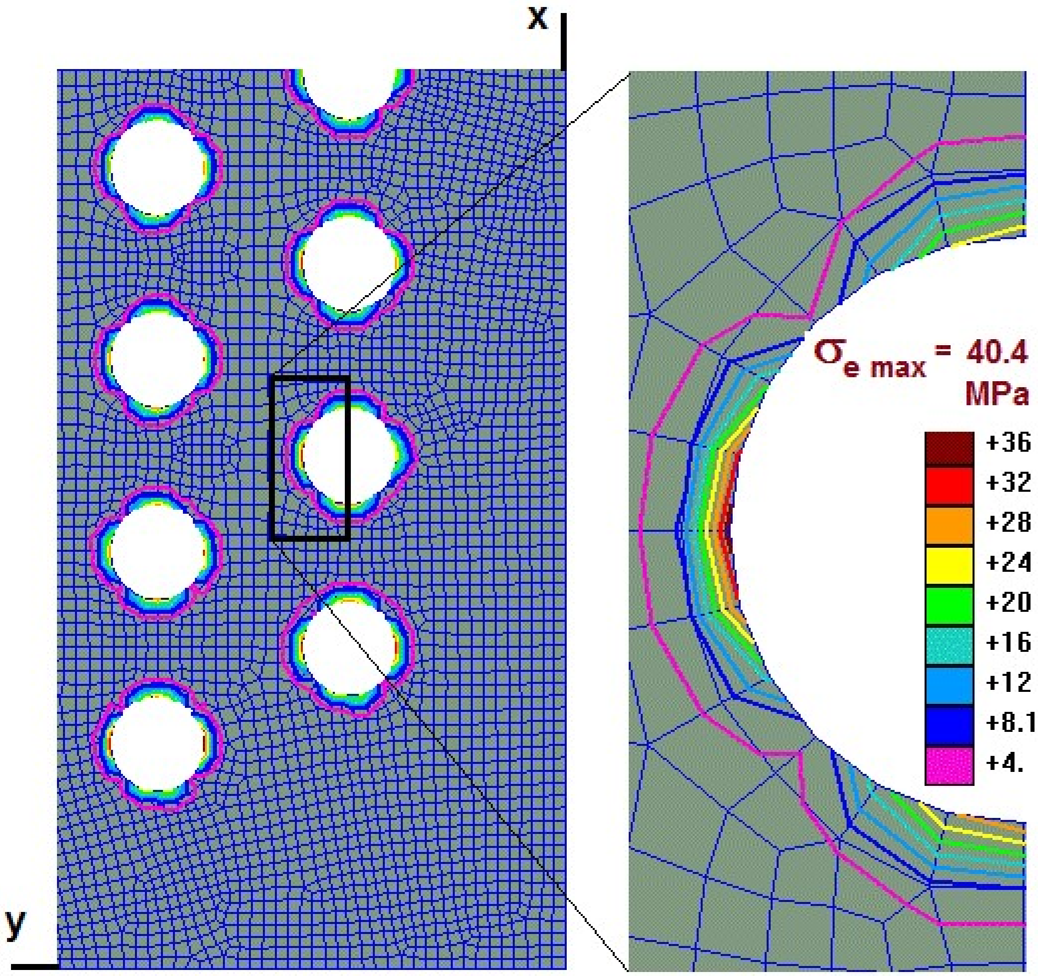


The distribution of maximum von Mises stresses approximately resembles that of the maximum bending moments: the most vulnerable part of the panel is located in its central region. In case when the wind pressure increases, the material will begin to experience plastic deformations first of all in the central part of the panel.

A question of the interal lateral (shear) forces in the panel should also be discussed. Generally, the theory of thin plates ignores those forces and, correspondingly, the stresses caused by them. The numerical experiment, which is discussed here, also demonstrated that the shear stresses have

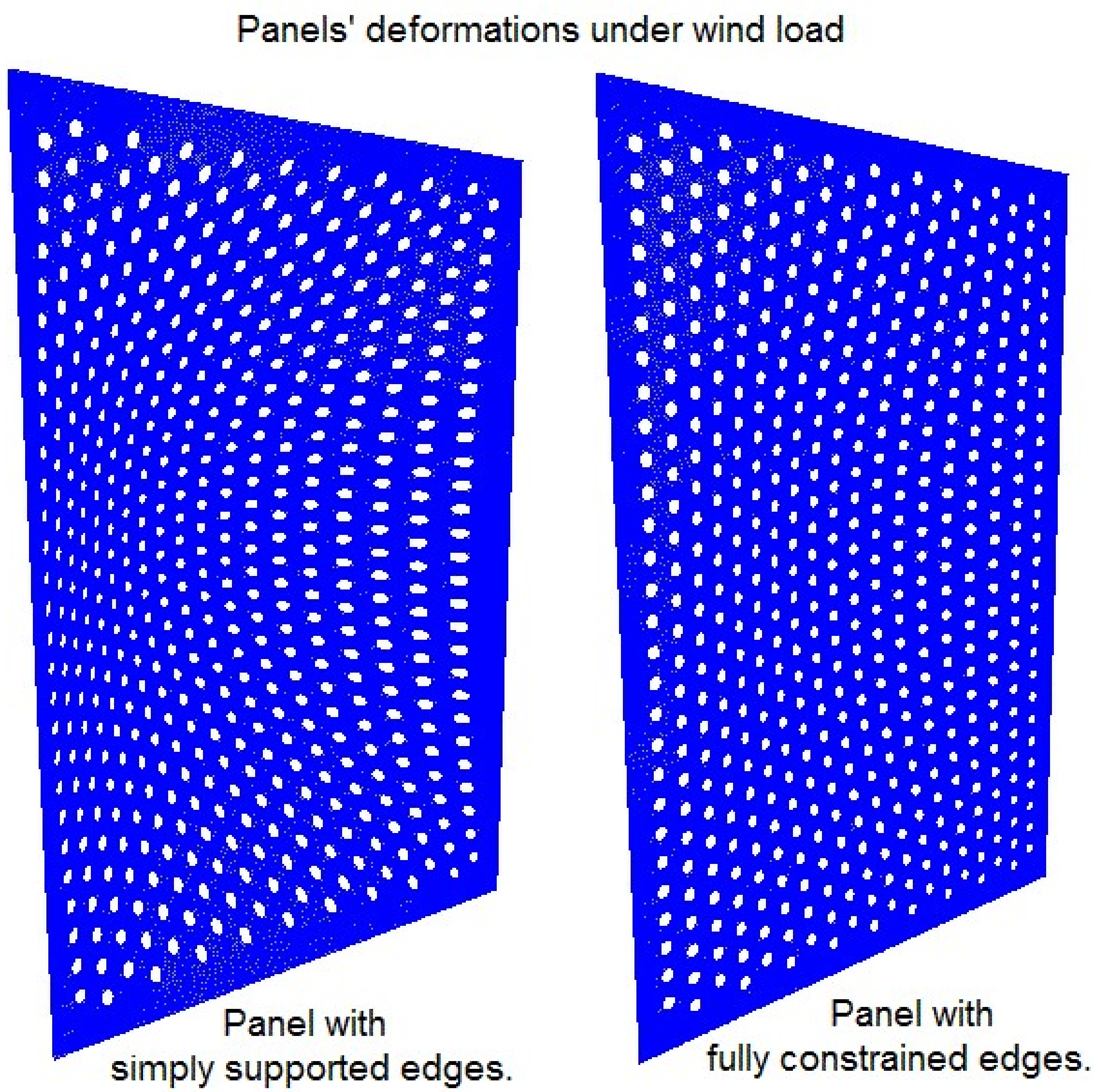
negligible values everywhere except of in close vicinities of the holes. That means that the arising stresses are *local* and therefore their influence on the overall structural integrity of the panel is negligible.

Von Mises stresses arising in the panel midplane due to the shear forces that appear because of the influence of the wind load.



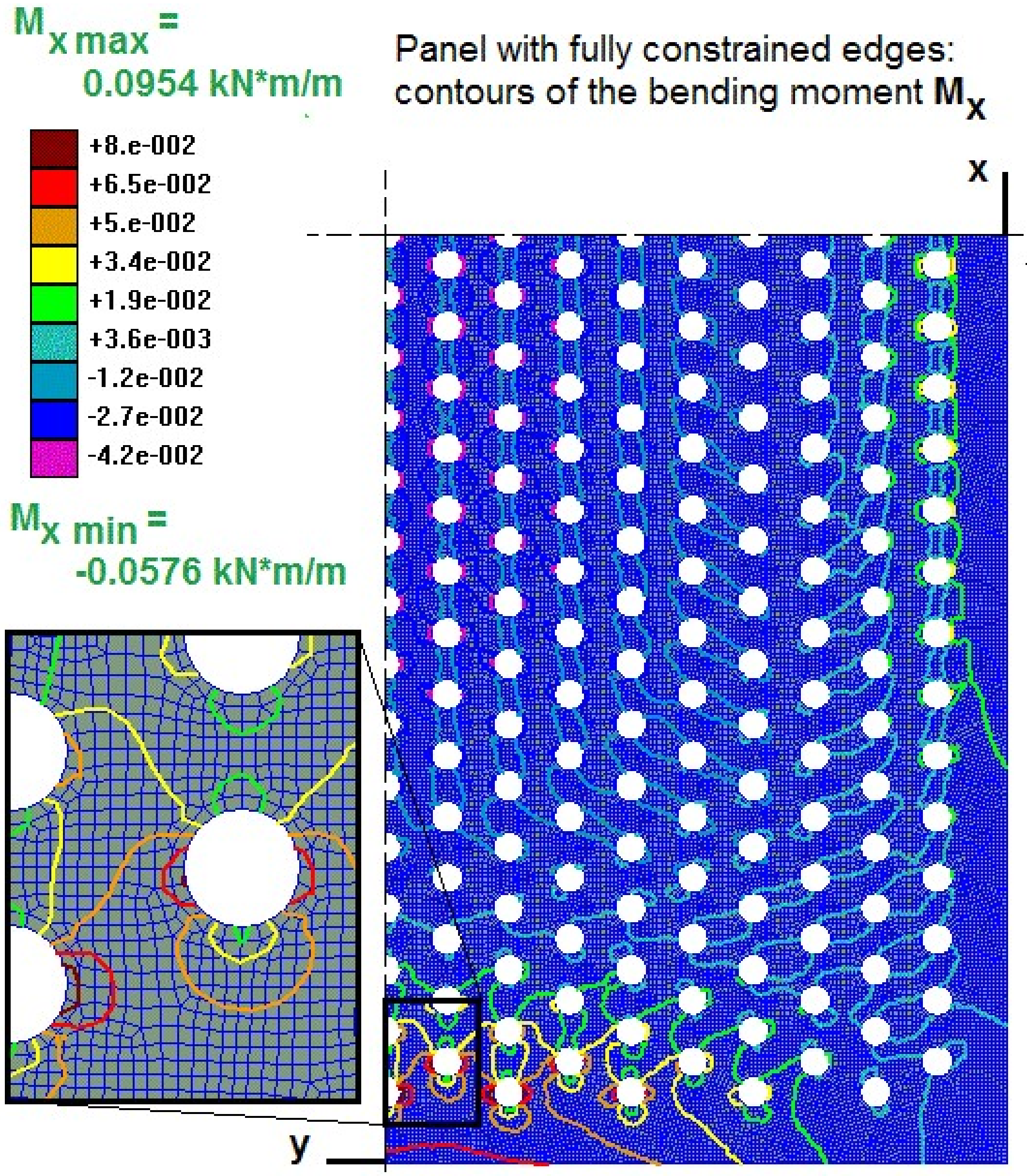
Now we turn our attention to the same panel with different boundary conditions applied: this time we assume that the edges are *fully constrained*

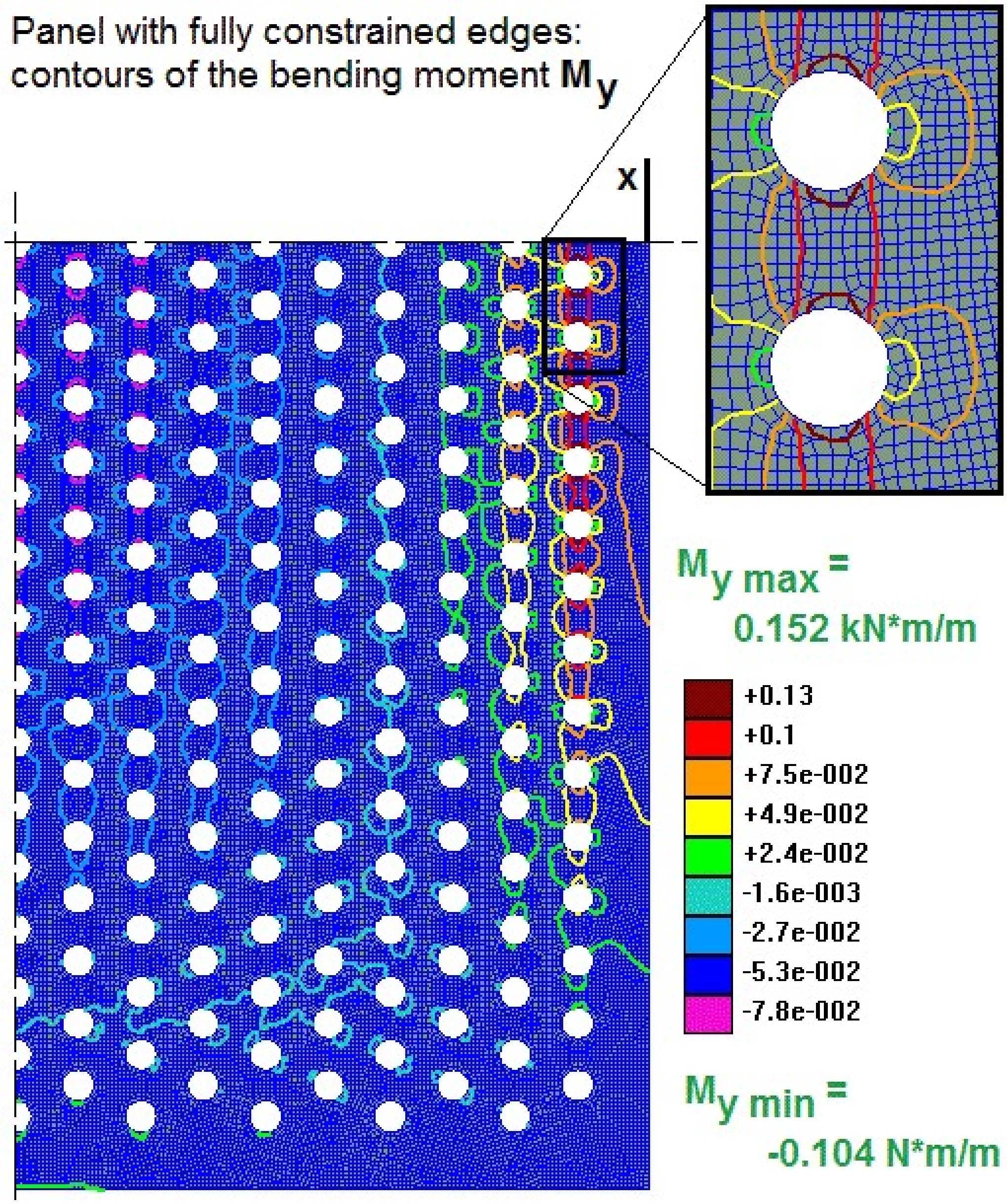
(or "jammed"), i.e. no rotations are allowed around any of the four edges. It is reasonable to suppose that the deflections would be much smaller than in the previous case, provided the lateral distributed load remains the same. For the sake of comparison, we provide images of both deflected panels (where the actual deflections are *scaled up by a factor of three*, in order to make the differences between the two more visible).

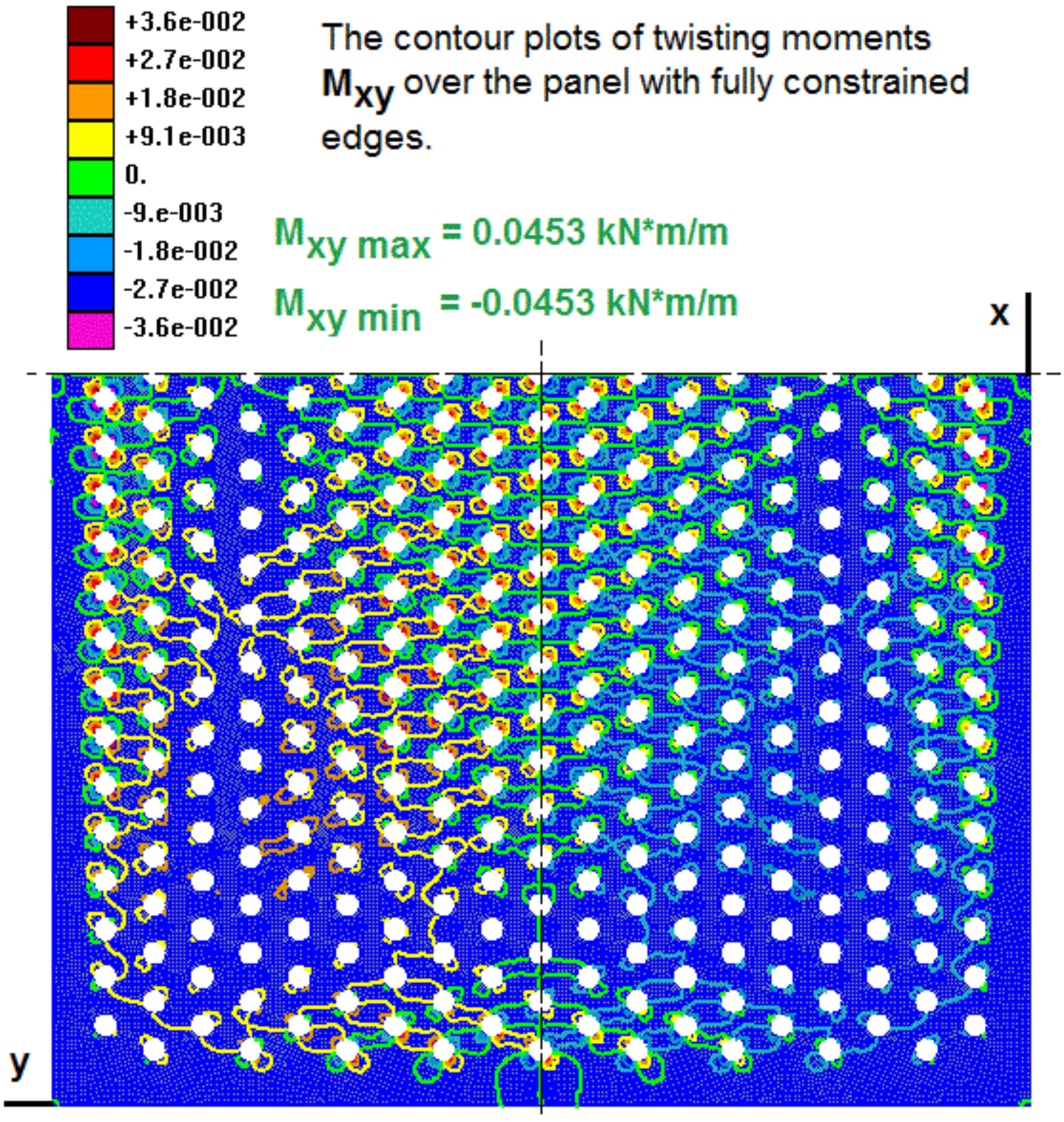


Whereas the deflections follow more or less of the same pattern, the bending and twisting moments as well as von Mises stress distributions in the second case are drastically different from the first one. Everything changes: the

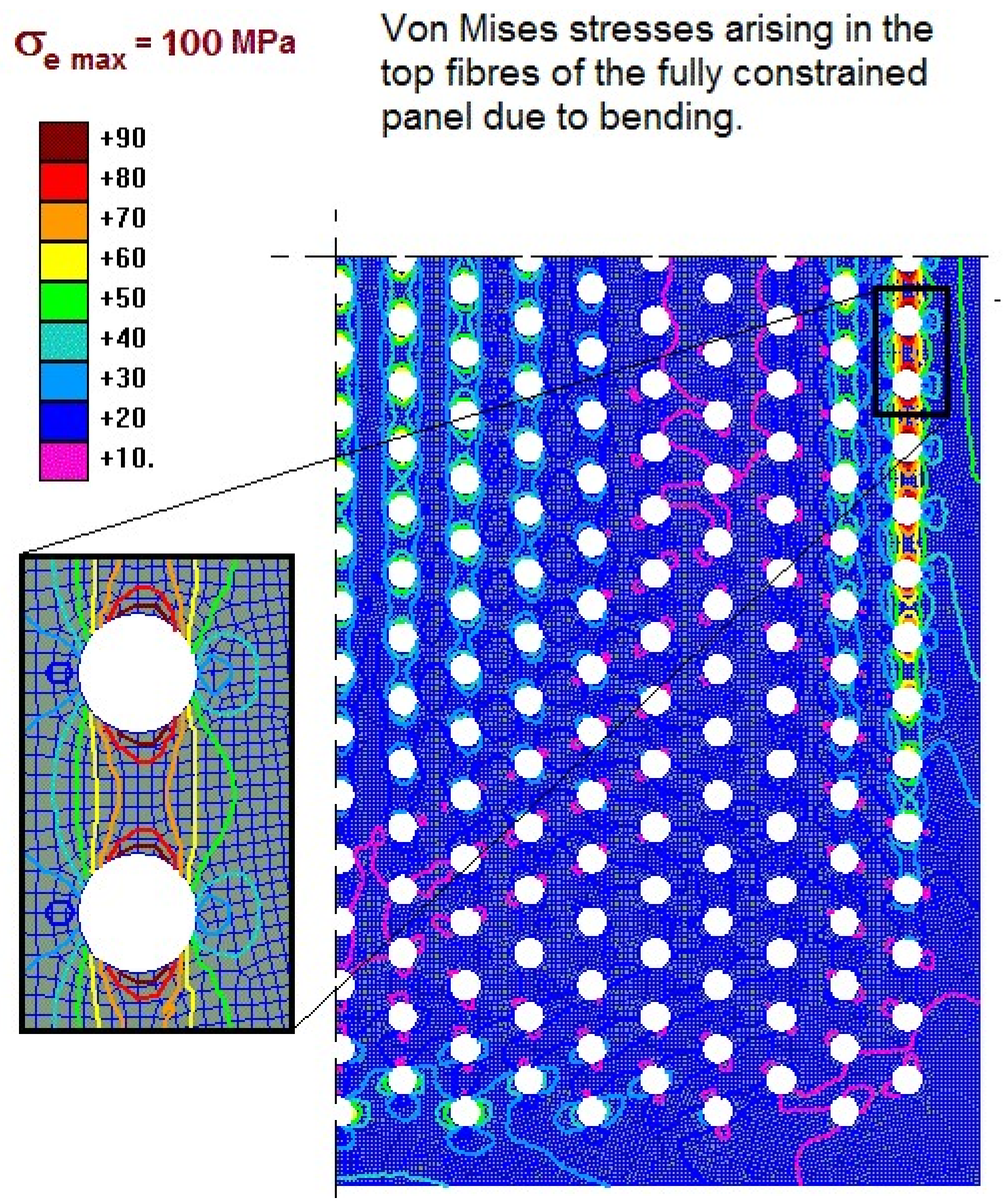
maximum stress values, their location and their gradients. Below we provide images of the contours of moments and stresses, geometrically over the same parts of the panel as before.




Panel with fully constrained edges:
contours of the bending moment M_y
x
$M_{y\,max}$ =
0.152 kN*m/m
+0.13
+0.1
+7.5e-002
+4.9e-002
+2.4e-002
-1.6e-003
-2.7e-002
-5.3e-002
-7.8e-002
$M_{y\,min}$ =
-0.104 N*m/m



+3.6e-002
+2.7e-002
+1.8e-002
+9.1e-003
0.
-9.e-003
-1.8e-002
-2.7e-002
-3.6e-002
The contour plots of twisting moments M_{xy} over the panel with fully constrained edges.
$M_{xy\ max}$ = 0.0453 kN*m/m
$M_{xy\ min}$ = -0.0453 kN*m/m
x
y



Comparing both sets of results: for the simply supported and for fully constrained panel, we can make several important conclusions, which were not obvious before the Finite Element Analysis performed.

1. Whereas smaller deflections in the second case were expected, a drastic difference in the actual stress distribution and location of the most vulnerable parts manifested itself.

In case of the simply supported panel, the largest (by absolute value) bending moments and, correspondingly, the largest von Mises stresses are observed in the central part of the panel. From the mechanical point of view,

it means that the material is likely to yield (and, eventually, lose structural integrity) around the openings located near the central part of the panel. In other words, the locations of maximum deflections and maximum von Mises stresses primarily coincide.

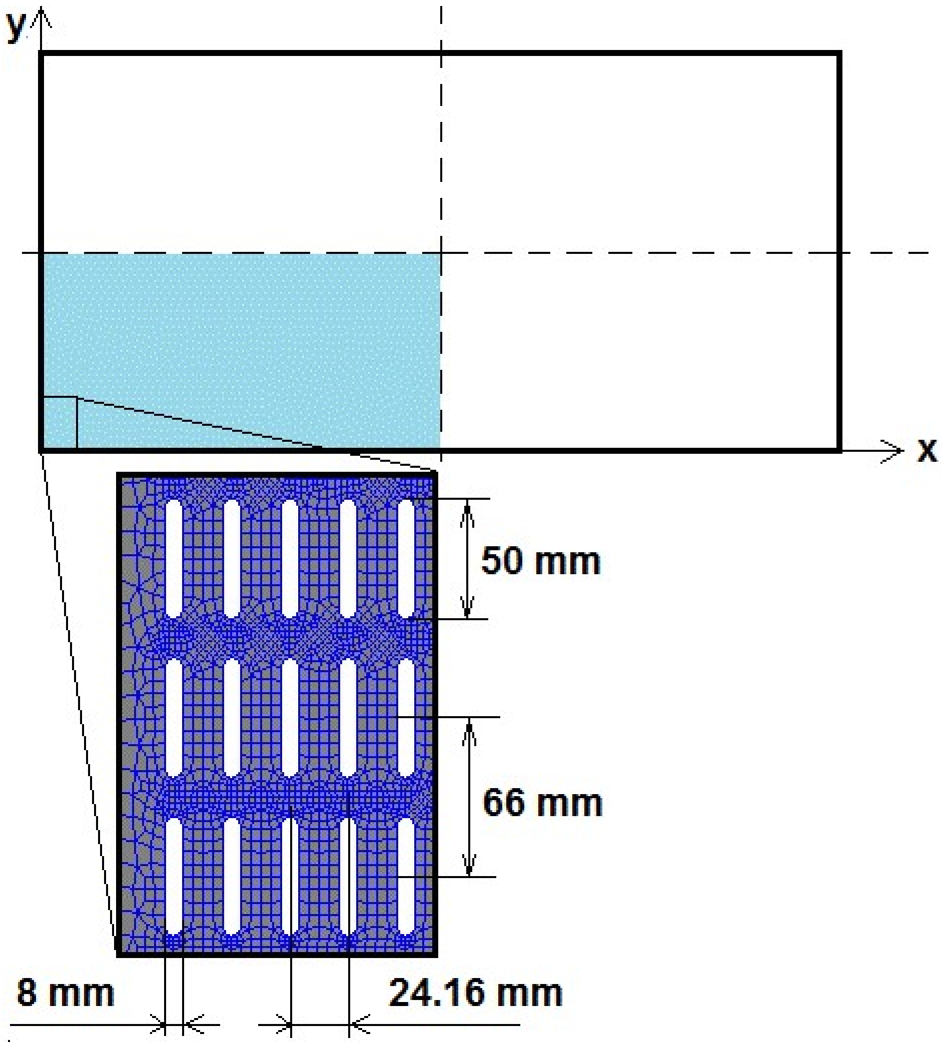
When the panel is fully constrained, the maximum deflections, again, are observed in the central part. However, this time the largest stresses are located in a totaly different place, namely along the row of holes which is closest to the longest edges. In practice it means that, should the wind pressure increase, the material will most certainly yield along that row of holes; or even a crack along those holes is likely to develop.

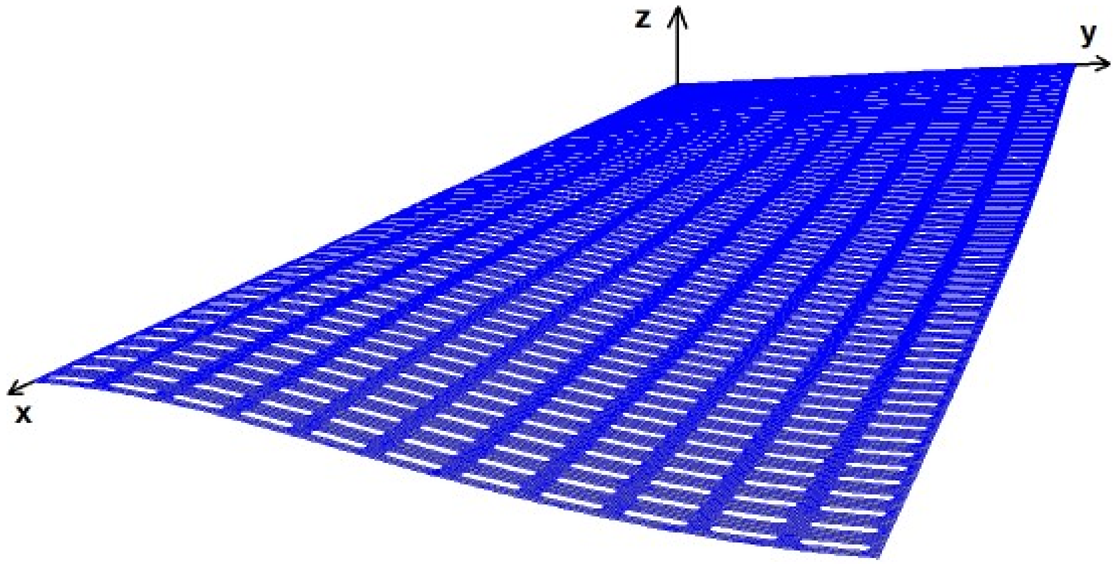
2. It is known from the mechanics of plates that normal stresses appear in the top and bottom fibres of the panel due to two bending moments **Mx**, **My** and the twisting moments **Mxy**. In turn, the von Mises stress is calculated at each particular point, using those three values. If at a particular point on the surface the von Mises stress exceeds the yield strength of the material, plastic deformations (and, possibly, a crack, if the load increases) would develop. As it can be seen in the second example, the localization of areas where the moments **Mx**, **My** and **Mxy** reach maximum, are very different. The maximum values of **Mx** are observed along the row of holes parallel to the short edge of the panel; the maximum values of **My** are observed along the row of holes parallel to the long edge; the twisting moments **Mxy** are distributed rather unevenly. Nevetheless, the von Mises stress, calculated as described, provide precise locations of possible material failure, namely: between the holes of the row closest (and parallel) to the long edge of the panel.

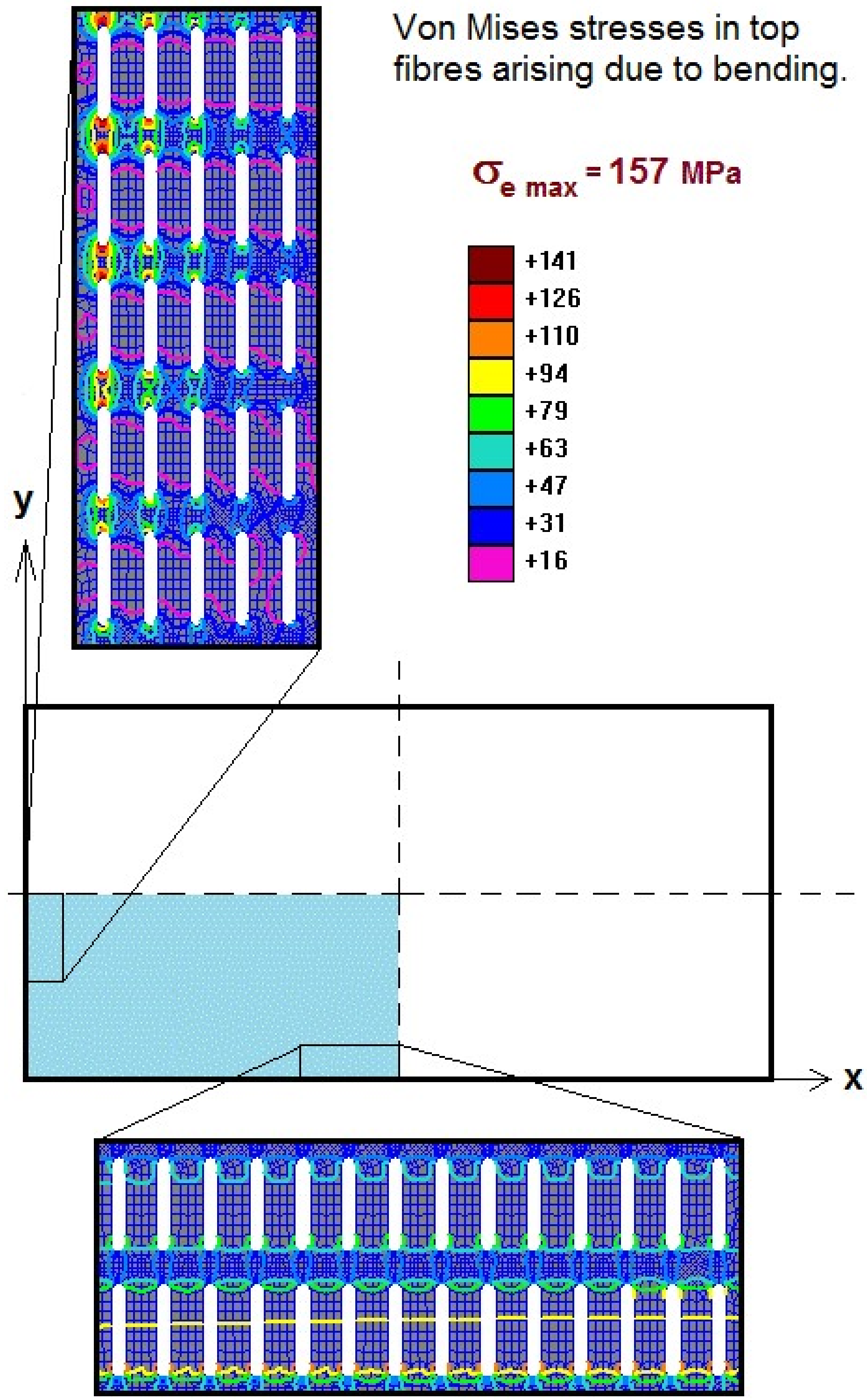
3. Another observation to be made is that, because of the wind load, a narrow area of the material around each hole experiences shear forces with rather large gradients. However, that area is local, and the maximum von Mises stress in the midsurface is smaller than the von Mises stresses in the top and bottom fibres. In the light of the above, we conclude that the shear forces do not play any significant role in this case, and we can safely limit our investigation to the analysis of stresses arising due to bending only.

Real-life panels may have perforations with much smaller dimensions and placed very close together. Our next example is devoted to modeling of such panel, manufactured and broadly used in practice. Consider a steel panel with slotted perforation pattern, as shown in the image below. Due to its size (**2833**x**1452** mm) we will perform stress and deflection analyses of

one (bottom-left) quarter of the panel, having imposed the corresponding constraints so that the model, as well as its mechanical behaviour, retain symmetry with respect to the two perpendicular axes drawn through the center point of the panel.




z
y
x

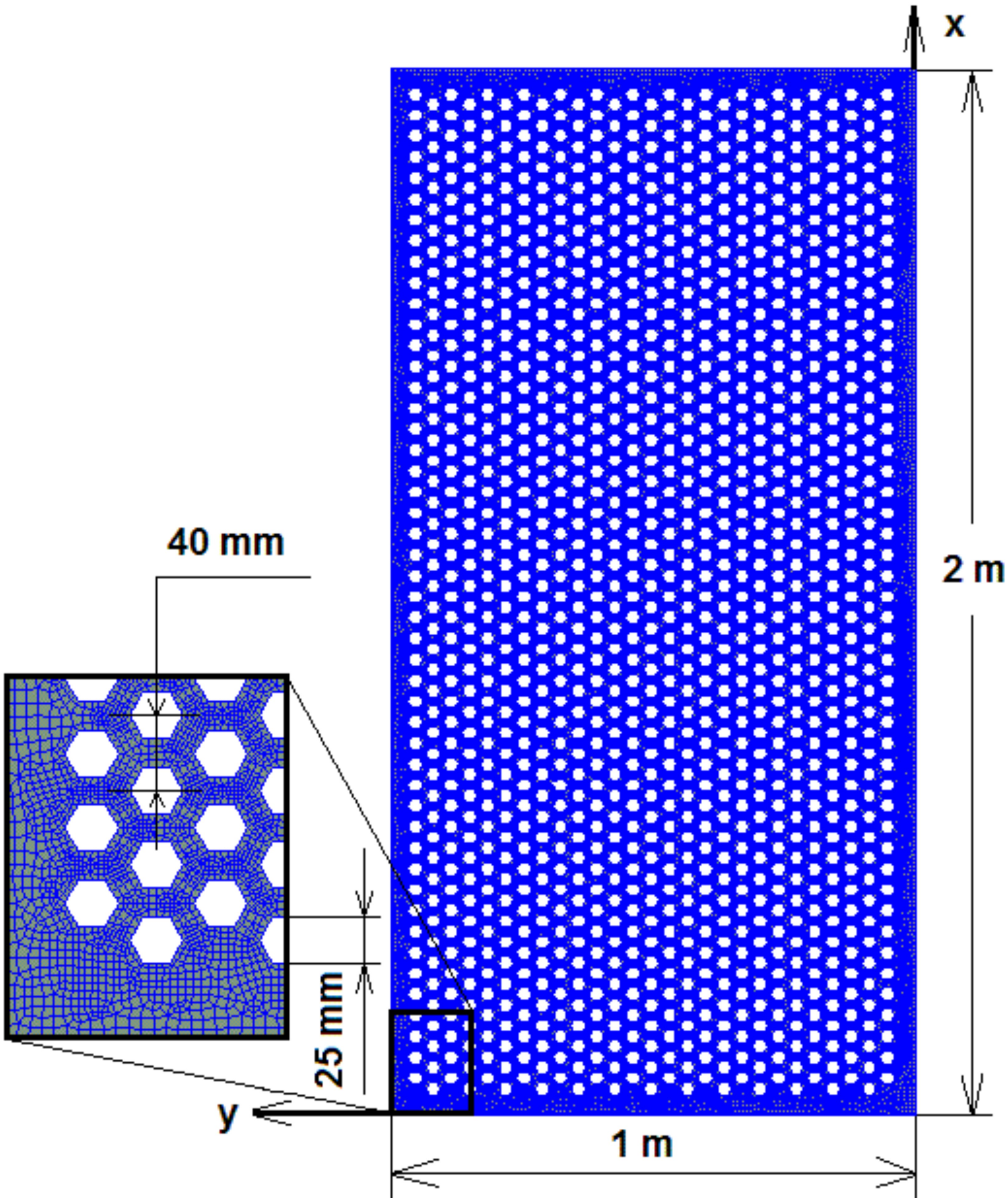


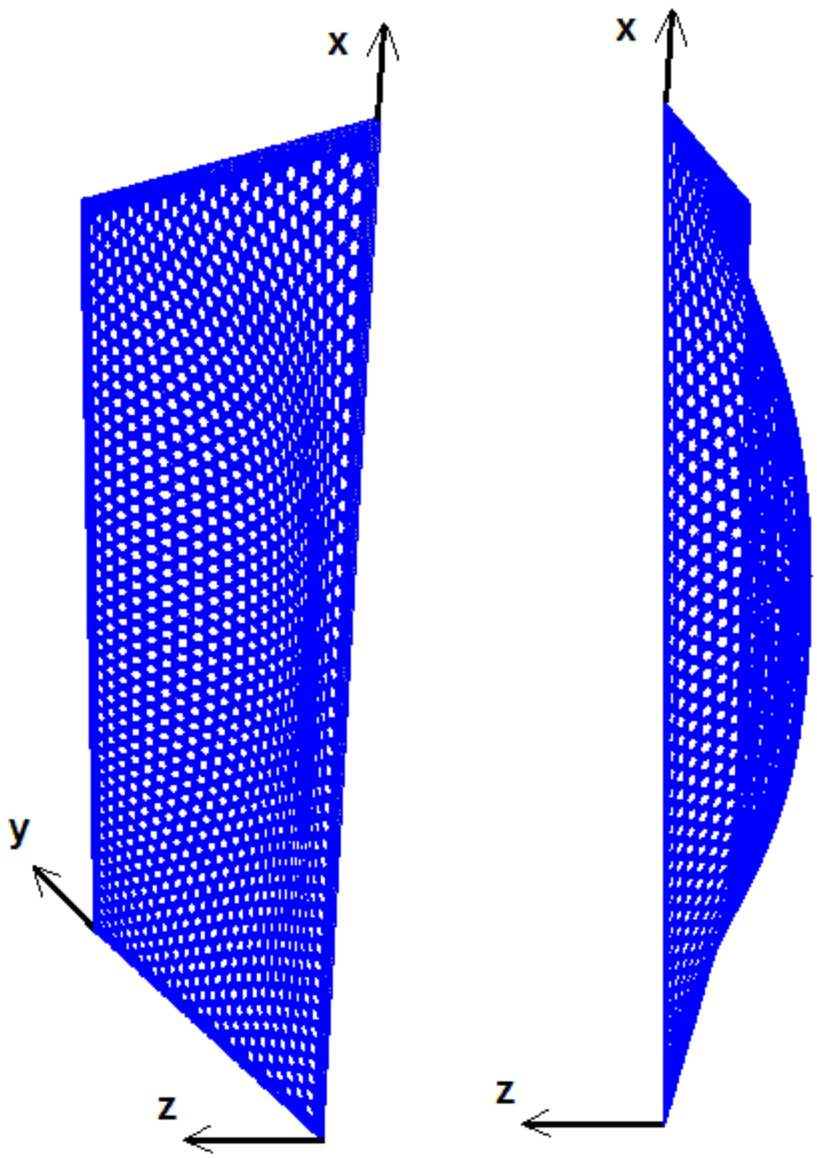
The deformed state of the panel demonstrates the expected shape: the central part experiences largest deflections in the direction opposite to Z-axis. However, this time the maximum von Mises stresses are observed not

along the long edges, but along the short edges. This result is solely attributed to the perforation pattern: maximum stresses are observed where the material in the vicinity of long-and-narrow openings experiences large bending moments, and also because the openings are located close to each other.

Von Mises stresses near the long edges of the panel, although increasing as well, do not reach the maximum values observed between the openings along the short edges: the difference is about 30%.

Our last example is devoted to panel with hexagonal openings. We consider 2000x1000 mm aluminium panel with staggered perforation pattern; geometric parameters of the pattern are presented in the image below. The panel is loaded by the same wind pressure of 375 Newtons per square meter. (Below, we provide an image demonstrating the deformed state of the panel with all the displacements increased tenfold, for better visual inspection.)


x
40 mm
2 m
25 mm
y
1 m



All edges of the panel are fully constrained, so our expectations are that *the highest values of stresses would be observed along the row of openining that are most close to the edges*. Indeed, that turned out to be the case; however, there are several other important observations to be made.

Suppose that the wind pressure increases to such level that the von Mises stresses reach the yield strength of the material. In that case, the material begins to experience *plastic deformations* alond the abovementioned row of openings, practically without any significant increase of the observed stresses. If the wind pressure continues to rise, the stresses in other parts of the panel will grow. The FEA gives an answer to the question: where exactly that is expected to happen. As it can be seen, the next largest values

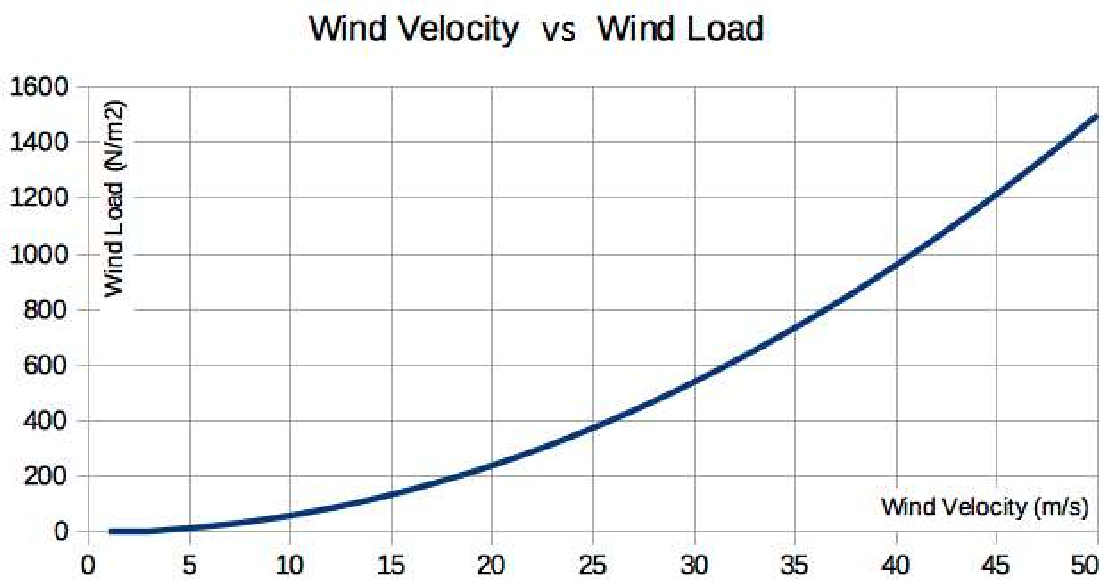
of von Mises stresses are observed in the *central region* of the panel.

Summarizing the above : there are two possible areas where the material

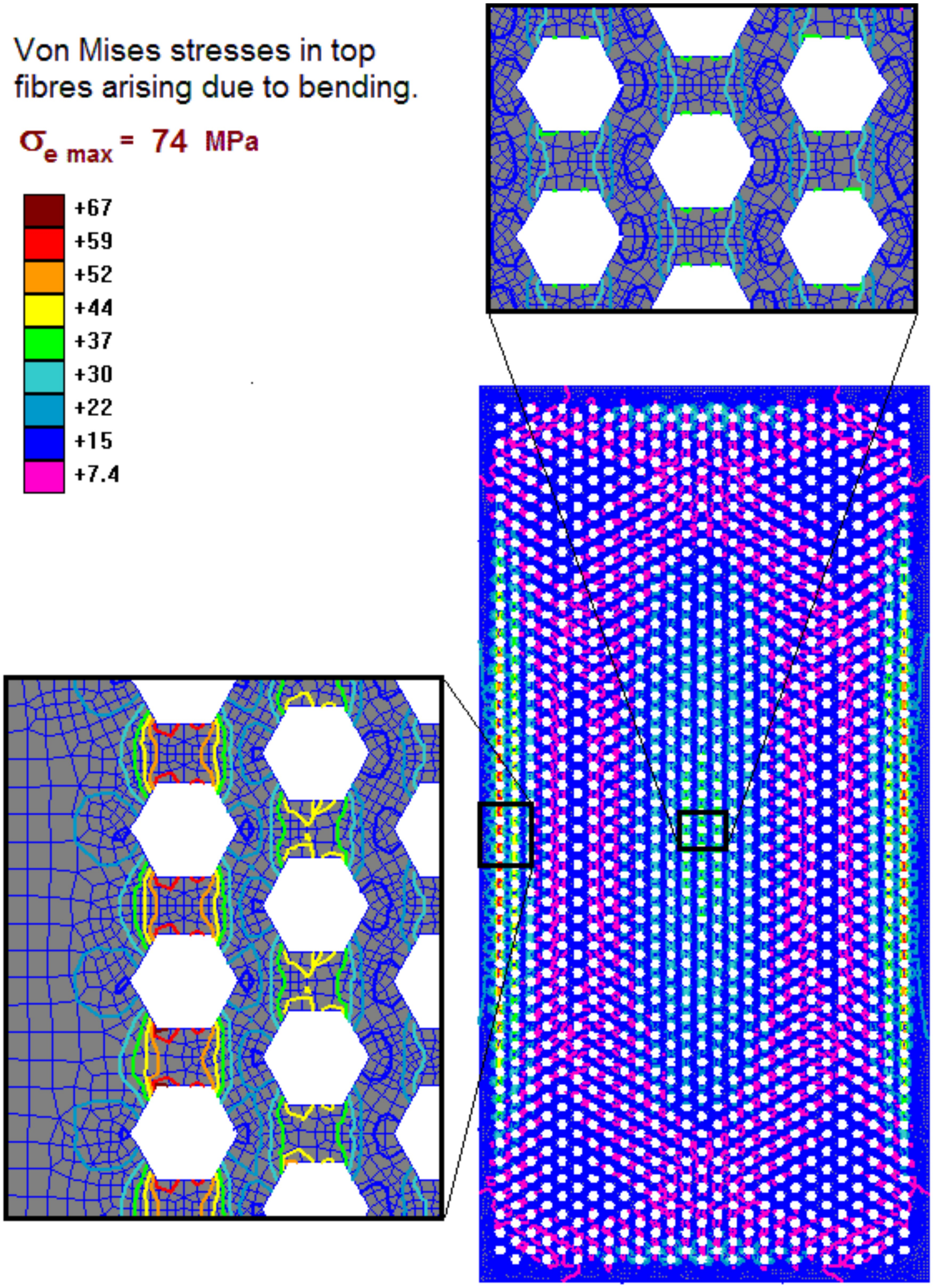
of the panel is likely to experience *plastic deformations* with the wind speed growing: first, around the row of openings along the long edges, and, second, in the central area of the panel.

Therefore, further increase in the wind speed will lead to the material along the left and right vertical rows of openings to behave like virtual "hinges": the central part of the panel will be pushed further inside. Ultimately, the von Mises stresses in the central part will reach the yield strength, i.e. a second zone of plastic deformations will be formed. The panel will ultimately develop a crack in either of those two zones.

The qualitative analysis above can be expanded further, in order to allow some quantitative assessment. For the wind speed of 25 m/s (which corresponds to the lateral load of 375 N per sq.m) the maximum von Mises stresses are evaluated as equal to 74 MPa; the maximum stresses around the center of the panel correspond to the green contours (as seen in the image), i.e. just about 37 MPs. Suppose that the yield strength of the material (approximately) equals the same 74 MPa. Therefore, further increase in the wind speed would lead the central part of the panel to be pushed further inside. When the von Mises stresses in the central part reach the yield strength, a second zone of plastic deformations will arise. Using the Wind Velocity vs Wind Load diagram (which is, actually, a non-linear function) it is easy to observe that a *twofold* increase in the wind pressure (from 375 to 750 N per sq.m) corresponds to just a relatively moderate wind speed increase from 25 m/s to approximately 35.5 m/s.



Further increase in the wind speed will most likely lead to the panel developing a crack in either of those two zones.


Von Mises stresses in top
fibres arising due to bending.
σe max = 74 MPa
+67
+59
+52
+44
+37
+30
+22
+15
+7.4

Conclusions.

The Finite Element Analysis allows deep insight into mechanical behaviour of perforated panels, since significant amounts of information can be obtained using the numerical modeling. The benefits are numerous: stress analysis and investigation of general patterns of mechanical behaviour are possible for different materials, perforation patterns, loads, constraints applied to the edges, etc. For each particular case, the Finite Element Analysis allows to obtain clear and accurate results, related to the evaluation of maximum stresses and their precise location. Overall deformation patterns of the panels, including maximum deflections, are also obtained by means of the FEA. As a result, compehensive information about the mechanical behaviour of the panels can be used in the design process, in order to ensure that perforated panels retain structural integrity and do not manifest undesirable deformations.