Analysis of stability of stressed-skin constructions for transport of bulk raw materials

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Abstract. An algorithm has been developed to assess the technical condition of stressed-skin constructions which constitute load-bearing structures and casing for conveyors. The description of the methodology is presented in the form of an algorithm. An important feature of the methodology is the measurement of main and intermediate structural nodes and then the comparison of measurement results with records in the documentation. The results of the measurements are used to simulate and assess the actual technical condition of the structure. If the deformation of the coating casing, ribbing, supports and other elements of the process line exceeds the limit values, it should be preventively decommissioned and assigned for repair or replacement. The developed methodology used for collecting the necessary information on the technical condition of the conveyor's structure is aimed at its implementation to a wider use in industrial plants with developed inter-operational transport. The utilitarian aim of the study is to increase the level of users' safety and to maintain the continuity of transport system performance.

1. Introduction
In the 1970s, industrial plants dealing with the mass processing of raw resources used in their process lines transport systems housed in specially-developed steel structures commonly referred to as stressed-skin constructions (figure 1). This solution is commonly encountered presently in industrial fields as well, and it still provides fast transport of raw materials e.g. from a storage hall to a different production hall, where processing machinery is set up. The advantage of this solution is the possibility of access to transporter maintenance areas (transporter band tensioning, support roll settings, driving drums, bearings, chain wheels, motors, etc.). The service personnel may traverse the entire length of the raw resource transporter. The stressed-skin constructions are composed of a single section or several sections (e.g. a section of ca. 80 metres set at an angle against the ground, and a horizontal section of approx. 30 metres) depending on the plant type, where the transporter is installed. The studied structures were designed by the Biuro Projektów Przemysłu Nieorganicznego (Pl. Inorganic Industry Design Office) of Gliwice, Poland, and manufactured by the company Mostostal Pracownia of Kraków, Poland. The considered structures cover issues of architecture, civil engineering, material engineering, mechanical engineering as well as the environment, mining and energy, and hence, in industrial practice, maintenance as well as the assurance of their safe use is an interdisciplinary issue that is technically complicated and costly.
The assurance of safety of operation of stressed-skin constructions is a challenge for maintenance personnel and company owners. In order to accommodate expectations of the industry, a methodology was developed of supervision of the technical condition of stressed-skin constructions. Correct evaluation of the technical condition on the basis of reliably collected information is supposed to aid company management bodies in the undertaking of suitable corrective measures, should those be necessary. The procedure presented in the latter part of the article may be useful not only for the purpose of evaluation of structures already present in industrial infrastructure, but new solutions as well (figure 1).

![Diagram of a section of a stressed-skin structure; View of power plant infrastructure with a large volume of transport systems placed in covered “stressed-skin” structures [1].](image)

**Figure 1.** a) Diagram of a section of a stressed-skin structure; b) View of power plant infrastructure with a large volume of transport systems placed in covered “stressed-skin” structures [1].

### 2. Technical condition evaluation procedure for stressed-skin constructions

#### 2.1. Structural safety of stressed-skin constructions

Stressed-skin constructions have supports spaced far apart from each other (several metres) and are placed at elevations ranging from a few to several metres over the ground. Unequivocally important is the suitable oversight and supervision of hazards they may pose in case of loss of relevant strength properties.

Structural safety per [2] (with respect to fulfilment of the condition of strength) as discussed by the standard boils down to the inspection of the level of utilisation of the load-bearing capacity of critical components against the estimated internal forces that may emerge in them. The calculation formulae given in papers [2, 3] refer to standard PN-EN 1993, to the effective stressed-skin construction cross section field. Geometric characteristics of cross-sections influence structural safety as defined in [3] according to the following formula:

\[
\frac{E_d}{R_d} = \frac{E_d(F_{kq} \gamma_F)}{R_d(F_{kq} \gamma_R)} \leq 1
\]

where: \(\gamma_F\) – partial load safety coefficient, \(\gamma_R\) – partial load-bearing capacity safety coefficient, \(F_{kq}\) – quantiles of characteristic load values, \(R_{kq}\) – quantiles of characteristic load-bearing capacity values, \(E_d\) – effect of the influence (loads) on the load-bearing system, \(R_d\) – structure load-bearing capacity.

A. Biegus described in [3] in a very detailed manner the safety rules for structures. M. Suchodola utilised in [4] calculation procedures presented in standards [5–7]. In order to be able to determine the actual cross- and lengthwise section of a stressed-skin construction it is necessary to correctly collect measurement values of all significant components of the entire structure both of the cover as well as the reinforcements and support pillars for the purpose of comprehensive supervision of the technical condition.
2.2. Assurance of safety of stressed-skin constructions

The structure of stressed-skin constructions, along with transporters, can be destroyed for the following reasons:

a) loss of balance of any of its parts,
b) excess deformation caused by:
   • overload,
   • loss of stability of any of the structural components,
   • unfavourable change in the stability of the base surface,
c) base surface deformation:
   • washing away or erosion of the foundations,
   • setting of the foundations,
   • cracks,
d) fatigue-based damage,
e) lack of maintenance, repair and correct upkeep,
f) accidents, e.g. damage by a vehicle moving under the stressed-skin construction, a crane operating in the area of the stressed-skin construction or the supports.

On the basis of conducted visual inspections of several stressed-skin constructions utilised as the housing and support for transport bands providing manufacturing equipment at industrial plants with raw resources, it could be stated that in course of their long-term intense use, an uneven reduction in the thickness of flat sheets of compressed, base and top panels emerges, and a reduction of the cross-section area of shaped profiles takes place. This process is caused by external factors (load by wind, snow, torrential rain) that are taken into account for the purposes of calculations of structures, but it is also caused by possible dust load from the transported material. Cross-sections are damaged among others in the area of ribbing of the covers in locations where the dust from the transported resources remain. The dust collected on the beam flanges facilitates the emergence of corrosion spots (figure 2).

![Example locations of collection of contaminations](image)

**Figure 2.** Internal structural components facilitate the collection of contaminations (dust from the transported materials).

The technical culture in the area of maintenance, the financial capacities of companies in terms of prevention (elimination of contaminations, corrosion protection, technical analyses), financial expenditures for suitable maintenance that would correspond to engineering knowledge – are all decisive for the technical condition of the transport system. The fusion of knowledge and financial capacities of users permits the maintenance of existing structures on the level of the original condition of their use, or otherwise – the lack of suitable preventive work causes excess degradation and, as a consequence, safety hazards. On the basis of the conducted analysis of stressed-skin constructions constituting load-bearing and service structures for belt transporters it can be concluded that after years of operation, the thickness of structural components varies for the individual areas of the entire structure. It would be risky to assume a single simplified cross-section area reduction coefficient, as the strength calculations...
would not reflect the actual condition, meaning, several local weakness spots of the structure. Water and snow intruding inside through open or leaky windows causes the water drops to trickle down to local concavities contributing to uneven wear by corrosion, and accordingly to the weakening of strength of the entire stressed-skin structure. The persisting dust and duff, taking on water, can have a different weight than dry dust, and, accordingly, cause an additional load. It is recommended to measure the weight of the water-soaked dust remaining on the beam flanges, as the weight of a cubic centimetre of dry and wet dust may differ greatly. Over years of use, in many industrial applications, changes of the transported resources were introduced – hence, there exists the risk of a change to the load influencing the structure. The change of transported resources may influence the operation of transporters, the load, the distribution of vibrations and contaminants, raising or reducing the safety of the entire structure (depending on the transported specific load of raw resources). It is thus recommended to perform measurements and update documentation as part of maintenance of the discussed process lines.

It is also important to estimate the value of the actual safety coefficient of the structure being influenced by a variety of factors: period of operation, actual geometric dimensions influencing the actual cross-sections and the actual cross-section indicators in terms of bending (twisting), loads in the structure in the form of forces and torques both in the static and dynamic perspective, the course of dynamic loads over time (the character of impulse loads caused by extreme phenomena, e. g. wind), etc. [8]:

\[
X_R = \frac{R_x(t_e \theta(t_e |x,y,z,c_z))}{L_{F,T}(F_S,F_D,T_S,T_D,t_F,t_T)} I_{AR}^{AR}
\]

where: \(X_R\) – actual safety coefficient, \(R_x\) – material strength, e. g. yield limit, \(t_e\) – operation time, \(g(x,y,z)\) – actual dimensions of the cross-sections being considered, \(c_z\) – external factors (exposure to high temperature differences, climate conditions), \(L_{F,T}\) – load condition, \(F_S\) – static forces, \(F_D\) – dynamic forces, \(T_S\) – static torques, \(T_D\) – dynamic torques, \(t_F\) – variability of dynamic forces over time, \(t_T\) – variability of dynamic torques over time, \(A_R\) – considered cross-sections, \(I_{AR}\) – bending coefficients, etc., of cross-sections.

2.3. Algorithm of supervision of the technical condition of structures

All maintenance services need the presentation of a clear instruction of procedure with complex technical structures that include stressed-skin constructions. The order of procedure during the analysis of the technical condition of a transport system placed in a stressed-skin construction is presented in figure 3.

![Figure 3. Algorithm of collection of measurements to monitor the technical condition of stressed-skin constructions.](image-url)
2.4. Gathering documentation
Before commencing works related to the evaluation of the technical condition of a transport system and a stressed-skin structure, it is necessary to analyse the entire documentation held by the Investor, including calculations, structural and execution documentation, protocols of execution of assembly work, construction logs, logs of the structure including all entries, copies of documentation confirming the scope of maintenance and repair work conducted in the past (from the beginning of installation of the transport system in the stressed-skin construction and its transfer into use).

2.5. Analysis of documentation
Of particular significance is the analysis of entries of protocols of technical inspections, documentation related to the construction permit decision, the decision concerning the permit of use, all historic available protocols of tests and reports. It is necessary to conduct an interview with the system service personnel to exclude or confirm any hazardous symptoms that could include cracking noises, vibrations and shaking of the structure, e.g. during material transport or strong storms and winds; an analysis of all correspondence related to the discussed structure.

2.6. Preparing the stressed-skin construction for measurements
In many industrial applications, the inside of the stressed-skin construction has high levels of dust and contaminations that hinder the execution of measurements. It is necessary to factor in the time necessary to clean up and bring into order all locations that have contaminant deposits even before the commencement of measurements. The locations to be tested/measured must be scratched free of deposits and possible rust and degreased. Regular cleaning of the internal surfaces of the stressed-skin construction is necessary not only for aesthetic reasons, but also primarily so as not to cause excess additional loads that might accidentally be omitted during strength calculations (dust soaked in water may be a catalyst for corrosion processes) and to protect the environment against possible uncontrolled egress of dust to the outside.

2.7. Macroscopic tests of the condition of the stressed-skin construction and its supports
Upon a detailed analysis of existing structural documentation, one may commence the development of a plan of macroscopic measurements. Transfer onto a copy of documentation a grid of control measurement points. For the indicated points, one conducts macroscopic measurements. The trials make use of a photographic camera capable of producing sharp photographs in difficult conditions, with a good, bright [fast] lens, a zoom and a flash lamp. It is recommended for the photographs to be taken with a tripod and a rule permitting the determination of the size of the photographed component. The photographs are aimed at imaging the condition of the stressed-skin construction at various spots, and the created zooms should reflect the level of wear. Using a rule and an electronic rangefinder capable of recording measurement values, one collects the real measurements of relevant components. The verification of size values with respect to documentation provisions is aimed at providing a reference to actual cross-sections. Checking dimensions is aimed at the verification of information of the mutual placement of the upper and lower part of the structure; checking, whether transporter components, structural nodes of the stressed-skin construction did not move with respect to each other. A comparison of the distances of the stressed-skin construction covers with respect to the road (reference point) level is used to check the deflection of the cover sheets. The measurement of the deflection of the stressed-skin construction from the vertical and an inspection of the diagonals permits the determination, whether it did not become twisted or deflected over the years, or whether deformations emerged in course of long years of operation. Using a caliper where possible, e.g. at windows, on slide bearings and support spans, one measures the thickness of structural components. Before making measurements using the caliper and a precision compass, one has to additionally and thoroughly clean the surfaces so as not to take into account protective coatings during measurements and so as not to measure the thickness of steel sheets together with contaminants. In specially designated measurement locations (supports, bearings, points of maximum deflection, grate nodes, supports, existing openings in the outer skin of
the construction), as shown in figures 4 and 5, measurements should be made with the transport units off and with them operating. At full speeds and full loads, it may be determined whether the operation of the system does not give rise to additional hazardous deformations, and if so, the trials must be expanded to include tests of vibrations and tensions with the use of tensometric sensors. Making measurements, one needs to exercise caution in relation to OHS provisions.

2.8. Detailed tests of skin and profile thickness
A subsequent stage entails the development of a test procedure for non-destructive testing, e.g. in line with EN 14127:2001 Non-destructive testing. Ultrasonic thickness measurement. The designation of a few of the most important measurement points and the execution of a series of measurements – inspection of the thickness of walls of the analysed structure, including the skin sheets and profiles by way of an ultrasound thickness gauge. The device may be used at locations that can be accessed on only one side.

Figure 4. Diagram of outer measurements for the purpose of comparison of macroscopic measurements with the content of construction documentation.

Figure 5. A diagram of the measurement grid required to properly determine the deformations of a studied structure and its supports (the density of the measurement grid depends on the precision of representation of the shape)
The test entails the calculation of the thickness of steel at the point of measurement on the basis of the time of passage of a lengthwise ultrasound wave (through the analysed gallery component). The measurements are conducted:

1) for the upper surface of the stressed-skin construction,
2) on side walls,
3) the structure underside,
4) on the ribbing made of profiles and sheets,
5) on selected joints, mainly where nodes are joined,
6) on supports at points of contact of steel with concrete,
7) on other components of supports.

Example photographs made during ultrasound measurements of the steel sheet coat are presented in figures 6a and 6b.

![Figure 6. a) Measurement of the sheet thickness of a side wall; b) Measurement result readout.](image)

2.9. Processing the results

The volume of measurements depends on the technical condition, and on the fact whether inspections are carried out regularly. At points particularly threatened by hazards or in areas, where significant thickness reductions of the cross-sections were discovered, the measurement grid should be denser. The processing of measurement results entails, among others:

1) a presentation of the arithmetic mean of the results,
2) a description of the minimum and maximum value as well as of locations where they emerge,
3) a comparison of results of measurements and thicknesses of sheets and profile with documentation,
4) a statistical analysis of measurement results,
5) an estimation of the level of wear of the structural material at spots characterised by the highest expected wear and at spots most susceptible to damage,
6) a statistical interpretation of the test results, e.g. estimation of the mean value, reliability range per the PN-ISO 2602:1994,
7) a statistical interpretation of data, e.g. by way of estimates and test related to means and variances per the PN-ISO 2854:1994,
8) on the basis of the conducted trials, an attempt at describing the actual speed of corrosion of metals in mm/year with respect to standard PN-76/H-04601,
9) consultations with an engineer holding a relevant construction licence.

2.10. Materials testing

If it would be possible to take a sample of the material for destructive testing, such samples should be properly cleaned and photographic documentation should be created, and thicknesses of the cut components, samples, should be measured. The estimation of the loss of parameters of structural steel used for the execution of the stressed-skin construction from the 1970s may be performed on the basis of:

1) hardness tests,
2) strength tests in terms of elongation and, additionally, compression,
3) microscopic trials of the sample in terms of changes that emerged in the microscopic structure of the steel.

An analysis of the test results and the influence of operation on the strength parameters of the structure require cooperation with an engineer holding permits in terms of steel structures for the construction industry.

2.11. Development of assumptions for strength simulations of structures for various loads
Industrial experience shows that stressed-skin constructions exhibit uneven wear (uneven corrosion wear of the structure, emergence after years of operation of the lack of precision of execution of the structure and of assembly). Such uneven wear is very difficult to model in practice, and in case of calculations using advanced numerical systems, a very high-performance computer is required. The development of a spatial 3D model is performed on the basis of measurements. Such work requires a very high-performance computer system and software as well as suitable experience of researchers dealing with the interpretation of simulation results.

2.12. Execution of calculational checks
Over forty years of use of stressed-skin constructions in Poland permits the conclusion that this structural solution had been proven for industrial practice. It may be assumed that design assumptions were prepared very well, and that documentation was developed with utmost care and that the stressed-skin construction was constructed in line with the project stipulations and that assembly was calculated properly. Climate change and ever higher probability of very strong gusts of wind are very real across the entire country. In the opinion of the authors of the present paper, one version of calculations must be prepared that takes into account strong wind storms and intensive rain and hail. The calculation guidelines and procedures can be found in many sources, for instance, in the following standards [5–7, 9–12]:

1) PN-EN 1993-1-1:2006. Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings [5],
2) PN-EN 1993-1-5:2008. Eurocode 3, Design of steel structures – Part 1-5: Plated structural elements [6],
3) PN-EN 1993-1-6:2009. Eurocode 3, Design of steel structures – Part 1-6: Strength and stability of shell structures [7],
4) PN-EN 1990:2004. Eurocode, Basis of structural design [9],
5) PN-EN 1991-1-1:2004. Eurocode 1, Actions on structures – Part 1-1: Densities, self-weight, imposed loads for buildings [10],
6) PN-EN 1991-1-3:2005. Eurocode 1, Actions on structures – Part 1-3: General actions - Snow loads [11],
7) PN-EN 1991-1-4:2008. Eurocode 1, Actions on structures – Part 1-4: General actions - Wind actions [12].

Pursuant to construction requirements, the calculation formulae are presented, among others, in [2, 3, 4, 13], and the procedure of measurement value gathering presented in the present paper (recorded in a simplified manner via the algorithm from figure 3) is supposed to provide precise input data for further calculations. The fundamental advantage of the designed methodology is the possibility of determination of actual dimensions of the structure and drawing up updated drawing documentation representing its current technical condition. Such detailed updated drawings simplify analyses and conclusions. On the basis of conclusions, the company management may reach decisions concerning the further course of safe use of the structure. For every calculation methodology, the fundamental parameter is the determination of the cross-section surface at the place of transfer of loads. An example of a measured component that would include material loss alongside an original unit (without material loss) is presented in figure 7. On the basis of the sample diagram (figure 7) one can determine the basic strength parameters for each cross-section. An example of the set of analysed calculation results including comments is presented in table 1. The report, as a table, simplifies the representation and comparison of results; apart from this, the table may be adapted precisely to the needs of the end user.
(the table may be expanded to include calculation details and all collected measurement results as well as key data copied from historic documentation). On the basis of the prepared documentation and the collected information, one may commence modelling the work conditions using MES systems.

![Figure 7a](image1). Example of a cross-section of a structural component „weakened” in the lower part over a length of ca. 490 mm (sheet thickness in this area is from 0.91 mm to 2.5 mm with a total loss of material over a length of ca. 290 mm, where sheet thickness is zero).

![Figure 7b](image2). Example of a cross-section of a structural component in an undamaged spot, with a nominal thickness of 3 mm.

Table 1. Example of a table representation of results of the simulation of influence on a structure by a constant load of 28 Nmm for a weakened and an undamaged cross-section.

| Symbol | Description                | Units | Results for weakened cross-section | Results for original cross-section | Change in percent | Remarks |
|--------|----------------------------|-------|------------------------------------|-----------------------------------|-------------------|---------|
| I₁     | Moment of inertia I₁       | mm⁴   | 1.94254E+11                        | 1.94288E+11                      | 99.98%            | moment for the weakened cross-section |
| I₂     | Moment of inertia I₂       | mm⁴   | 9.481E+10                          | 9.976E+10                        | 95.04%            | moment for the weakened cross-section |
| Sₑ     | Extreme fibre distance    | mm    | 1 526.900                          | 1 580.400                        | 96.61%            | distance from edge fibre for the weakened cross section |
| A      | Cross-section area         | mm²   | 67 127.050                         | 6 9837.20                        | 96.12%            | cross-section area (for the weakened cross section) |
| ST3SX  | Material strength ST3SX    | N mm⁻²| 230.000                            | 230.000                          | 100.00%           | identical parameters of steel were assumed |
| Eᵧ     | Young's modulus Eᵧ         | N mm⁻²| 210 000.000                        | 210 000.000                      | 100.00%           | identical parameters of steel were assumed |
| S₁     | Maximum deflection S₁      | Mm    | 21.190                             | 20.140                           | 4.96%             | higher deflection in the weakened cross-section by approx. 5 % |
| Mg₁    | Maximum bending moment Mg₁ | Nm    | 3 765 300                          | 3 765 400                        | 0.00%             | bending moments have values very close to each other |
| S₂     | Maximum deflection S₂      | mm    | 0.072                              | 0.059                            | 18.06%            | a change in deflection as high as 18 % to the disadvantage of the weakened cross-section |
| Res    | Maximum stress Res         | N mm⁻²| 60.642                             | 59.653                           | 1.63%             | stress increase by ca. 1.63 % to the disadvantage of the weakened cross-section |
| X      | Safety coefficient X       | -     | 3.7927                             | 3.8556                           | 1.63%             | reduction of the factor by ca. 1.63 % to the disadvantage of the weakened cross-section |
3. Conclusion
A significant achievement of the conducted research work was the development of a detailed procedure of evaluation of the technical condition of stressed-skin constructions constituting coating and supports for industrial transporters. The hypothesis assumed during the execution of the trials that „visual impressions may not be the basis for the evaluation of the technical condition of steel stressed-skin constructions” was verified. The visual evaluation is unsuitable as it only permits the observation of the condition of paint coats, notice large openings in the skin (caused by loss of material in the corrosion process) and contaminant deposits. Observation without geometric measurements and measurements of structure wall thicknesses does not describe the actual value of loss of mass of the crosswise and lengthwise section of the structure. Simplified assumptions of uniform mass loss across the entire surface do not reflect the actual condition of industrial stressed-skin structures intensely operated over many years. The conducted research clearly shows that assuming even loss of the skin material mass for the calculations is an error, as such a calculation model does not reflect reality but only constitutes an estimate that misleads when making important operation decisions. According to the developed procedure, it is necessary to reflect the actual spatial arrangement, with the inclusion of areas experiencing steel mass loss due to corrosion, the determination of steel deflections, twist values and deflections as well as divergences of the structure from the vertical, furthermore the determination of the level of setting of the ground as well as other mechanical damage (e.g. damage caused by impacts of forklift trucks against one of the structure walls). The execution of measurements in line with the methodology presented in the paper permits the preparation of precise 2D and/ or 3D models of the existing structure and the execution of calculations, and then a percentage determination of the level of reduction of strength values. Calculations and the determination of the level of structure stability and safety must conform to EU directives and standards [5–7, 9–12]. Each stressed-skin structure should be considered individually and a similar level of degradation of similar structural solutions cannot be assumed. The conducted studies show that the durability of a stressed-skin construction depends, among others, on the type of dust and contaminants between the walls and profiles of the structure. Hygroscopic dust causes increased corrosion and additional loads that should be taken into account in the calculation model. The usage of modular coating panels for transporters according to the solution described in utility design [14] constitutes a technical solution aimed at the limitation of emission of contaminants and of uncontrolled additional loads, translating at the same time to structure operation safety. In case of calculations aimed at the evaluation of the loss of stability, the actual safety coefficient $X_0$ is used.

4. References

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