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SAFETY FACTORS IN THE DESIGN OF CORRUGATED BOARD PACKAGING

WSPÓŁCZYNNIKI BEZPIECZEŃSTWA W PROJEKTOWANIU OPAKOWAŃ Z TEKTURY FALISTEJ

ABSTRACT: The paper briefly presents the most important safety factors that are most often used in the process of estimating the load-bearing capacity of corrugated board packaging. First, the coefficients taking into account storage and transport under various environmental conditions are discussed. These factors directly increase the safety of the transported packaging by increasing the required load capacity. Coefficients that indirectly affect the value of the estimated load capacity of the packaging are discussed next. They are usually added during the estimation of the theoretical load-bearing capacity by taking into account the uncertainty related to the declared quality of the material, as well as the impact of damage to the structure of corrugated board during converting. Both types of coefficients are shown through the schemes adopted by packaging manufacturers. Unfortunately, these procedures are subject to errors or simplifications, which often lead to overestimation or underestimation of the load-bearing capacity of packaging. In both scenarios, wrong estimation involves additional costs that can be easily avoided. Therefore, determining the appropriate values of these coefficients is very important, but at the same time difficult, especially when the designed packaging will be stored in varying environmental conditions, with multiple handling and additionally transported by different means of transport.
Key words: corrugated cardboard, packaging strength, safety factors

STRESZCZENIE: W pracy pokrótce przedstawiono najważniejsze współczynniki bezpieczeństwa, które najczęściej stosuje się w procesie szacowania nośności opakowań z tektury falistej. W pierwszej kolejności, omówiono współczynniki uwzględniające warunki magazynowania i transportu. Współczynniki te bezpośrednio wpływają na zwiększenie bezpieczeństwa transportowanego opakowania poprzez zwiększenie wymaganej nośności. Omówiono również współczynniki, które pośrednio wpływają na wartość szacowanej nośności opakowania. Najczęściej są one wykorzystywane w trakcie estymacji wartości teoretycznej nośności, poprzez uwzględnienie niepewności związanej z deklarowaną jakością materiału, a także wpływem uszkodzenia struktury tektury falistej w trakcie przerobu. Oba rodzaje współczynników pokazano przez pryzmat schematów przyjętych przez producentów opakowań. Procedury te obarczone są niestety błędami lub uproszczeniami, które często prowadzą do przeszacowania lub niedoszacowania nośności opakowań. W obu scenariuszach błąd oszacowania nośności wiąże się z dodatkowymi kosztami, których łatwo można uniknąć. Dlatego tak ważne, ale jednocześnie trudne, jest określenie odpowiednich wartości tych współczynników, szczególnie gdy projektowane opakowanie będzie magazynowane w zmiennych warunkach środowiskowych, z wieloma przeładunkami i dodatkowo przewożone będzie różnymi środkami transportu.
Słowa kluczowe: tektura falista, wytrzymałość opakowań, współczynniki bezpieczeństwa

INTRODUCTION

Each professional plant converting corrugated board has implemented certain standards and procedures for selecting the optimal cardboard for packaging production. In large enterprises, this is done in centralized units by experienced designers who, in addition to skills in designing various packaging geometries, also have basic knowledge about the strength of material. Other packaging manufacturers assign to this task the quality control employees or experienced laboratory technicians, who deal with corrugated board on a daily basis, performing dozens of mechanical tests on cardboard and packaging. Finally, some companies, have set up special units in their production management departments responsible for selecting the best papers for the production of corrugated board converted into packaging. However, even the most experienced designer or quality department employee occasionally falls into the trap of routine, which can lead to costly mistakes. Sometimes these are simple mistakes, and sometimes they are long-term, systematic errors that may never have revealed themselves in any serious crisis. This article presents certain knowledge and guidance that may be useful to those responsible for the selection of the right quality material for the production of corrugated board packaging, to protect them against the pitfalls lurking ahead. Especially when routine and many years of experience begin to blind them to problems that may lead to erroneous habits.

Most of the problems related to the design of corrugated board packaging stem not from the geometry of the box but from the strength of the corrugated board, which, unlike other typical construction materials, depends to a large extent on: (a) weather conditions, (b) storage conditions and (c) transport conditions. If, on top of all these correlations, one adds a strong relationship between the static strength of corrugated board and (i) the type of paper for individual layers, (ii) the geometry of the corrugated layer, (iii) the gluing quality, (iv) the amount and type of printing, (v) the cutting technique, etc., one can quickly come to the conclusion that corrugated board is a very complicated material. The effects of the complex mechanics of corrugated board are felt by both cardboard producers and convertors.

Corrugated board manufacturers specify produced materials by providing basic information such as grammage, thickness, and, among others, the resistance of cardboard to edge crushing, popularly called in papermaking jargon the ECT parameter (from the laboratory test name – Edge Crush Test [14]). Cardboard converters base the box strength calculations primarily on the ECT specification. In order to accurately estimate the load capacity of packaging, the simple analytical calculators [1,2,6,7,10-13,16,17] or advanced numerical tools [3,8,9] can be utilized. However, in the face of a possible complaint, in addition to verification of the accuracy of the formula that was used to calculate the load capacity, other factors must also be verified. In the complex decision-making chain, there are other important factors that influence the final value of the packaging's load-bearing capacity. They are called correction or safety factors and they result from: (a) the types and number of processes that the corrugated board has gone through during the production of the packaging, (b) the environmental conditions in which the packaging is to be transported, (c) the dynamic impacts of transport (d) the palletization scheme, (e) the type of goods transported in the box, (f) the time and conditions during long-term storage, and (g) the discrepancy between the actual value of ECT and the technical specification of the material given by the cardboard manufacturer.

LOAD CAPACITY OF PACKAGING ENHANCED WITH SAFETY FACTORS

The following paragraphs describe all the most important factors influencing the assessment of the load-bearing capacity of the box. The discussion ignores the obvious uncertainty in the load acting on the most vulnerable package, usually located at the bottom of the pallet. This load depends on the number of packages placed in a single stack (i.e. above the lowest box on the pallet) and on the weight of the goods contained in each package (see Figure 1).

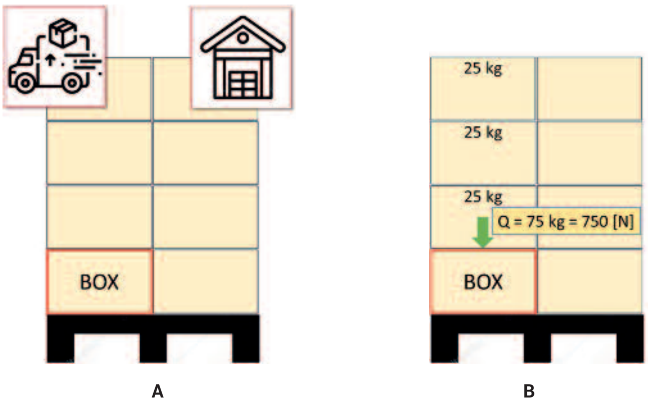

FIG.1. PALLETIZATION: (A) BOTTOM BOX DURING STORAGE AND TRANSPORT ; (B) LOAD ACTING ON THE MOST STRESSED PACKAGING

The load, Q, estimated in this way (given in [N] or [kN], less often in [kg] - remembering that [1kN] is approximately [100kg]) can be interpreted as a computational indicator determining the static load capacity of the packaging. The actual or required load capacity of the packaging is therefore obtained from the following equation:

$$P_T = Q \cdot \hat{\gamma}_d \cdot \hat{\gamma}_t \cdot \gamma_e \cdot \gamma_p, \tag{1}$$

where: $\hat{\gamma}_d \geq 1$ is a factor related to the impact of the dynamic load on the load-bearing capacity of the packaging (see Fig.2a),

$\hat{\gamma}_t \geq 1$ is a factor related to the impact of storage time (see Fig.2b) and the type of goods in the box, $\gamma_e \geq 1$ is a factor related to the influence of humidity and temperature on the load-bearing capacity of the packaging (see Fig.2c), $\gamma_p \geq 1$ is a factor related to the influence of palletization on the load-bearing capacity of the box.

The values of these coefficients depend on several parameters, e.g. on: (1) material, *m*, i.e. the type and quality of cardboard used to produce the packaging; (2) dimensions of the box, *l* x *b* x *w* (where: *l* is the length, *b* – width, and *w* – height of the packaging); (3) storage/transport time, *t*, and (4) temperature/humidity, *e*. An additional parameter may also be the type of transport, *r* (i.e. plane, ferry, car, train, etc.). Figure 2 summarizes these impacts.

Assuming that in the logistic chain the packaging may be in one of two 'states': (i) it may be stored for a certain period of time, under known or expected humidity and temperature conditions or (ii) it can be transported by one of the possible means of transport for a specified period of time and under specified environmental conditions. Of course, these states can be repeated in any configuration and for a certain finite number of cycles. If one additionally assumes that the palletization coefficient depends only on the type of cardboard, *m*, the dimensions of the box, *l* x *b* x, and the arrangement of the package on the pallet, *g*, then equation (1) takes the form:

$$P_T = Q \cdot \gamma_d(m, l \times b \times w, t, r, e) \cdot \gamma_t(m, l \times b \times w, t, e) \cdot \gamma_p(m, l \times b \times w, g), \quad (2)$$

where γ_d is a coefficient that takes into account the dynamic loads acting on the packaging under various temperature and humidity conditions, while γ_t is a coefficient taking into account long-term storage (often leading to permanent deformations, so-called material creep) under different environmental conditions.

Therefore, the correct definition of the coefficients γ_d, γ_t and γ_p requires, in addition to determining the material used to produce the packaging and its main dimensions, also the exposure time (i.e. storage or transport), the type of transport, the temperature and humidity conditions under which boxes will remain, as well as the geometric placement of the packaging on the pallet (see Fig. 3). It should be noted that the use of a cardboard spacer between subsequent layers of packaging allows the γ_p coefficient to be significantly reduced.

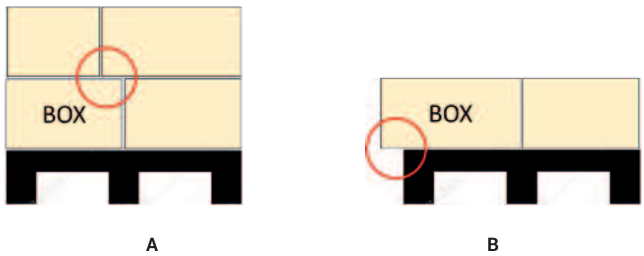

FIG. 3. PALLETIZATION: (A) SHIFTING BETWEEN SUBSEQUENT LAYERS OF BOXES (WITHOUT SPACER); (B) OVERHANGING THE PACKAGING BEYOND THE PALLET.

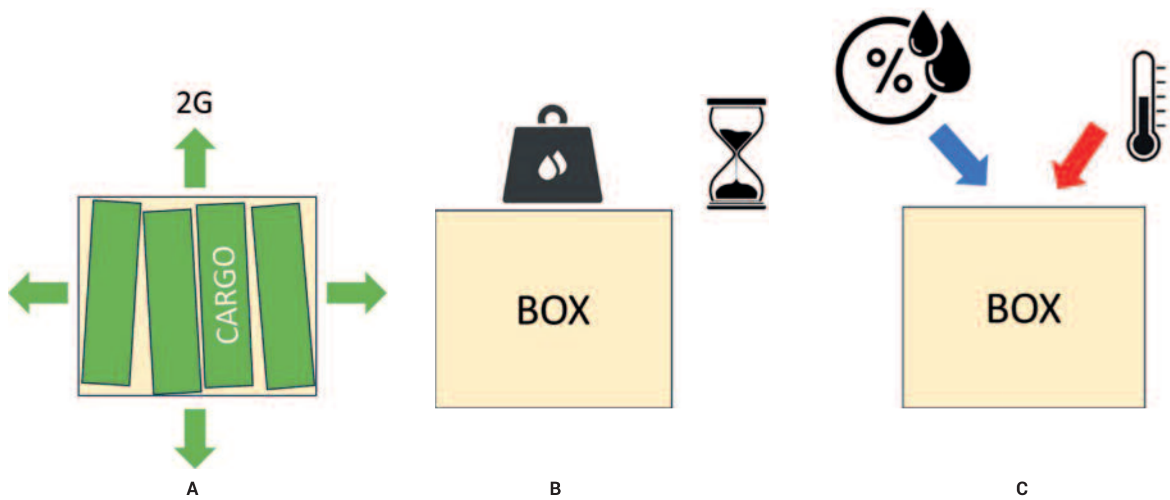

FIG.2. IMPACTS AFFECTING THE LOAD-BEARING CAPACITY OF THE PACKAGING: (A) DYNAMICS; (B) LOADING TIME; (C) TEMPERATURE AND HUMIDITY.

These coefficients are therefore complex functions of multiple variables with an a priori unknown equation. Of course, one can try to define these equations, e.g. by performing hundreds of tests and building a metamodel based on, for example, artificial neural networks. In both cases, the task is very complicated and without the use of numerical calculation tools rather impossible. In reality, many simplified tables and guides or standards are used, which are often based on simplified empirical observations.

In the next step, the value of the required load capacity of the packaging, P_T, should be verified with a static column compression test. If the obtained load-bearing capacity value, the abovementioned BCT [15], is higher than the required load-bearing capacity, then the goods transported in the packaging designed in this way should be completely safe.

Before discussing the impact of individual correction/safety factors, it should be added that in the design process, especially for repetitive transport packaging structures, various analytical formulas are increasingly being used to estimate their load capacity, instead of or in parallel with laboratory verification [1,2,10-12,16,17], analytical-numerical [6,7,13] or numerical [3,8,9]. In the case of the theoretical packaging design based on an automatic corrugated board selection procedure, further factors related to the material specification error and the impact of cardboard processing (printing, cutting, lamination, etc.) on its load-bearing capacity should be additionally taken into account. In order to illustrate this procedure, for simplicity, the most popular formula for BCT estimation is chosen, called the short McKee formula [12]:

$$P_M = \alpha \cdot ECT \cdot \sqrt{\hat{h}Z}, \tag{3}$$

where: α is the correlation coefficient, which should be determined by fitting the model to a selected, laboratory-tested set of packaging (it is often forgotten that this coefficient is not universal for all types of packaging), *ECT* is the value of edge crushing resistance of corrugated board – optimally, the *ECT* value of the exact material from which a given series of packaging will be produced should be used here (unfortunately erroneously, the average value given by the manufacturer in the specification often appears here – see Fig. 4), $\hat{h}$ is the thickness of the corrugated cardboard taking into account the impact of cardboard converting (unfortunately a cardboard thickness without taking into account the crushing caused by converting often appears here, which artificially inflates the BCT value), while *Z* is the circumference of the packaging base (*2l* + *2b*).

The incorrect use of the average value and the initial (uncreased) cardboard thickness value does not have to be noticed, even by experienced designers. This is due to the 'magical' properties of the α coefficient, which can take any value during the calibration process. Unfortunately, the incorrect determination of this coefficient results in a systematic underestimation or overestimation of the BCT values of other packages estimated using formula (3) calibrated with incorrect *ECT* and $\hat{h}$ values. Figure 4 shows the average value of ECT compared to the actual values obtained during the year. This chart clearly shows that using the average value instead of the actual ECT value in formula (3) can introduce significant error, especially when strength calculations are performed during periods when the relative air humidity reaches extreme values.

In order to take into account material uncertainties and crush effects, the following relationships can be introduced:

$$ECT = \gamma_m \overline{ECT}, \tag{4}$$

where: $1 \leq \gamma_m \leq 1$ is a reducing or increasing factor to account for the error related to the mismatch between the manufacturer's specifications and the actual *ECT* value, while $\overline{ECT}$ is the average value given in the specification.

The uncertainty associated with cardboard converting can be taken into account as follows:

$$\hat{h} = \gamma_n \cdot h, \tag{5}$$

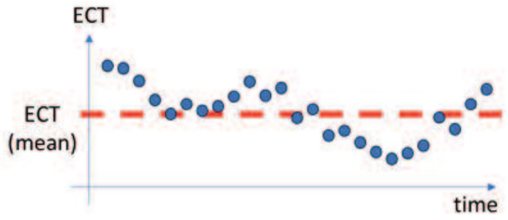

FIG.4. AVERAGE VALUE ($\overline{ECT}$) VS ECT VALUES AS A FUNCTION OF TIME

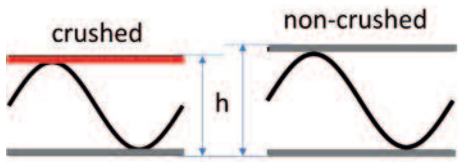

FIG.5. THICKNESS OF CORRUGATED BOARD, h, AFTER AND BEFORE CONVERTING.

where: ≤ 1 is a reducing factor that allows to take into account micro-damage to the cardboard caused by printing (number of colors and printing area), lamination, die used, etc., while h is the initial thickness of undamaged cardboard.

Figure 5 shows the impact of crushing the fluting on the change in height of the cardboard (unfortunately, the additional change in the thickness of the corrugated board often remains "hidden", among others, in micro-damages in the fluting, which, due to its elasticity, often returns almost to its original shape, although the actual change in thickness as a result of crushing is much greater than the change in thickness that we observe with the naked eye).

The theoretical load capacity of the packaging, taking into account material uncertainties and the impact of converting, is therefore:

$$P_M = \alpha \cdot \gamma_m \overline{ECT} \cdot \sqrt{\gamma_n h\, Z}. \tag{6}$$

Finally, one can obtain the following relationship:

$$P_T \le BCT \le P_M, \tag{7}$$

from which an important observation can be derived – the calculated value of P_T should be lower than the actual (measured) value of *BCT*, which in turn should be lower than the theoretical (estimated) P_M value.

Using the above relationship, one can directly determine, for example, the optimal cardboard through an iterative process of maximization the load-bearing capacity of the package or by directly modifying equations (3) and (6) to determine the *ECT* value for the selected flute.

For example, for an initially adopted three-layer corrugated board with B flute and an a priori assumed thickness of h = 2.5 mm (which in the general should not take a constant value, because it depends on the type and grammage of the utilized papers) and for an exemplary packaging with base dimensions of 200 mm and 200 mm, one gets:

$$\overline{ECT}_B = \frac{Q \cdot \gamma_d \cdot \gamma_t \cdot \gamma_p}{\alpha \cdot \gamma_m \cdot \sqrt{\gamma_n 2.5 \cdot 800}}. \tag{8}$$

The α coefficient can be estimated relatively quickly on the basis of many laboratory tests and the experience of designers or quality control staff. It is equally easy to obtain the load value *Q*, which can be obtained by multiplying the weight of one package with the goods by the number of layers of packaging in a single stack on a pallet (see Fig. 1b).

However, estimating the remaining coefficients is not a trivial issue – selecting appropriate values requires extensive experience, and their underestimation may result in costly complaints. Therefore, these coefficients are usually taken with a large margin, resulting in other underestimations (e.g. an incorrectly selected safety factor γ_m related to the specification error is often omitted).

As already mentioned, each coefficient is responsible for certain specific environmental and transport conditions that directly or indirectly influence its decline. However, often these conditions are not known a priori or only limited information is available. In such situations, estimating correction factors is quite a challenge. So let's focus on those coefficients whose estimation is much simpler. These include, for example, γ_m which takes into account the discrepancy of the actual *ECT* value with the manufacturer's specification.

The specification of corrugated board is usually based on average *ECT* values that have been determined for the individual qualities of cardboard offered by the manufacturer. However, adopting an average value for calculations may involve a significant error, which is related, among others, to the fact that the *ECT* of a particular corrugated board varies depending on the season in which it is produced. Additionally, manufacturers often change the input papers to produce a specific quality of corrugated board. This is due to a change in supplier or lack of a particular paper in stock. Of course, these changes are not recorded in the specification. This results in differences ranging from several to dozen of percent (see Fig. 6). If we add to this the change in the mechanical parameters of corrugated board, that result from differences in humidity in different seasons, the differences between the current value and the averaged one (in the specification) may reach up to 20%. This leads to a situation where the correction factor γ_m can reach a value of 0.8 in extreme cases.

Another underestimated correction (safety) factor is the γ_n factor, which takes into account micro-damage to corrugated board resulting from cardboard converting. It is often forgotten that both the specification and the thickness of corrugated board provided by the manufacturer refer to freshly produced cardboard and do not take into account converting processes, i.e. printing, lamination and the type of die-cutting on flat or rotary dies. All the mentioned processes always have a destructive effect on the cardboard, but this impact is rarely taken into account by designers. Publication [5] presents a method for estimating the impact of micro-damage on corrugated board, i.e. the so-called crush created during converting, on its mechanical parameters. This work shows that this impact can again reach several dozen percent and can be easily estimated using, e.g., torsion tests [4].

Another safety factor should be related to the impact of holes and perforations on the load-bearing capacity of the packaging. Obviously, the formula presented in equation (3) does not allow for the inclusion of holes or perforations in the procedure for estimating the load-bearing capacity of corrugated board packaging. However, a number of methods can be found in the literature that make it possible to precisely determine the weakening of the packaging's strength, e.g. resulting from holes [6] or perforations [7]. However, the application of these techniques requires complex calculations of the critical forces of individual packaging walls. To avoid this, one can use commercially available calculation systems, e.g. BSE System [3], which also takes into account the impact of holes and perforations on the load-bearing capacity of packaging, but at the same time requires the correct definition of the hole geometry and the type of cutting used in the perforation.

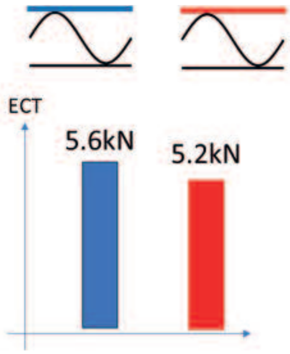

FIG.6. VALUE FOR THE SELECTED CORRUGATED CARDBOARD (E.G. B300), FOR THE PRODUCTION OF WHICH TWO DIFFERENT PAPERS WERE USED ON ONE OF THE FLAT LAYERS (BLUE COLOR – PAPER FROM THE SPECIFICATION; RED COLOR - SUBSTITUTE PAPER).

Incorrect definition of perforation (cutting type) and/or ventilation holes may result in errors of up to several percent.

SUMMARY

Failure in determining all possible correction factors correctly can lead to errors of several dozen of percent in the estimation of the load capacity of the packaging. As already mentioned, the lack of negative effects resulting from not taking some of them into account at all (the value is one) or misestimating their value may still go unnoticed even by qualified designers, because even poorly chosen safety factors can compensate their impact with other overestimated factors in the global equation. This happens when the designer does not have full knowledge of the transport conditions or, out of pure precaution, assumes safety factors at a very high level, e.g.

$$\gamma_d \cdot \gamma_t \cdot \gamma_p = 5.0 \tag{9}$$

instead of e.g. 3.0 or 3.5. This is a significant overestimation, which of γ_n course allows to avoids costly claims, but at the same time completely blocks the possibility of real savings, and also limits the correct use of the full capabilities of computational tools, such as [3].

The correct determination of safety factors is not easy and requires many a great deal of research, both under the various climatic conditions affecting the packaging and taking into account the dynamic impacts arising during transport, as well as combination of these factors, while taking into account the timing of the individual effects, their order (sequence of changes) and full interaction between them. Although this seems very difficult and time-consuming, intensive research is already being carried out worldwide, especially in Europe, including Poland, to determine all these coefficients. Ultimately, the stakes are high, because reducing safety factors by even a few or a dozen percent, while maintaining the required load capacity, can result in huge savings. Fortunately, more and more large packaging manufacturers, as well as their key customers, are increasingly aware that the sound knowledge of their own product and processes during production, as well as after leaving the factory, brings financial benefits. This allows us to remain realistically optimistic that newer solutions based on knowledge and science in the packaging and corrugated board industry will come sooner rather than later.

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