Failure analysis of anchorage of cable-stayed bridge with internal defects

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Abstract
The influence of the internal defects in the anchorages of cable-stayed bridges, generated either during the fabrication process or due to the usage time on their mechanical properties and failure probability is studied. Internal defects were distributed according to the probability density functions of types, sizes, quantities, and locations obtained from the experimental studies. The Finite Element Method (FEM) is applied to simulate the behaviour of the anchorages with and without internal defects under external forces, which affect the bridge, such as wind and traffic. It was shown that the mechanical properties of the anchorage without internal defects are in the range of its application, but in the case of an anchorage with internal defects, approximately 0.1% of the observed maximum stresses approximate the yield stress. The latter could result in permanent material deformation or fracture. The probability of failure of an anchorage is discussed.

Keywords
Failure analysis, cable-beam anchorage, finite element method, internal defects, probability distribution function

1. Introduction
A cable-stayed bridge consists of foundation, control piles, board, main columns, secondary columns, cables, and upper and lower anchorages that join the cables with columns, and anchorages that join the cables with the bridgeboard. The cable-beam anchorage zone is the vital load-bearing component in a suspension bridge. All these elements are affected by the external loads such as vehicle traffic, winds, temperature changes...
and seismic forces, and constantly subjected to periodic monitoring to verify that their state during the service time satisfies the design parameters, as the mechanical properties of the anchorage are directly related to the safety of the whole bridge.²

Mechanical failures occur due to four fundamental factors: design problems, failures in the construction material, construction procedures and operation under external loads.³ These causes of failure result in internal or external defects in the structural elements. In addition, failure can occur when the design loads are exceeded, for example, due to an increased vehicular flow, winds with speeds higher than normal, earthquakes with greater intensity than the designed ones or a combination of the above-mentioned factors.⁴

We analyze the structural behavior of “Papaloapan River” bridge (Figure 1), located in the state of Veracruz (Mexico) and has been in operation since 1995.⁵

Due to repeated failures in the bridge cables collapsing for no apparent reason, a research program in the Instituto Mexicano del Transporte (IMT) was developed to determine the operating conditions of the bridge.⁵ These accidents are potentially dangerous as if several cables collapse simultaneously bridge can suffer major damages or even breakdown. Visual inspections, non-destructive penetrating liquid tests and ultrasound tests (Figures 2 and 3), as well as destructive tests for tension stresses and fracture toughness,

Figure 1. Bridge “Papaloapan River”.
were performed by the researchers of IMT. It was found that the origin of cable’s fracture comes from the upper anchorages of the bridge, and the main causes of failures were: poor mechanical properties of the steel, inadequate manufacturing processes and poor chemical compounds.\textsuperscript{5}

In structural health monitoring, there are traditional methods of analysis by non-destructive techniques and novel techniques that use non-contact sensors and self-powered wireless sensors\textsuperscript{6} that allow to determine the quantities, geometries, locations of defects, and determine whether a structural element should remain in operation or it needed to be replaced by a new one. To perform this type of analysis it is necessary to close the bridge, to satisfy the conditions of experimental testing, and, in most cases, to unmount all the anchorages, which is an expensive procedure.
In turn, it is possible to carry out the analysis without closing the bridge by using numerical methods.\textsuperscript{7,8} One of the commonly used numerical methods for this purpose is the Finite Elements Method (FEM), which allows to create a computational model with experimentally obtained parameters for probabilistic analysis of failure.\textsuperscript{9–11} The FEM is a technique for solving partial differential equations in two or three space variables (i.e. some boundary value problems).\textsuperscript{12} The FEM is based on the variational approach, where the region is discretized into finite elements interconnected at different joints called nodes. Depending on whether the region, where the problem is raised, is 1, 2, or 3-dimensional, it can be divided into segments, triangles, rectangles, or parallelepipeds (respectively). In nodes the values of the unknowns are approximate, and a system of equations is solved, so the displacements of the nodes due to the external forces and boundary conditions can be obtained. The FEM is also used to study many other physical phenomena (mechanical stresses, fluid flows, heat transfer, mechanic vibrations, etc.).\textsuperscript{13}

In this work, the probability of failure of the upper anchorage of a cable-stayed bridge under two conditions: an ideal anchorage model without defects and a model with internal defects, is investigated to determine the influence of the internal defects incorporated in finite element analyses\textsuperscript{14} on the behavior of the structural elements.

2. Top anchorage of the bridge “Papaloapan River”

There are three types of upper anchorage at the bridge “Papaloapan River”, which are related to the locations of the cables they hold. Figure 4 shows an arrangement between the anchorages and cables and the location of these elements in one of the main columns of the bridge.

A three-dimensional analysis using the FEM was carried out to determine the probability of failure at the upper anchorage #2, as in this anchorage the fractures were observed, and internal defects were detected. Figure 5 shows the model of the anchorage, which has an irregular geometry.

In the studies of the bridge carried out by the Instituto Mexicano del Transporte (IMT),\textsuperscript{5} undamaged and damaged anchorages were found, so two types of numerical analysis were performed: for the anchorage without defects and for the anchorage with small internal defects. The calibration of numerical models\textsuperscript{15} of anchorages was performed using the parameters estimated from empirical studies carried out by the IMT in order to investigate their reliability. To perform the analysis without defects the following mechanical properties and variables related to the operating conditions were considered: modulus of elasticity ($E$), density ($\rho$), Poisson’s ratio ($\nu$), the axial load due to the vehicle flow (FTR), and the side load of wind (FWI) (Figure 6).

The anchorage is made from the A36 steel with $\rho = 7854$ kg/m$^3$ and $\nu = 0.3$.\textsuperscript{16} According to the data obtained by IMT the modulus of elasticity $E$ for the anchorage without defects has a mean value of 218 GPa and the critical value of the yield stress of 434 MPa, however, in the case of the anchorage with internal defects the mean value of $E$ is 199 GPa, and the critical value of the yield stress is 312 MPa.

To determine the external loads, an axial load or tensile force of 200 tons applied to the rear section of the anchorage cylinder was considered.\textsuperscript{5} The traffic flow generates
Figure 4. Arrangement of the anchorages and cables in the main column of the bridge “Papaloapan River.”
variations in the axial load, so the tensile force is a probabilistic variable in terms of pressure ($P_{TR}$). The pressure is modeled as a uniformly distributed load in the transverse section of the anchorage. According to the parameters of the anchorage and the tensile force, it was obtained that $P_{TR}$ has a normal distribution with the mean value of 28.7 MPa and a standard deviation of 12.5 MPa.

The wind strength was determined by the standard N-PRY-CAR-6-01-004/01 provided by IMT, and due to the wind variation, the wind force was also considered as a probabilistic variable. Considering the parameters of the anchorage, the bridge height above the sea level ($h_m = 0$) and the design wind speed of 200 km/h, it was

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**Figure 5.** Geometrical model of the upper anchorage #2 of the bridge “Papaloapan River.”

**Figure 6.** Location of axial or traction force (a) and wind force (b).
determined that the actual pressure due to the wind force applied to the anchorage \( (P_V) \) has a normal distribution with the mean value of 2.28 MPa and standard deviation of 0.57 MPa.

For the analysis of the anchorage with defects, the same parameters of density, Poisson ratio, tractive force, and wind force as for the analysis without defects were considered. The elasticity modulus was modified for this case, as according to the IMT the presence of defects modifies the physical properties of the anchorage. Based on the experimental results provided by IMT, the elasticity modulus was considered as a normally distributed variable with the mean value of 199 GPa and a standard deviation of 13.5 GPa. In addition, it was considered that an anchorage with internal defects has the yield stress of 312 MPa and the ultimate tensile strength of 620 MPa. Studies performed by the IMT detected the presence of defects with a size in the range of 2–2.5 mm in diameter inside the anchorage, some of them had a smaller size, but they were not considered due to the complexity of the solution in the finite element analysis. For the analysis of the anchorage with internal defects, 50 random spherical defects were located inside the anchorage. The diameters of the spherical defects were considered as continuous uniform random variables in the range of 2–2.5 mm. The IMT detected three zones where the defects were located inside the anchorage: the embedding zone, the transition zone, and the cylindrical zone (Figure 7).

The largest number of internal defects (20 hollow spheres) were randomly located in the embedding area using the polar coordinates \((R, \alpha, \beta)\), as in this area is situated the bezel for the welding of the anchorage with the main column of the bridge. At first, a new origin of coordinates was defined, the radius \(R\) was determined, and the ranges of the angles \(\alpha\) and \(\beta\) were calculated. Thereafter, 20 hollow spheres were randomly generated inside the anchorage so their centers were located at \((R + \epsilon, \alpha, \beta)\), with \(\epsilon \sim N(0, (\Delta_1/6)^2)\), \(\Delta_1 = 25\) mm, \(\alpha, \beta\)–continuous uniform random variables within their corresponding ranges, and the diameters were considered as continuous uniform random variables in the range of 2–2.5 mm (see Figure 8).

In transition zone 15, internal defects were randomly located using the cylindrical coordinates \((y, z, \theta)\) and considered as hollow spheres with the diameters generated as continuous uniform random variables in the range of 2–2.5 mm. The coordinates \((y, z, \theta)\) of centers of the hollow spheres were randomly generated as \(y \sim N(0, (\text{DIAM}/6)^2)\), \(z = DC - \delta\), with \(\delta \sim N(0, (\text{DA}/3)^2)\), and \(\theta \sim N(0, 2\pi)\) (see Figure 9), where \(\text{DIAM} = 316\) mm, \(DC = 280\) mm.

In the cylindrical zone, the coordinates of the centers of 15 internal defects were randomly generated using the cylindrical coordinates \((R, z, \phi)\) as \(R \sim N(0, (\text{DIAM}/6)^2)\), \(\text{DIAM} = 316\) mm, \(z\)-continuous random variable in the interval \([0.28, 0.55]\), and \(\phi\)– continuous random variable in the interval \([0, 360]\), as it is shown in Figure 10.

3. FEM model

For both kinds of anchorages (with and without internal defects) the same geometric model presented in Figure 5 was considered. This model was generated within the ANSYS program interface using simple geometric figures (see Figure 11).
In the analysis of the anchorage without internal defects the model shown in Figure 11 was the final one, meanwhile for the analysis of the anchorage with internal defects additionally 50 hollow spheres (that represent the internal defects) were subtracted as they was described in Section 2. To obtain the solution using the FEM, at first the geometry is generated, then its discretization is performed, and then the boundary conditions are applied. For the discretization of the anchorage, the SOLID92 element was used. This element was chosen because it is a 10-node prismatic element, and it gives a possibility to calculate the displacements, stresses, and deformations. Figure 12 shows the anchorage discretization, where the mesh has 17,244 nodes and 11,031 elements.

For the analysis of anchorage with internal defects the same geometric model as for the analysis of anchorage without defects was used, but with subtracted hollow spheres (internal defects) located in the embedding, transition, and cylinder areas, with a variable diameter of 2–2.5 mm using the program’s SPH4 tool. Figure 13 shows the defects generated inside the anchorage for one of the tests.

Figure 7. Three zones of defect's locations in the upper anchorage: 1 (red)—embedding zone, 2 (blue)—transition zone, 3 (green)—cylindrical zone.
The model of the anchorage with subtracted hollow spheres was discretized using the SOLID92 element. Figure 14 shows the discretization of the anchorage with defects, where the mesh has 205,739 nodes and 168,496 elements. As the discretization cannot be displayed inside the anchorage, it is presented by showing the mesh nodes.

For all types of analysis, Young’s module, vehicular traffic force (traction), and wind force were considered as random variables, and the Poisson’s ratio and the density of the anchorage material were considered as deterministic variables.

4. Results and discussion

For both kinds of anchorages (with and without internal defects) three sets of tests of 50, 100 and 250 randomly generated samples were performed. Each test was carried out using an algorithm in ANSYS, which allows to model numerically the stress distribution in the anchorage in dependence on the external forces (traction and tension) and climatic conditions (wind and temperature). The maximum stress observed in each test was taken as the result. After that, a statistical analysis of the results in each group was carried out.

At first, the histograms of the corresponding maximum stresses were generated, choosing the number of classes ($NC$) according to the set size ($SS$) as $NC = \sqrt{SS}$. Then, an adjustment of the probability density functions was carried out to determine the type of probability density function and its parameters that correspond to the theoretical distribution of the maximum stresses for the anchorages with and without internal defects.
defects. Thereafter, the results obtained for each type of anchorages were compared to determine whether there are any significant changes in the probability density functions corresponding to the theoretical distributions of the maximum stresses for the anchorages with and without internal defects.

4.1. Analysis of the anchorage without defects

In Table 1 the maximum stresses obtained from the analysis of the anchorage without defects for a set of tests of 50 samples (under randomly generated external forces and climatic conditions) are shown.

The maximum stresses in the anchorage without internal defects for the sets of tests of 100 and 250 randomly generated external forces and climatic conditions were calculated.

Statistical analysis of the data was performed in Minitab with a confidence level of 95%. The histograms of maximum stresses generated using the data obtained for the three groups of tests for the anchorage without internal defects are presented in Figure 15.

Figure 9. Location of internal defects in the transition zone in the plane (x,0,z).
Figure 10. Location of internal defects in the cylindrical zone.

Figure 11. Geometric modeling of the anchorage in ANSYS.
For the data obtained for each one of these three sets, distribution tests\textsuperscript{18} were used to identify the probability distribution function that maximum stresses for the anchorage without internal defects follow.

\textbf{Figure 12.} Discretization of the anchorage for the analysis without defects.

\textbf{Figure 13.} Location of 50 defects inside the anchorage.

For the data obtained for each one of these three sets, distribution tests\textsuperscript{18} were used to identify the probability distribution function that maximum stresses for the anchorage without internal defects follow.
Table 1. Maximum stresses for 50 samples from the analysis of the anchorage without defects.

| No. | Stress (Pa) | No. | Stress (Pa) | No. | Stress (Pa) | No. | Stress (Pa) | No. | Stress (Pa) |
|-----|-------------|-----|-------------|-----|-------------|-----|-------------|-----|-------------|
| 1   | 3.84×10^7  | 11  | 1.32×10^8  | 21  | 1.55×10^8  | 31  | 1.13×10^8  | 41  | 1.16×10^8  |
| 2   | 6.42×10^7  | 12  | 2.06×10^8  | 22  | 1.04×10^8  | 32  | 9.08×10^7  | 42  | 9.08×10^7  |
| 3   | 5.98×10^7  | 13  | 1.81×10^8  | 23  | 7.62×10^7  | 33  | 1.31×10^8  | 43  | 1.14×10^8  |
| 4   | 1.45×10^8  | 14  | 1.67×10^8  | 24  | 7.67×10^7  | 34  | 5.45×10^7  | 44  | 1.23×10^8  |
| 5   | 1.42×10^8  | 15  | 1.40×10^8  | 25  | 1.81×10^8  | 35  | 1.51×10^8  | 45  | 9.82×10^7  |
| 6   | 1.23×10^8  | 16  | 2.37×10^7  | 26  | 1.05×10^8  | 36  | 2.20×10^8  | 46  | 1.13×10^8  |
| 7   | 1.62×10^8  | 17  | 1.02×10^8  | 27  | 9.46×10^7  | 37  | 7.18×10^7  | 47  | 1.17×10^8  |
| 8   | 1.56×10^8  | 18  | 1.88×10^8  | 28  | 1.50×10^8  | 38  | 8.46×10^7  | 48  | 7.30×10^7  |
| 9   | 1.58×10^8  | 19  | 1.03×10^8  | 29  | 1.36×10^8  | 39  | 8.75×10^7  | 49  | 8.09×10^7  |
| 10  | 1.32×10^8  | 20  | 4.60×10^7  | 30  | 1.26×10^8  | 40  | 1.70×10^8  | 50  | 4.59×10^7  |

Figure 14. Discretization of the anchorage for the analysis with defects.

Figure 15. Histograms of maximum stresses obtained in the anchorage without internal defects for the sets of tests of 50 (a), 100 (b) and 250 (c) samples.
Table 2. Distribution tests of maximum stresses obtained in the anchorage without internal defects for the sets of tests of 50 (a), 100 (b) and 250 (c) samples, with highest p-values.\textsuperscript{18}

| Set size | Fitted distribution | Anderson–Darling statistics | p-value | Parameters of fitted distribution |
|----------|---------------------|-----------------------------|---------|----------------------------------|
| 50       | Normal              | 0.076                       | 0.999   | mean = $1.164 \times 10^8$ std. dev. = $4.461 \times 10^7$ |
|          | Weibull             | 0.068                       | >0.250  | scale = 2.883 form = $1.306 \times 10^8$ |
| 100      | Normal              | 0.117                       | 0.990   | mean = $1.167 \times 10^8$ std. dev. = $4.529 \times 10^7$ |
|          | Weibull             | 0.058                       | >0.250  | scale = 2.806 form = $1.310 \times 10^8$ |
| 250      | Normal              | 0.176                       | 0.922   | mean = $1.165 \times 10^8$ std. dev. = $4.531 \times 10^7$ |
|          | Weibull             | 0.126                       | >0.250  | scale = 2.801 form = $1.308 \times 10^8$ |

Figure 16. Fitted probability density functions for the data obtained for the set of tests of 250 samples for the anchorage without internal defects.

From Table 2 follows that all three sets of tests for the anchorage without internal defects have almost the same results. Therefore, it is possible to conclude that a set of tests of 50 samples is statistically representative and it can be used to identify the probability distribution function that maximum stresses for the anchorage without internal defects follow. Note that, a set of tests of 250 samples gives a better estimation of the parameters of fitted distribution as compared to the sets of tests with 50 or 100 samples, however, the computation time grows significantly in that case. In Figure 16 the fitted probability density functions for the data obtained for a set of tests of 250 samples for the anchorage without internal defects are plotted.

From Figure 17 of the p-p plots\textsuperscript{18} of he fitted normal and Weibull distributions it follows that both distributions are suitable candidates.
Note that, a failure in the anchorage without internal defects can occur when the maximum stress exceeds the critical yield stress of 434 MPa and in that region, the fitted probability density functions almost coincide (Figure 18).

Moreover, a random variable with a Weibull distribution cannot take negative values, which is the case of the maximum stresses, therefore in our investigations, the fitted

**Figure 17.** p-p plots of the fitted probability density functions for the data obtained for a set of tests of 250 samples for the anchorage without internal defects: normal (a) and Weibull (b).

**Figure 18.** Critical region of the fitted probability density functions.
The distribution of the maximum stresses for the anchorage without internal defects is the Weibull distribution with the scale value of $2.801,27$ and form value of $1.30816 \times 10^8$.

### 4.2. Analysis of the anchorage with defects

Maximum stresses in the anchorages for the sets of tests of 50, 100 and 250 samples with randomly generated internal defects, external forces and climatic conditions were calculated. The histograms of maximum stresses generated using the data obtained for the three sets of tests for the anchorage with internal defects are presented in Figure 19.

For the data obtained for each one of these three sets, distribution tests were used to identify the probability distribution function that maximum stresses for the anchorage with internal defects follow.

Note that, in contrast to the results presented in Table 2 for the analysis of the anchorage without defects, from Table 3 follows that all three sets of tests for the anchorage with internal defects have different results. Therefore, it is possible to assume that statistically representative set should have the largest size of 250. In following Figure 20, the fitted probability density functions for the data obtained for the set of tests of 250 samples for the anchorage with internal defects are plotted.

The p-p plots of the fitted normal and Weibull distributions are presented in Figure 21 and it can be noted that both distributions are suitable candidates.

| Set size | Fitted distribution | Anderson–Darling statistics | Parameters of fitted distribution |
|----------|---------------------|-----------------------------|----------------------------------|
| 50       | Normal              | 0.411                       | $\text{mean} = 1.212 \times 10^8$ | $\text{std. dev.} = 4.543 \times 10^7$ |
|          | Weibull             | 0.464                       | $\text{scale} = 3.002$          | $\text{form} = 1.359 \times 10^8$   |
| 100      | Normal              | 0.564                       | $\text{mean} = 1.203 \times 10^8$ | $\text{std. dev.} = 4.853 \times 10^7$ |
|          | Weibull             | 0.293                       | $\text{scale} = 2.695$          | $\text{form} = 1.354 \times 10^8$   |
| 250      | Normal              | 0.634                       | $\text{mean} = 1.224 \times 10^8$ | $\text{std. dev.} = 5.210 \times 10^7$ |
|          | Weibull             | 0.670                       | $\text{scale} = 2.491$          | $\text{form} = 1.378 \times 10^8$   |

Table 3. Distribution tests of maximum stresses obtained in the anchorage with internal defects for the sets of tests of 50 (a), 100 (b) and 250 (c) samples, with the highest p-values.

**Figure 19.** Histograms of maximum stresses obtained in the anchorage with internal defects for the sets of tests of 50 (a), 100 (b) and 250 (c) samples.
However, as it was mentioned above, a random variable with a Weibull distribution cannot take negative values, which is the case of the maximum stresses, therefore in our investigations the fitted distribution of the maximum stresses for the anchorage with internal defects is the Weibull distribution with the scale value of 2.491,45 and form value of $1.37831 \times 10^8$.

**Figure 20.** Fitted probability density functions for the data obtained for the set of tests of 250 samples for the anchorage with internal defects.

**Figure 21.** p-p plots of the fitted probability density functions for the data obtained for the set of tests of 250 samples for the anchorage with internal defects: normal (a) and Weibull (b).

However, as it was mentioned above, a random variable with a Weibull distribution cannot take negative values, which is the case of the maximum stresses, therefore in our investigations the fitted distribution of the maximum stresses for the anchorage with internal defects is the Weibull distribution with the scale value of 2.491,45 and form value of $1.37831 \times 10^8$. 
4.3. Analysis of failure probability

In the Sections 4.1 and 4.2 it was found that the fitted probability distribution functions of maximum stresses for both kinds of anchorages (with and without internal defects) are Weibull distributions and their parameters were estimated. Also, it was found that in the case of an anchorage without internal defects a statistically representative set should have at least 50 samples, and in the case of an anchorage with internal defects it should have at least 250 samples. Therefore, the comparative analysis of the fitted probability distribution functions of maximum stresses for both kinds of anchorages should be carried out for the sets with 250 samples. The purpose of this analysis is to determine whether there are significant differences in the parameters of the fitted Weibull distributions and in the probability of failure of an anchorage. The p-value of 0.173 for the 2-sample t-test performed on the data obtained from the two sets of 250 samples for anchorages with and without internal defects suggests that there is no evidence to reject the hypothesis that the mean values of maximal stresses are equal. For the same data, two-sample F-test (Bonett’s test) was used to examine the hypothesis that the variances of the data for anchorages with and without internal defects are equal, and its p-value of 0.052 close to the significance value of 0.05 suggests that this hypothesis is false. Therefore, it can be concluded that there is a significant difference between the parameters of the fitted Weibull distributions for maximum stresses in the anchorages with and without internal defects. Figure 22 shows the cumulative probability for

![Figure 22. Cumulative probabilities for the fitted Weibull distributions in the range 165–300 MPa.](image-url)
the fitted Weibull distributions in the range 165–300 MPa, that is, in an interval of high values of maximum stresses.

The cumulative probability in this interval for an anchorage with defects is 20.8%, while for an anchorage without defects the corresponding probability is 14.7%. As might be expected, the significant difference between these two percentages implies that high maximum stresses are more likely to occur in the case of an anchorage with internal defects.

The probability of failure of anchorage with internal defects (i.e. when the maximum stress is greater than the yield stress of 312 MPa) is 0.045% and the probability of failure of an anchorage without internal defects is 0.001% (see Figure 23), so the probability of failure is 45 times higher for an anchorage with internal defects. As it was mentioned above, the bridge suffered from the repeated failures in the cables collapsing for no apparent reason, however, the obtained results imply that these failures are probable to occur because the failure probability is not neglectable. Therefore, it is necessary to take into account the presence of internal defects in the design process of the anchorage to reduce the probability of failure and avoid collapses of the bridge cables.

5. Conclusions

A computational model using the FEM for the upper anchorage of a cable-stayed bridge with the incorporation of small internal defects was developed, and the influence of the internal defects on the mechanical properties of the anchorage was investigated.
Probability distribution functions of maximum stresses for the anchorages with and without internal defects under random external forces (wind strength and forces generated by vehicle traffic) were determined.

The fitted probability distribution functions of maximum stresses for both kinds of anchorages (with and without internal defects) are found to be Weibull distributions, and their parameters were estimated.

Also, it was found that in the case of an anchorage without internal defects a statistically representative set of tests should have at least 50 samples, and in the case of an anchorage with internal defects, it should have at least 250 samples.

Using the 2-sample t-test for the data obtained from the two sets of tests of 250 samples for anchorages with and without internal defects it was found that there is no evidence to reject the hypothesis that the mean values of maximal stresses are equal as the calculated p-value is 0.173. The p-value of 0.052 of the two-sample F-test (Bonett’s test) performed on the same data suggest that there is a significant difference between the variances, and therefore in the parameters of the fitted Weibull distributions for maximum stresses in the anchorages with and without internal defects.

It was determined that there is a significant change in the distribution parameters of maximum stresses due to the incorporation of the internal defects in the anchorage, so the probability of failure is 45 times higher for an anchorage with internal defects.

For all the tests in the analysis of anchorage without internal defects 100% of the maximum stresses were observed within the range of 0–300 MPa, that is, below the yield stress. However, in the case of an anchorage with internal defects in the set of 250 samples approximately 0.1% of the observed maximum stresses exceeded the value of 300 MPa, which is close to the yield stress of 312 MPa. The latter could result in permanent material deformation or fracture, so it is necessary to perform a plasticity analysis to determine if the yield stress is exceeded.

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