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Estimation of the Compressive Strength of Cardboard Boxes Including Packaging Overhanging on the Pallet

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Abstract: In this study, a numerical investigation was conducted on a verified packaging model, which sticks out beyond the pallet base area, which will evidently weaken its load-bearing capacity. This could lead to damage of the protected goods transported within this packaging. It might also result in the unnecessary overengineered design of the packaging, particularly when the potential for overhanging is anticipated beforehand, but its exact extent is not known. The article analyzed hundreds of cases, varying in terms of packaging dimensions (from 150 mm up to 600 mm), the extent of protrusion beyond the edge of the pallet (from 1% to 50% of box dimensions) and the use of various corrugated boards (B-, C-, EB- and BC-flute), in order to assess the decrease in the load-bearing capacity of the packaging compared to reference packaging, which was not overhanging on a pallet. For instance, it appeared that the decrease in the load-bearing capacity of the packaging when overhanging was insensitive to the corrugated cardboard material used. Additionally, the decrease in box strength was rapid while overhanging, even for a small value of overhanging.

Keywords: pallet overhanging; finite element method modeling; computational mechanics; composite structures; box strength

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1. Introduction

The packaging and distribution industry, which is constantly evolving, plays a crucial role not only in the corrugated board sector but also for its consumers. Cardboard, a leading material for packaging a wide range of goods, is predominantly chosen due to its biodegradable properties and environmental benefits. The production of corrugated board packaging offers ease and flexibility, enabling the creation of boxes with various shapes and sizes [1]. These boxes can be designed with ventilation options and also serve dual functions for transport and display. The potential for extensive graphic design on cardboard boxes makes them highly appealing, often leading to increased customer interest in the products inside.

Modern e-commerce significantly leverages corrugated board for the efficient distribution and transportation of goods, including return processes. It is commonly used in the form of e-commerce parcels or on base pallets. Amid the current financial crisis, companies are increasingly focused on cost-saving measures [1,2]. In this context, corrugated board emerges as an ideal packaging material due to its compact storage and ease of disposal. Its added ecological value, particularly in terms of recyclability, also contributes to reducing waste management costs [3]. From a mechanical perspective, cardboard packaging offers remarkable strength and durability relative to its weight [4]. After transportation, these boxes are easily opened while maintaining the quality of the packaged products, thus enabling their reuse and saving both time and money.

Several methods are available in the market for assessing the strength of corrugated board boxes. One option is to utilize advanced systems, such as FEMAT [5], or to employ well-established analytical procedures [6–13]. A commonly used approach involves conducting a series of iterative experiments. This process includes the design phase of the box, followed by validation and optimization testing in a cyclical manner. More sophisticated techniques, such as numerical methods [14–19], necessitate the measurement of various material parameters, but only a limited number of laboratories are equipped with all the necessary tools for such detailed analysis. In packaging technology, the strength of corrugated board is typically tested for its compressive, bending or bursting capabilities. Another crucial material property—especially significant for the durability of corrugated board boxes—is humidity. From a practical standpoint, the most important and useful tests for determining this are the box compression test (BCT) [20] and the edge crush test (ECT) [21].

In the field of corrugated board research, the literature offers a variety of analytical formulae designed to predict the compressive strength of boxes. It is essential for these formulae to be as straightforward as possible to ensure their practicality and effectiveness. Various methods have been proposed, and the parameters involved in these methods can be categorized into three main groups: those pertaining to paper, cardboard and boxes [6]. Within the first group, two notable tests are recognized: the ring crush test (RCT) and the Concora liner test (CLT). This group also considers factors such as the type of liner, weights of liner and fluting, corrugation ratio and a constant related to fluting. For the analysis of cardboard, the important parameters include the thickness, flexural stiffnesses in the machine direction (MD) and cross direction (CD), edge crush test (ECT) and moisture measurement. Lastly, the parameters describing the packaging encompass dimensions, perimeter, the factor of applied load, duration of stacking, buckling and printed factors.

The parameters previously mentioned, such as those for paper (RCT, flute constant) and for boxes (perimeter, box constant), were utilized by Kellicut and Landt in 1952 to predict the compressive strength of boxes, marking one of the earliest theses in this field [7]. Maltenfort linked the critical force in the box compression test (BCT) with paper parameters (Concora liner test (CLT), liner type) and the dimensions of the box [8]. In 1963, the most popular and widely adopted model was proposed by McKee, Gander and Wachuta [9]. This model considered the parameters for paperboard (edge crush test (ECT), flexural stiffnesses) and box perimeter. It was primarily used for relatively simple containers as a practical formula. Several researchers have since attempted to broaden the scope of McKee's model. In 1985, Allerby et al. [10] modified the formula to adjust McKee's constant and exponents. Two years later, Schrampfer et al. [11] expanded the range of equipment and cutting methods based on McKee's concept. Building on this, Batelka et al. [12] incorporated the box dimensions into the equation. Concurrently, Urbanik et al. [13] factored in the Poisson ratio. In McKee et al.'s publication [9], a specific constant value was decisively selected, requiring calibration for various types of boxes, resulting in a somewhat limited method suitable only for certain standard boxes. More recently, in 2020, Garbowski et al. [14] analyzed this constant in more complex scenarios. If the analysis needed to include transversal shear stiffness, additional tests were required. This aspect was further examined and modified by Aviles et al. [22], and again, in 2020, by Garbowski et al. [23].

Conversely, numerical methods are frequently employed for advanced analysis of the strength of corrugated boxes. The finite element method (FEM) stands out as the most comprehensive and effective technique for this purpose. It is extensively used in the analysis of corrugated board boxes, particularly for studying buckling phenomena [16] and the transverse shear stiffness of corrugated boards [17,24].

Corrugated paperboards are often modeled as sandwich panels [25], a technique widely used in numerical modeling by numerous scientists. In today's context, where cost savings are a primary goal, it is crucial to minimize computational expenses. Simultaneously, achieving precise results is essential, underscoring the importance of using models, which realistically simplify the analyzed bodies without losing touch with actual conditions. Multi-layered materials [26–28] and thus structures composed of layered materials can be effectively utilized in numerical simulations by applying a process known as homogenization [1,14]. This process simplifies the structure of the corrugated board cross-section, allowing the material composed of various layers to be represented as a single layer with composite effective properties. As a result, external loads applied to the homogenized structure are expected to produce effects very similar to those on a structure with a core made of different materials.

Hohe [29] proposed a homogenization method based on strain energy for sandwich panels. In this proposal, he considered representative elements of both heterogeneous and homogenized structures. Buannic et al. [30] introduced a series of homogenization methods, leading to the derivation of a shell equivalent to pure bending. Biancolini [31] utilized the FEM for the micromechanical analysis of plates. The torsional rigidity of orthotropic sandwich plates was determined by decomposing the plates into two beams along their respective directions, a method developed by Abbès and Guo [32]. Marek and Grabowski compared two homogenization approaches: one based on the classical laminated plate theory and the deformation energy equivalence method [33], and the other on inverse analysis [34].

In their study, Kim et al. [35] presented the results of box compression tests and analyzed various regression models to explore how pallet overhang affects the reduction in effective box compression strength (BCT). Their observations revealed that effective BCT diminishes as the overhang increases, a trend also noted in prior studies. Specifically, they found that effective BCT could decrease by about 33% when transporting boxes with a substantial overhang on one side. The key factors in determining the degree of effective BCT reduction due to pallet overhang include the overhang's magnitude on the short and/or long side of the box, the presence of an adjacent overhang, the box perimeter and the board type. The study indicates the need for more comprehensive research to thoroughly understand the impact of pallet overhang on effective BCT, especially in terms of the box height, aspect ratio and board types not yet investigated. Moreover, examining a wider array of scenarios, particularly those involving a 7.6 cm (3 in.) overhang, is essential to overcoming the limitations on fit and leverage identified in the current study.

In conclusion, the strength of corrugated board boxes is known to be influenced by various factors, including common ones, such as perforation, printing and moisture. Additionally, logistical factors may lead to a change in the position of boxes in the pattern of their arrangement on pallets, which also directly affects the load-bearing capacity of the transport packaging. This work focused on the numerical analysis of a large number of packaging cases, which, due to overhanging on a pallet, experience a reduction in their load-bearing capacity. Following the initial calibration of the model with data from Kim et al., the numerical model was employed to analyze numerous cases. These varied not only in the box dimensions and overhang size but also in the type of material used for the packaging.

2. Materials and Methods

2.1. Workflow of the Study

The main aim of the study is to estimate the influence of packaging overhanging at the pallet on the box compression strength of the FEFCO F201 packaging. To achieve this goal, the finite element method models of the box compression test were built for different packaging geometries and using several types of corrugated boards. Moreover, to quantify the influence of the size of overhang comprehensively, several magnitudes of overhanging were considered for three directions, i.e., along the short side, long side and in the diagonal direction of the box. Reference models were prepared, in which the uniform upper and lower boundary conditions were assumed, i.e., without overhanging (for more details, see Section 2.2). Additionally, before the main computations, the validation of the model was performed using the experimental data presented by Kim et al. [35]. Details regarding validation are presented in Section 3.1. In Section 3.2, the main results of the computations are presented; the target models are also described in Section 2.2 with all numerical and modeling details, such as material modeling, both constitutive approach and material parameters, boundary conditions and finite elements used.

To investigate the topic comprehensively, various dimensions of the box were analyzed. The following dimensions of length L, width B and height H were considered: 150, 300, 450 and 600 mm. The box designs with all dimensional combinations without repetitions were modeled, resulting in 64 designs (4 × 4 × 4), which were finally reduced to 40 cases. All geometries are given in the tables in Appendix A. Later in the article, each packaging is labeled with its dimensions, e.g., a box with a length of 450 mm, a width of 300 mm and a height of 600 mm is marked as 450 × 300 × 600.

Several corrugated board materials were adopted, which also allowed the board type space to be explored. After successful validation of corrugated materials assumed based on the paper by Kim et al. [35], three- and five-layer boards were used in this study. Namely, the boards with fluting types B, C, EB and BC were assumed. The thicknesses of the boards were 2.95, 4.01, 4.15 and 6.65 mm, respectively. The material samples were conditioned in accordance with the TAPPI T402 laboratory standard [36], which specifies a standard atmosphere for conditioning and testing papers, cardboards, etc. Therefore, the relative humidity in the pre-conditioning chamber was set at 50% and the temperature at 23 °C.

The main topic of this study is to quantify the reduction in box compression strength due to packaging overhanging from the pallet. Therefore, nine overhang magnitudes were assumed, namely 1%, 3%, 5%, 10%, 15%, 20%, 25%, 35% and 50% of the shorter wall, longer wall and along the diagonal direction. The BCT results of these cases, labeled as BCT^{oh}, were confronted with reference cases, labeled as BCT^{ref}, where no overhanging was assumed. The schematic workflow of the study is presented in Figure 1.

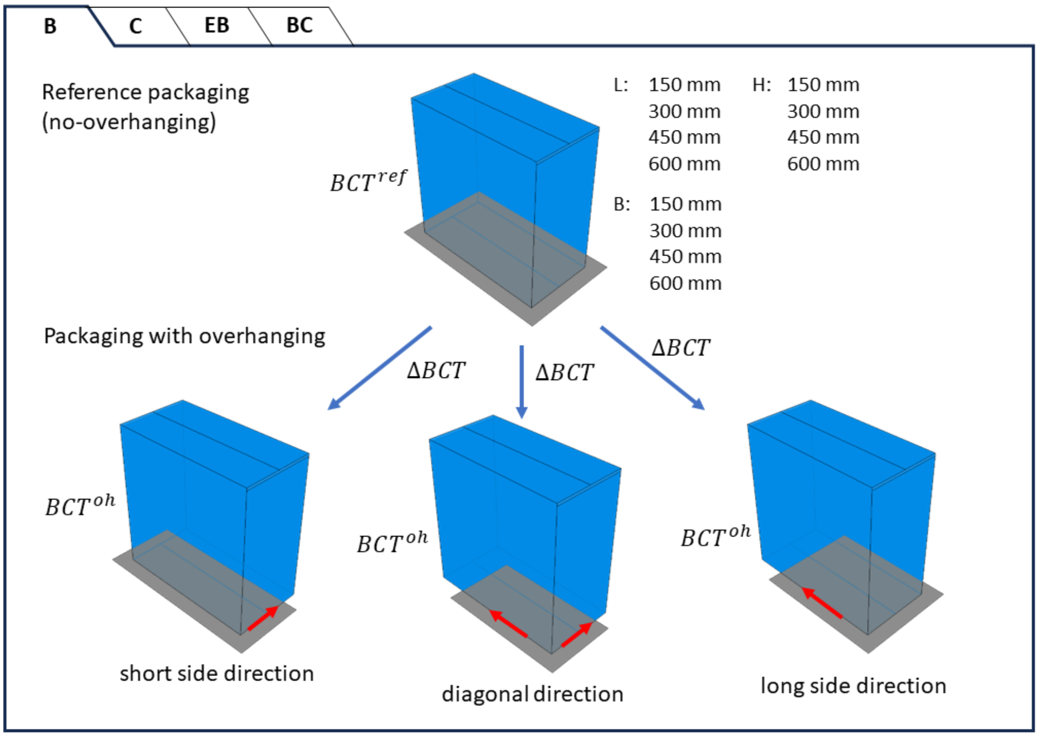


Figure 1. Graphical abstract of the study presenting the reference packaging and packaging with three types of overhanging.

2.2. Numerical Modeling of Corrugated Board Packaging including Overhanging

In order to examine the impact of overhang on the load-bearing capacity of the packaging, numerical models were created in commercial FE software (Abaqus Unified

FEA 2020 [37]). A total of 1120 different packaging variants with possible combinations of overhanging were analyzed for each of the four selected cardboards, which gave a total of 4480 cases. In all of the 4480 numerical models, the linear elastic orthotropic constitutive model with Hill plasticity [38] was adopted. The Hill model is an extension of von Mises plasticity. The addition of the Hill potential indirectly decreases the strength of the cardboard in the machine direction. The material parameters of the boards were acquired using BSE System [5] via mechanical tests of bending, edge crushing, shearing and twisting.

Five board samples were used for each test of the particular board to obtain a reliable representation of mechanical properties of the material for later use in numerical modeling. The final material parameters used in the study are presented in Table 1, where E_1 is the Young modulus in the machine direction; E_2 is the Young modulus in the cross direction; ν_{12} is the Poisson ratio; G_{12} is the Kirchhoff modulus; G_{13} and G_{23} are the transversal shear stiffnesses; σ_0 is the yield strength; and R_{11} is the yield strength factor according to the Hill potential, which is applied in the machine direction [37].

Table 1. Material constants for the constitutive models of corrugated boards used in the computations.

Board	E_1 (MPa)	E_2 (MPa)	ν_{12} (–)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)	σ_0 (MPa)	R_{11} (–)
B	2317	969	0.46	3348	3	5	1.833	0.857
C	1420	833	0.39	3516	3	5	1.538	0.701
EB	954	585	0.38	2344	4	8	1.363	0.800
BC	1176	684	0.39	2397	4	6	1.720	0.800

In the finite element method (FEM) model built in Abaqus FEA environment, only the load-bearing walls of the box were simulated. The top and bottom flaps were taken into account by applying appropriate boundary conditions, specifically blocking out-of-plane translational displacements at the top and bottom edges of the packaging. In preliminary analyses, the behavior of the packaging with modeled top and bottom flaps was checked. The resulting decreases in load capacity due to overhanging turned out to be smaller than those obtained in the main phase of calculations. It follows that replacing the flaps with appropriate boundary conditions places us on the safe side. To simulate the compression test, downward vertical displacement was applied to the upper edges until the maximum load capacity of the box was achieved. Moreover, depending on the presence or absence of overhanging, vertical displacement was blocked on the entire length of the bottom edges or only on their part depending on the overhanging magnitude assumed. In Figure 2, the boundary conditions and the finite element mesh for several overhanging variants for a 300 × 150 × 300 box are shown.

The strength analysis of each packaging consisted of two stages. In the first step, a buckling analysis was performed, from which the shapes of global imperfections were obtained. In the second calculation step, the first mode from the buckling analysis was applied to the box, which was loaded kinematically with vertical displacement until the maximum load-bearing capacity was achieved.

Buckling and compression analyses were performed for each of the 4480 variants of the material, geometry and overhanging, which gave a total of 8960 analyses. In all models, the four-node quadrilateral shell elements with full integration were applied, labeled as S4 according to Abaqus FEA [37]. For each variant, the FEM mesh was selected individually in order not to exceed 1000 finite element nodes. For example, for the 300 × 150 × 300 box with 20% diagonal overhang (shown in Figure 2d), a global mesh size of 19 mm was assumed, which resulted in 884 nodes, 768 elements and 5304 degrees of freedom. A thorough convergence study was conducted to ensure the accuracy of our results. Given the extensive computations involved—almost 9000 in total—a thoughtful choice was made regarding the number of finite element analyses. This decision was aimed at maintaining computational efficiency while ensuring the precision required for meaningful outcomes, ensured by the convergence study.

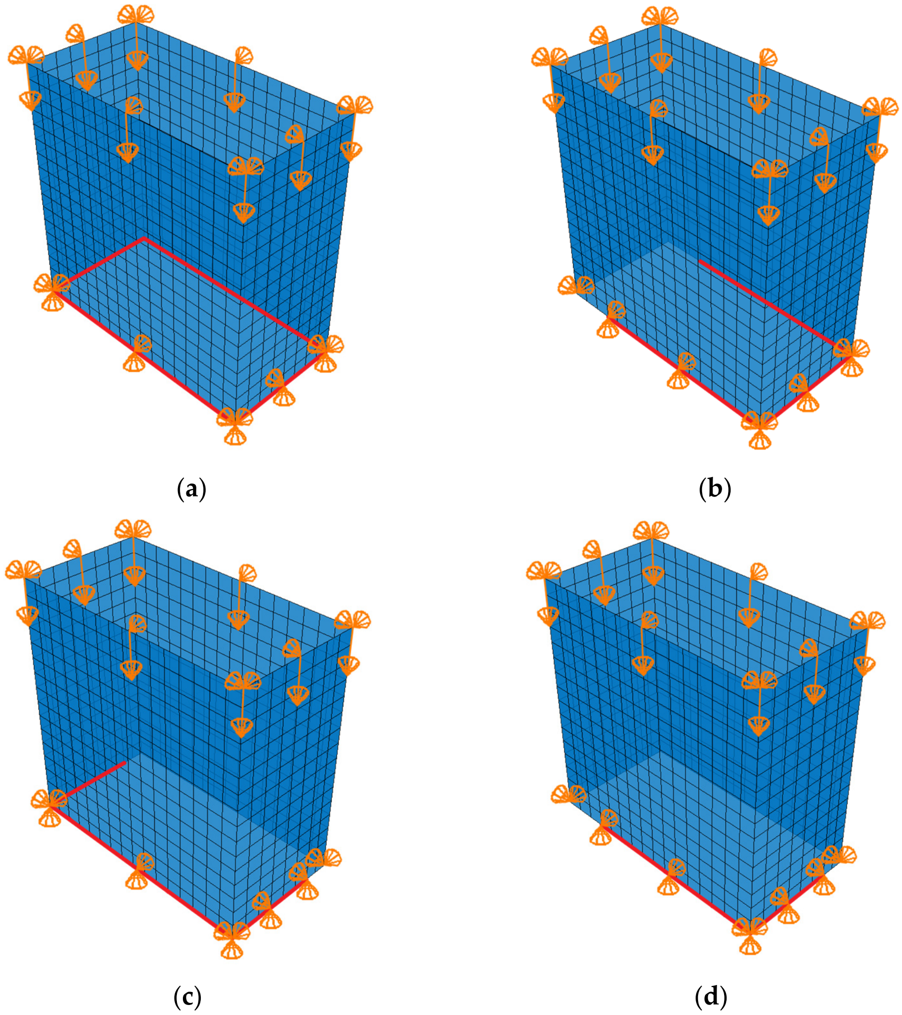


Figure 2. Boundary conditions and finite element mesh of a 300 × 150 × 300 box with (**a**) no overhanging, (**b**) 20% long-side overhanging, (**c**) 20% short-side overhanging and (**d**) 20% diagonal overhanging.

3. Results

3.1. Validation of Numerical Model of Corrugated Board Packaging

The finite element model of packaging with overhanging subjected to column compression used in this paper was validated with reference to the literature outcomes achieved by Kim et al. [35]. In that paper, many compression tests were carried out on overhanging packaging for various dimensions of flap boxes (FEFCO code F201) and multiple scenarios of overhanging, i.e., along the short, long and diagonal direction. Two corrugated boards, labeled as 32 ECT C-flute and 48 ECT BC-flute, were considered. The validation consisted of mimicking the selected tests conducted for two materials considered in the reference study. For this purpose, based on the board specifications in Ref. [35], two similar boards were found and mechanically tested to acquire the material parameters via BSE System [5] for validation. For comparison, please see Table 2.

For validation, the case with dimensions of 300 × 250 × 250 was selected and modeled using the same approach, which was described in Section 2.2. The numerical results, which prove the successful validation of both boards used (32 ECT C-flute and 48 ECT BC-flute), are shown in the last column in Table 2. The percentage error for 32 ECT C-flute and 48 ECT BC-flute boards—comparing the test outcome in Ref. [35] with the simulated outcome obtained with the modeling approach used in this study—was 4.4% and 0.9%, respectively. This was a very good result, keeping in mind that the material selection was difficult.

Table 2. Specifications of boards used in Ref. [35] and for validation of the numerical model (with standard deviation, where it was possible to calculate).

Board	Grammage ± σ (g)	*ECT* ± σ (N/mm)	Compression Strength of F201 Box ± σ (N)
32 ECT C-flute [35]	468	5.60	2390 ± 158
C flute	458 ± 2	5.47 ± 0.07	2495 (4.4%)
48 ECT BC-flute [35]	707	8.40	3970 ± 246
BC flute	730 ± 53	8.25 ± 0.34	4006 (0.9%)

3.2. The Influence of Packaging Overhanging on the Load-Bearing Capacity of the Packaging

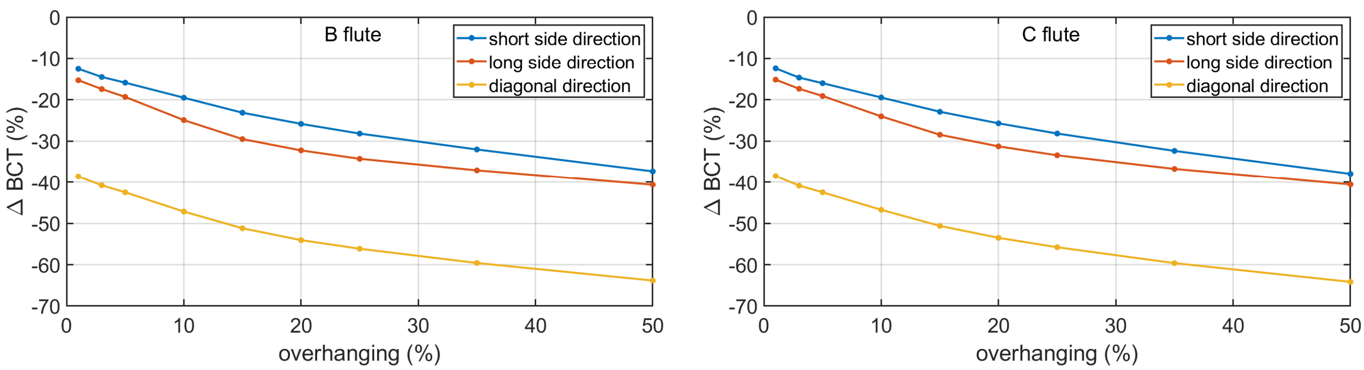
According to the numerical research scenario designed, 4480 strength FE simulations were performed. This included 40 different box dimensions, 10 overhanging positions (including the reference as no-overhanging and 9 shifts from 1% to 50%) for 3 directions (short-side direction, long-side direction and diagonal direction) and 4 types of corrugated board (B, C, EB and BC). All results data were sorted by types of corrugated board and attached in Appendix A. Due to the extensiveness of the results, only selected ones are presented in the paragraphs below with specific design features. The reference BCT values, i.e., for the no-overhanging case, are shown, as well as their counterpart cases with overhanging; the percentage BCT reduction is also presented. The BCT reductions were computed as

$$\Delta BCT = \left(\frac{BCT^{oh}}{BCT^{ref}} - 1 \right) \times 100\%, \quad (1)$$

where BCT^{oh} is the box compression strength with particular overhanging (along the short-side, long-side or diagonal direction), while BCT^{ref} is the reference box compression strength, i.e., for the no-overhanging case.

3.3. Influence of the Type of Corrugated Board

In the research study, four types of corrugated board were analyzed, namely B-, C-, EB- and BC-flute boards (for more details, see Sections 2.1 and 2.2). In this section, for easier comparison, the data for each board type are averaged for all 40 boxes, varied with dimensions and presented in Figure 3. Therefore, for each board type, the short-side, the long-side and the diagonal direction BCT reduction curves were obtained for various overhanging types considered.



(**a**) (**b**)

Figure 3. *Cont.*

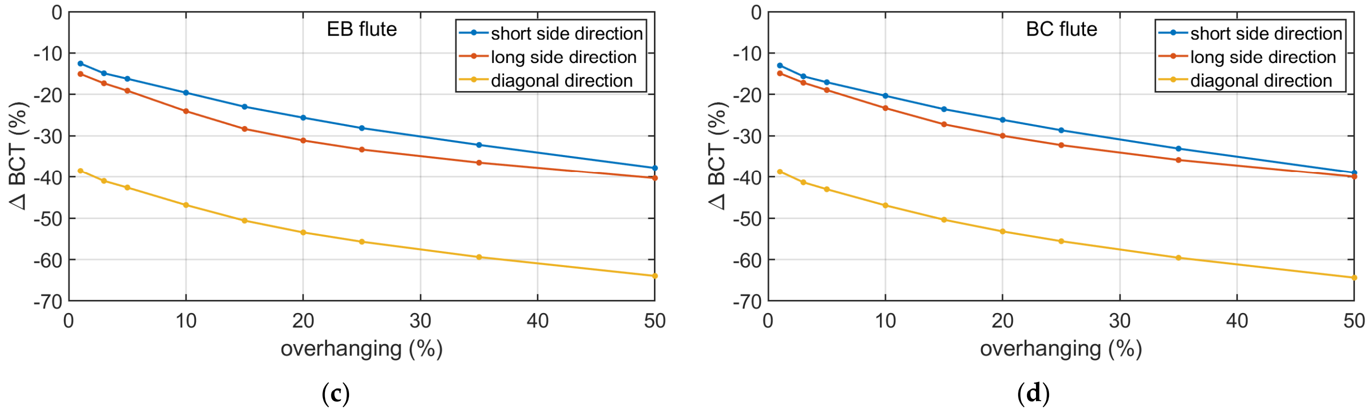


Figure 3. Mean box compression strength reduction in packaging with overhanging made of different corrugated boards: (**a**) B-flute, (**b**) C-flute, (**c**) EB-flute and (**d**) BC-flute.

3.4. Cubic Packaging

In the research study, four designs of boxes with cubic shape were considered, namely 150 × 150 × 150, 300 × 300 × 300, 450 × 450 × 450 and 600 × 600 × 600 (for more details, see Section 2.1). The results for those cases are shown in Figure 4 for all board types analyzed. Here, the short side and long side do not apply; therefore, only the side and diagonal directions are presented in the figure. The curves for the same box dimensions are grouped by colors.

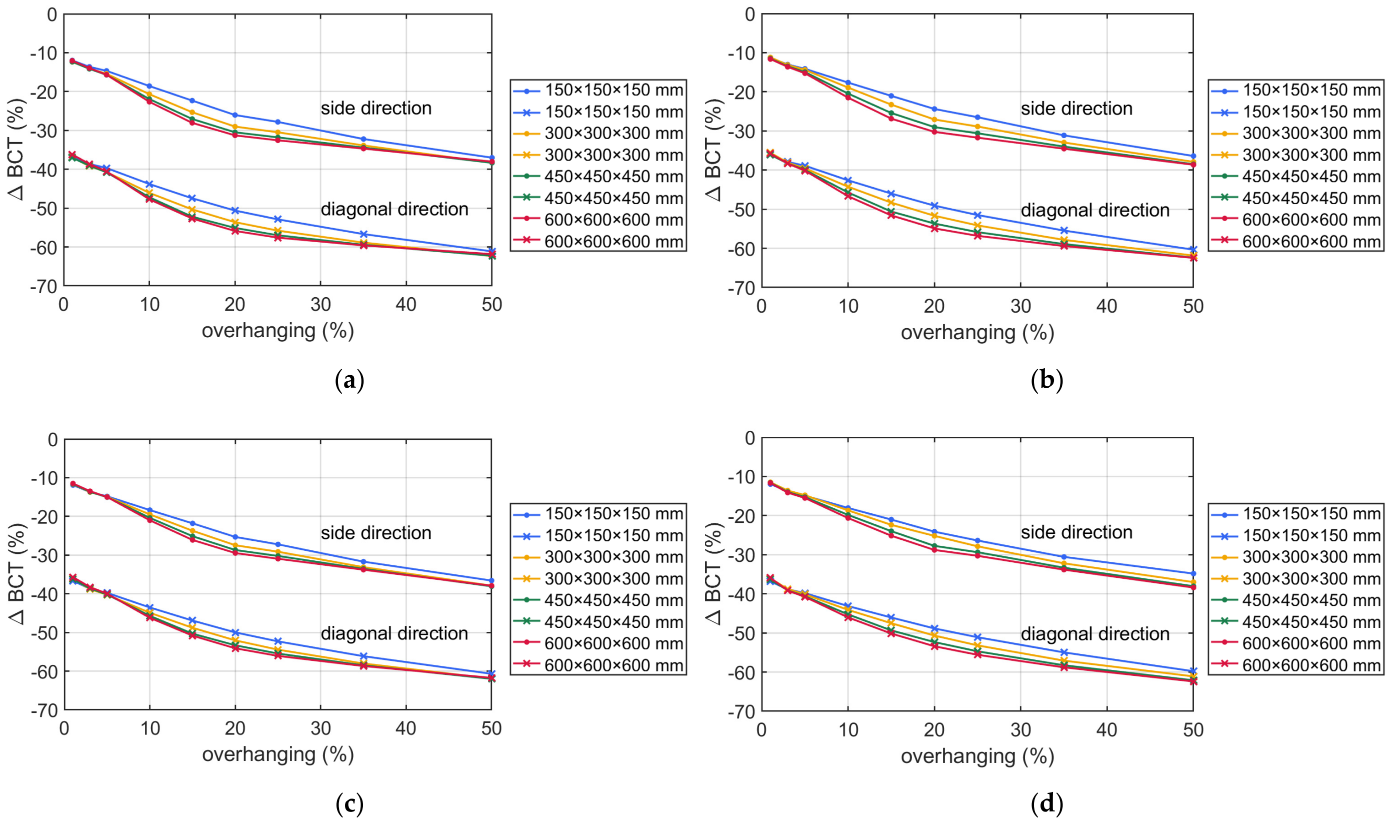


Figure 4. Box compression strength reduction in cubic packaging with overhanging made of different corrugated boards: (**a**) B-flute, (**b**) C-flute, (**c**) EB-flute and (**d**) BC-flute.

3.5. Column Type Packaging with a Square Base

Based on all cases computed in the research study, the results of cases with a square base (150 × 150 mm) and increasing height are selected and presented in Figure 5 for all types of boards considered. Here, the short side and long side do not apply; therefore, only the side and diagonal directions are presented in the figure. The curves for the same box dimensions are grouped by colors.

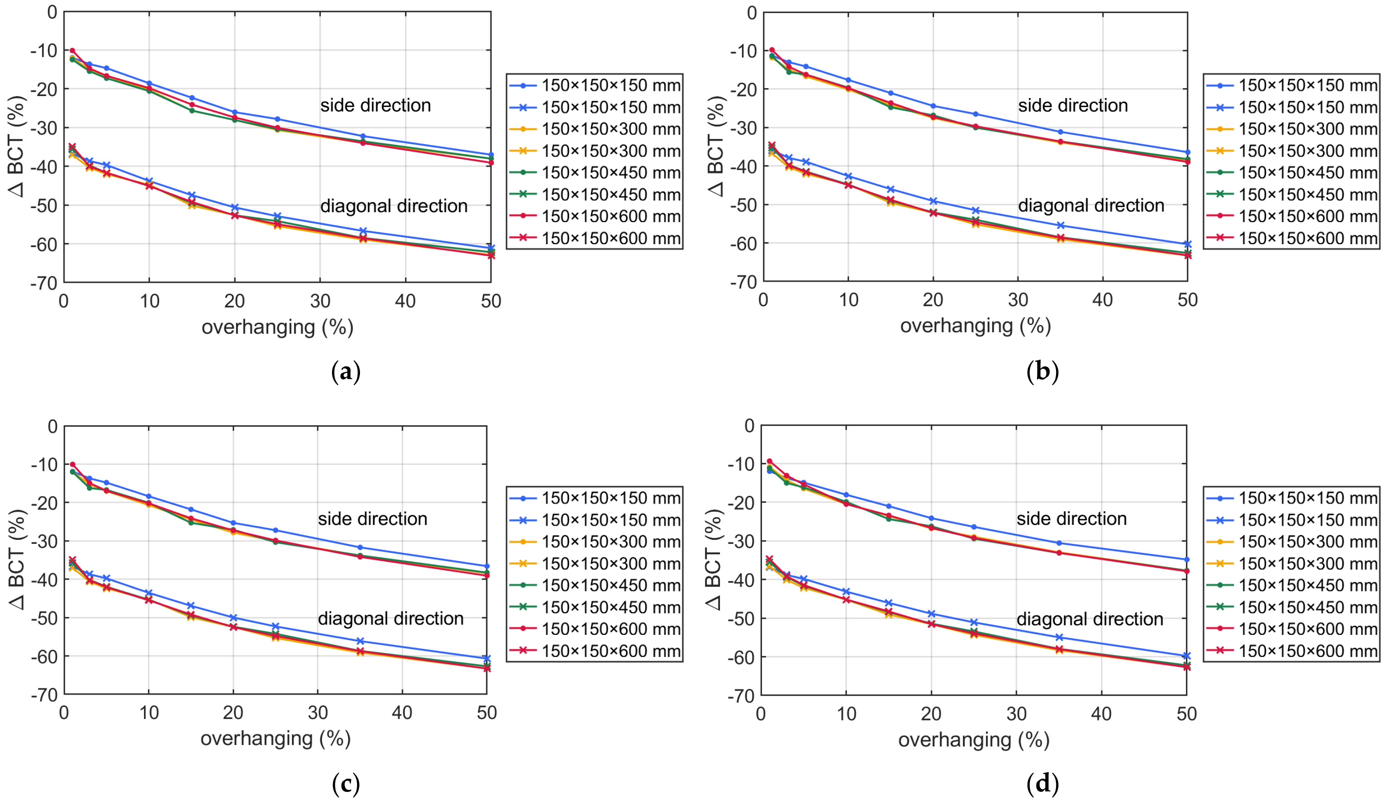


Figure 5. Box compression strength reduction due to overhanging in packaging with a square base (150 × 150) with increasing height made of different corrugated boards: (**a**) B-flute, (**b**) C-flute, (**c**) EB-flute and (**d**) BC-flute.

3.6. Flat Type Packaging with a Square Base

Based on all cases computed in the research study, the results of cases with a square base (600 × 600 mm) and increasing height are selected and presented in Figure 6 for all types of boards considered. Here, the short side and long side do not apply; therefore, only the side and diagonal directions are presented in the figure. The curves for the same box dimensions are grouped by colors.

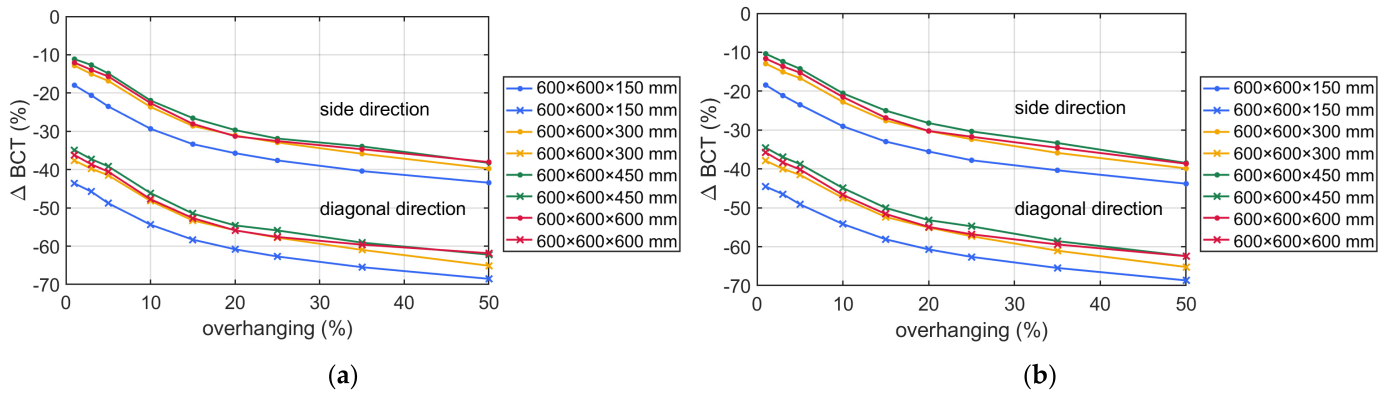
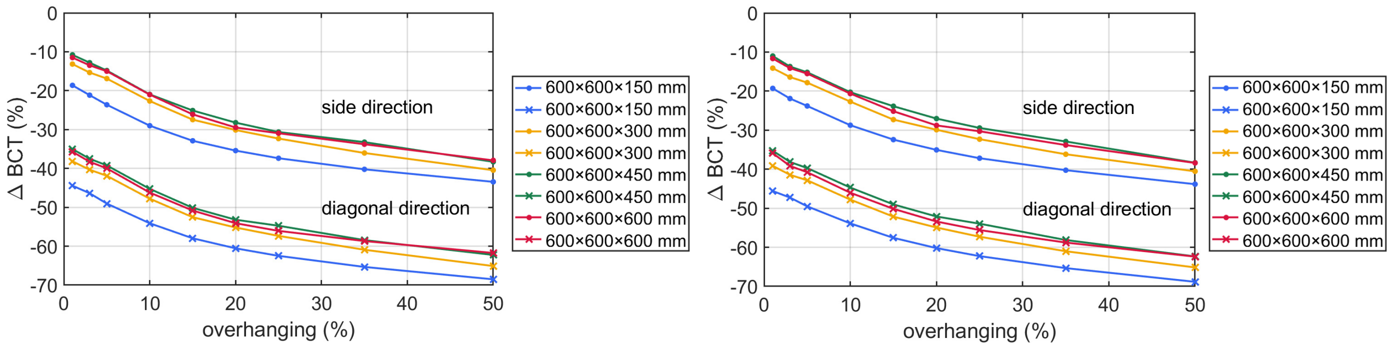


Figure 6. *Cont.*

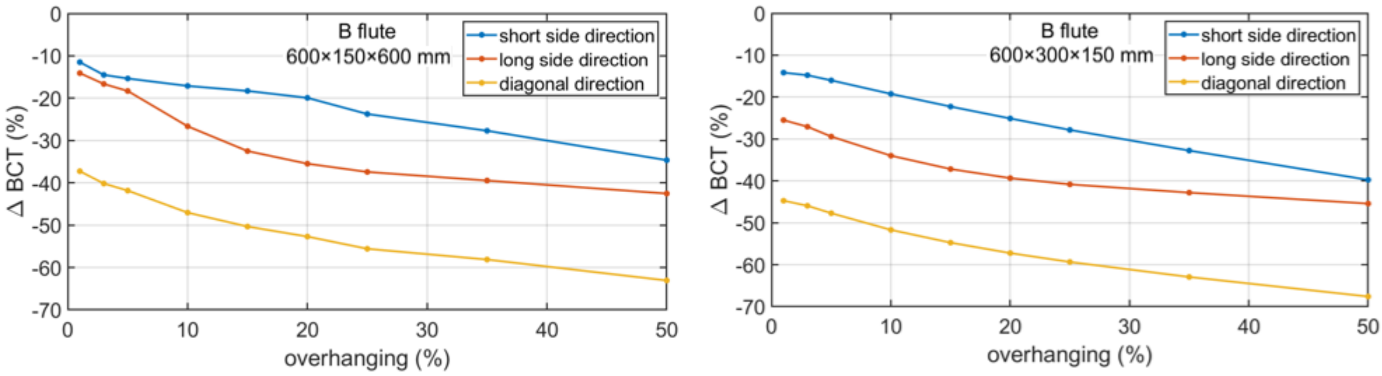


(**c**) (**d**)

Figure 6. Box compression strength reduction due to overhanging in packaging with a square base (600 × 600 mm) with increasing height made of different corrugated boards: (**a**) B-flute, (**b**) C-flute, (**c**) EB-flute and (**d**) BC-flute.

3.7. Special Cases

In Figure 7, the results of 600 × 150 × 600 and 600 × 300 × 150 boxes are presented. The diagrams of overhanging curves are shown for B-flute boards and the short-side, long-side and diagonal direction.



(**a**) (**b**)

Figure 7. Box compression strength reduction due to overhanging in packaging (B-flute): (**a**) 600 × 150 × 600 and (**b**) 600 × 300 × 150 boxes.

4. Discussion

In Section 3, the selected numerical results obtained within the research studies are described. In Section 3.1, the validation of the numerical model with the literature data is presented with very good results, comparing the box compression strength obtained in tests in the literature with the numerical outcome computed using the FE model developed in the paper. In Section 3.2, selected results of systematic numerical studies on the box compression strength drop due to overhanging are presented. It is worth noting that all results are supplied in Appendix A. Nevertheless, many practical conclusions can be drawn from Section 3.2.

First, in Figure 3, where the data displayed are averaged through box dimensions, one may observe that, independently of the board used for the short-side, long-side and diagonal direction, the ΔBCTs are almost identical. Bearing in mind that a relatively wide spectrum of boards were selected, it may be concluded that the material (board) properties have a negligible effect on BCT drop due to overhanging. Similar conclusion may be drawn from the tests performed in Ref. [35], where two types of board were used with similar properties to the C and BC boards. It appears that the primary influence on the ΔBCT

drop lies in the overall structure, specifically alterations in overhanging lengths or box dimensions, rather than a change in the material itself.

Second, in Figure 4, cubic packaging is shown to verify whether the size of such type of packaging influences the drop in box compression strength. Based on Figure 4, it may be observed that the size of cubic boxes plays a minor role. For overhanging between 15% and 35%, the limit values of ΔBCT differ around 5 percentage points, and for other overhanging intervals, the difference is always less than 3 percentage points and often close to 0 percentage points. The spread for different sizes of boxes (from cubic 150 mm box to 600 mm box) is the same for the side direction overhanging as well as for the diagonal direction overhanging. Here, the ΔBCT is also independent of the material (board) used for computations (for instance, please compare Figure 4a,b).

Additionally, for boxes with a square base of 150 mm, with various box heights, the ΔBCT does not differ substantially (please see Figure 5). The spread between different heights, independently of the board used, is less than 4 percentage points. In fact, only the box with a height of 150 mm differs by 4 percentage points from the others (blue curves). This is valid for the whole overhanging interval analyzed. Similar observations may be drawn from Figure 6, where boxes with a square base of 600 mm are presented. Here, the material (board) effect is also negligible. The box with a height of 150 mm (blue curves) differs substantially from the 600 mm box case, but the mean difference between the limit values for the 150 mm box case is about 6–10 percentage points. The 150 mm box height curves lie on the other side of the plot compared with Figure 5; therefore, ΔBCT is larger than in the other cases. Analyzing Figures 5 and 6 together, it can be approximately concluded that the more the package dimensions differ from the cubic case, the greater the ΔBCT for a given overhanging. This conclusion was also confirmed in the results of other cases of all the 40 boxes analyzed. The conclusion gives a very practical indication for the paletting strategy: if one wants to maximize the pallet load capacity via intentional overhanging of the boxes, it would be recommended to use cubic boxes rather than cuboid ones. The strength of cubic boxes will be reduced less than other designs.

In general, it may be observed that even after small overhanging, e.g., 1%, the drop in the box strength is severe and rapid. For one-side overhanging (short-/long-side overhanging), this is caused by the non-supported wall, which does not stiffen its perpendicular walls in the out-of-plane direction on one side. For two-side overhanging (diagonal direction), the effect is similar but more severe; here, only two walls have their out-of-plane stiffeners in the remaining corner. A further increase in the overhanging usually results in a much less intensive drop in the box compression strength. However, the relations between the dimensions of the box determine various trends in decreasing the box strength. For example, in Figure 7a, for a 600 × 150 × 600 mm box, for the long-side direction of overhanging, after 5% of overhanging, the drop increases severely with increasing overhanging. Here, for the short-side overhanging, a similar intensive drop is visible much later, i.e., from 20% of overhanging. On the other hand, for a 600 × 300 × 150 mm box, in Figure 7b, for the short-side overhanging, the drop is almost linear. Additionally, for the long-side direction, the relation is smoother, but the trend is similar to that in Figure 7a.

It should be noted that the bottom of the packaging is not modeled; its influence is considered by the boundary conditions. When analyzing the overhang, such omission may result in underestimation of the compressive capacity, but the simplification appears to have a negligible effect on the box strength.

5. Conclusions

In the paper, the effect of overhanging of the corrugated board packaging on its box compression strength was investigated via numerical modeling. In the first part of the study, the numerical model used was validated based on the literature data. In the second part of the study, systematic numerical studies were conducted, where various cases of typical flap boxes, board types and overhanging were considered. The box dimensions varied from 150 mm to 600 mm. Boards with B-, C-, EB- and BC-flutes were analyzed. Three directions of overhanging were assumed, namely along the short-side direction, long-side direction and diagonal (mixed) direction. Such variation in the box dimensions, boards and overhanging allowed for obtaining a database representing a wide range of cases.

Based on the study, the practical conclusions for paletting and box stacking may be drawn. Namely, a decrease in the load-bearing capacity of the packaging is observed when the overhanging is insensitive to the corrugated cardboard material used. The decrease in box strength is rapid, even for a small value of overhanging. The reason for this is the lack of active wall stiffeners in their out-of-plane directions. Thus, the boundary conditions of the box panels change rapidly upon compression. Additionally, the overhanging in the short- and long-side directions results in an approximately similar drop in box compression strength of the packaging, while for the two-wall (diagonal) overhanging, the decrease is usually twice as large compared to one-side overhanging. Further, the more the packaging dimensions deviate from the cubic version, the larger the drop in box compression strength. Therefore, cubic packaging would be recommended as the best shape for corrugated boxes from the point of view of compression strength with overhanging.

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Appendix A

Table A1. The BCT values for four types of cardboard and all box designs without overhang.

Box	BCT (N)			
	B-Flute	**C-Flute**	**EB-Flute**	**BC-Flute**
150 × 150 × 150	1324	1700	1733	2622
150 × 150 × 300	1199	1587	1612	2437
150 × 150 × 450	1236	1637	1663	2534
150 × 150 × 600	1271	1670	1702	2547
300 × 150 × 150	2333	3005	2993	4364
300 × 150 × 300	1839	2417	2380	3675
300 × 150 × 450	2194	2933	2911	4276
300 × 150 × 600	2086	2702	2715	4025
300 × 300 × 150	1934	2585	2595	4082

Table A1. *Cont.*

Box	BCT (N)			
	B-Flute	**C-Flute**	**EB-Flute**	**BC-Flute**
300 × 300 × 300	2060	2607	2689	4046
300 × 300 × 450	1982	2526	2592	3942
300 × 300 × 600	1887	2505	2530	3862
450 × 150 × 150	2823	3669	3634	5338
450 × 150 × 300	2804	3465	3500	5066
450 × 150 × 450	2268	2809	2861	4147
450 × 150 × 600	2782	3400	3482	4948
450 × 300 × 150	3225	4512	4394	6881
450 × 300 × 300	2876	3750	3795	5926
450 × 300 × 450	2316	3643	3775	5683
450 × 300 × 600	2899	3747	3808	5901
450 × 450 × 150	2487	3415	3389	5462
450 × 450 × 300	2526	3206	3294	5034
450 × 450 × 450	2715	3370	3513	5211
450 × 450 × 600	2557	3774	3310	5962
600 × 150 × 150	3173	4148	4100	5942
600 × 150 × 300	3112	3788	3870	5496
600 × 150 × 450	3285	3917	4048	5648
600 × 150 × 600	2654	3195	3290	4619
600 × 300 × 150	4043	5652	5469	8345
600 × 300 × 300	3500	4601	4645	7082
600 × 300 × 450	3560	4559	4691	6996
600 × 300 × 600	2799	4469	4753	6832
600 × 450 × 150	4254	6140	5931	9425
600 × 450 × 300	3420	4529	4563	7189
600 × 450 × 450	3458	4382	4512	6813
600 × 450 × 600	3471	4324	4576	6665
600 × 600 × 150	3043	4265	4203	6875
600 × 600 × 300	2958	3795	3875	5978
600 × 600 × 450	3137	3901	4040	6046
600 × 600 × 600	3347	4096	4299	6269

Table A2. The ΔBCT values for B-flute and short-side overhanging.

Box	ΔBCT (%)								
	1%	3%	5%	10%	15%	20%	25%	35%	50%
150 × 150 × 150	−12.0	−13.6	−14.7	−18.6	−22.3	−26.0	−27.8	−32.2	−37.0
150 × 150 × 300	−12.1	−15.0	−16.7	−20.3	−25.7	−28.1	−30.6	−34.0	−38.0
150 × 150 × 450	−12.5	−15.5	−17.3	−20.6	−25.6	−28.1	−30.4	−33.6	−38.0
150 × 150 × 600	−10.1	−14.8	−16.7	−19.8	−24.1	−27.4	−30.1	−34.0	−39.1
300 × 150 × 150	−12.9	−14.4	−15.6	−18.5	−20.7	−23.7	−25.7	−31.6	−38.7
300 × 150 × 300	−8.1	−10.6	−11.6	−14.1	−18.4	−19.9	−22.9	−27.0	−34.0
300 × 150 × 450	−11.9	−13.9	−15.0	−17.1	−20.2	−22.6	−24.9	−29.8	−36.5
300 × 150 × 600	−11.0	−13.4	−14.4	−16.6	−18.6	−22.1	−24.5	−29.2	−34.6
300 × 300 × 150	−14.4	−16.3	−17.8	−22.9	−27.4	−30.0	−32.2	−35.7	−39.7
300 × 300 × 300	−12.4	−14.1	−15.4	−20.7	−25.3	−29.0	−30.5	−33.9	−38.3
300 × 300 × 450	−12.5	−15.0	−16.7	−21.0	−26.1	−28.4	−30.7	−33.7	−38.0
300 × 300 × 600	−10.8	−14.2	−17.0	−19.2	−27.3	−28.8	−31.8	−34.4	−37.3
450 × 150 × 150	−17.3	−19.3	−20.0	−21.0	−24.8	−26.2	−29.9	−35.1	−41.9
450 × 150 × 300	−14.4	−15.9	−17.0	−18.6	−21.5	−23.5	−25.5	−30.5	−37.6
450 × 150 × 450	−10.5	−13.1	−14.0	−15.9	−17.7	−20.9	−23.1	−27.6	−33.3
450 × 150 × 600	−13.4	−15.8	−16.9	−18.7	−20.3	−21.4	−25.4	−29.5	−36.7
450 × 300 × 150	−13.3	−14.3	−15.5	−19.0	−22.3	−25.4	−28.0	−32.5	−38.1
450 × 300 × 300	−9.9	−11.0	−11.9	−15.5	−18.1	−21.1	−23.6	−27.7	−33.7
450 × 300 × 450	−9.4	−11.5	−12.5	−17.0	−20.0	−23.2	−25.2	−29.0	−34.2
450 × 300 × 600	−10.2	−11.8	−12.8	−15.3	−19.1	−21.8	−24.6	−28.6	−33.8
450 × 450 × 150	−15.8	−17.8	−20.7	−26.2	−30.1	−33.8	−35.0	−38.1	−41.9
450 × 450 × 300	−11.2	−13.5	−14.7	−20.6	−25.5	−28.6	−30.7	−34.0	−38.6
450 × 450 × 450	−12.3	−14.2	−15.7	−21.9	−27.1	−30.5	−31.8	−34.4	−38.4
450 × 450 × 600	−12.3	−14.5	−16.0	−22.8	−26.8	−29.5	−31.3	−34.3	−38.7
600 × 150 × 150	−20.5	−22.3	−22.9	−24.5	−27.4	−28.6	−32.2	−37.0	−43.3
600 × 150 × 300	−16.8	−18.7	−19.7	−21.3	−22.3	−25.8	−27.7	−32.5	−39.2
600 × 150 × 450	−16.0	−18.3	−19.1	−20.5	−21.9	−24.9	−26.5	−30.0	−36.5
600 × 150 × 600	−11.5	−14.5	−15.4	−17.1	−18.3	−19.9	−23.7	−27.7	−34.7
600 × 300 × 150	−14.2	−14.8	−16.0	−19.2	−22.3	−25.1	−27.9	−32.8	−39.8
600 × 300 × 300	−10.9	−11.8	−12.7	−15.6	−18.2	−21.0	−23.3	−27.7	−33.8
600 × 300 × 450	−9.9	−10.8	−11.6	−13.5	−16.8	−18.8	−21.4	−25.3	−31.1
600 × 300 × 600	−9.7	−11.3	−12.3	−14.9	−18.6	−21.1	−23.6	−27.0	−32.4
600 × 450 × 150	−13.3	−14.7	−16.4	−20.7	−24.5	−27.5	−30.3	−34.9	−40.9
600 × 450 × 300	−10.6	−12.0	−13.4	−17.5	−21.3	−24.3	−26.9	−31.0	−36.6
600 × 450 × 450	−9.9	−11.1	−12.5	−16.6	−19.8	−23.0	−25.3	−29.4	−34.6
600 × 450 × 600	−12.1	−13.6	−15.0	−19.0	−22.3	−25.3	−27.0	−30.6	−34.8
600 × 600 × 150	−18.0	−20.6	−23.5	−29.3	−33.4	−35.7	−37.6	−40.4	−43.4
600 × 600 × 300	−12.9	−15.0	−16.8	−23.6	−28.6	−31.1	−32.9	−35.9	−39.7
600 × 600 × 450	−11.1	−12.7	−14.9	−22.0	−26.6	−29.7	−31.9	−33.9	−38.3
600 × 600 × 600	−12.1	−14.0	−15.7	−22.6	−28.1	−31.3	−32.6	−34.7	−38.0

Table A3. The ΔBCT values for B-flute and long-side overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−12.0	−13.6	−14.7	−18.6	−22.3	−25.1	−27.8	−32.2	−37.0
150 × 150 × 300	−12.1	−15.0	−16.7	−19.3	−25.7	−27.2	−30.6	−34.0	−37.8
150 × 150 × 450	−12.5	−16.2	−17.3	−19.7	−24.9	−27.4	−30.3	−33.7	−38.5
150 × 150 × 600	−10.1	−14.0	−15.9	−19.8	−23.6	−27.4	−30.2	−34.0	−38.3
300 × 150 × 150	−20.2	−21.4	−23.4	−27.7	−30.9	−33.5	−35.5	−38.6	−41.9
300 × 150 × 300	−17.7	−19.7	−21.1	−26.8	−31.3	−33.8	−35.5	−38.5	−41.6
300 × 150 × 450	−19.4	−21.3	−22.5	−27.7	−31.7	−34.0	−36.0	−38.6	−42.2
300 × 150 × 600	−17.1	−19.1	−20.8	−26.3	−30.4	−33.4	−35.4	−37.7	−41.5
300 × 300 × 150	−14.4	−16.3	−17.6	−22.6	−27.4	−29.8	−32.2	−36.0	−40.4
300 × 300 × 300	−12.4	−14.1	−15.4	−20.7	−25.3	−28.2	−30.5	−33.9	−38.3
300 × 300 × 450	−12.5	−15.0	−16.7	−21.0	−26.1	−28.4	−30.2	−33.7	−38.0
300 × 300 × 600	−10.8	−14.2	−15.9	−18.2	−26.2	−28.0	−31.2	−34.1	−37.1
450 × 150 × 150	−20.3	−22.1	−24.6	−29.1	−33.0	−35.6	−38.1	−40.4	−43.5
450 × 150 × 300	−13.8	−15.5	−18.0	−23.3	−27.9	−31.1	−33.3	−36.5	−39.9
450 × 150 × 450	−15.5	−17.9	−19.6	−26.8	−32.1	−34.9	−36.7	−39.0	−42.6
450 × 150 × 600	−14.4	−16.3	−18.4	−24.4	−29.0	−31.7	−34.2	−36.8	−40.9
450 × 300 × 150	−23.8	−25.3	−27.5	−31.8	−35.1	−37.4	−39.1	−41.8	−44.3
450 × 300 × 300	−14.4	−16.7	−18.3	−23.7	−28.4	−31.4	−33.3	−36.1	−39.7
450 × 300 × 450	−15.4	−17.7	−19.4	−27.4	−31.9	−34.5	−35.9	−38.7	−42.1
450 × 300 × 600	−15.7	−17.7	−19.4	−25.1	−29.6	−32.3	−34.1	−36.8	−40.2
450 × 450 × 150	−15.8	−17.8	−20.7	−26.2	−30.1	−33.7	−34.9	−38.1	−41.5
450 × 450 × 300	−11.2	−13.5	−14.7	−20.6	−25.5	−28.6	−30.7	−34.0	−37.6
450 × 450 × 450	−12.3	−14.2	−15.7	−21.9	−27.1	−29.8	−31.8	−34.4	−38.4
450 × 450 × 600	−12.3	−14.5	−16.0	−22.8	−26.0	−29.5	−31.5	−34.3	−38.4
600 × 150 × 150	−19.5	−21.7	−24.5	−30.4	−34.4	−36.5	−38.4	−41.6	−44.0
600 × 150 × 300	−13.2	−15.2	−18.2	−24.4	−29.2	−32.3	−34.4	−37.7	−41.7
600 × 150 × 450	−10.9	−12.8	−15.8	−22.3	−27.7	−31.2	−33.4	−36.2	−40.1
600 × 150 × 600	−14.1	−16.7	−18.3	−26.7	−32.5	−35.5	−37.4	−39.5	−42.5
600 × 300 × 150	−25.5	−27.1	−29.4	−34.0	−37.2	−39.4	−40.8	−42.8	−45.4
600 × 300 × 300	−17.0	−18.8	−21.4	−27.4	−31.5	−34.2	−35.9	−38.7	−42.1
600 × 300 × 450	−13.7	−15.5	−18.0	−24.2	−29.0	−32.5	−34.4	−36.7	−39.8
600 × 300 × 600	−15.2	−17.7	−19.1	−27.9	−33.2	−35.8	−37.3	−39.1	−42.3
600 × 450 × 150	−26.7	−28.2	−30.4	−34.7	−37.7	−39.8	−41.3	−43.2	−45.7
600 × 450 × 300	−16.5	−18.7	−21.0	−26.6	−30.8	−33.5	−35.3	−38.2	−41.6
600 × 450 × 450	−13.5	−15.5	−17.2	−23.6	−28.8	−31.8	−33.7	−35.9	−38.9
600 × 450 × 600	−15.0	−17.0	−18.7	−25.9	−31.0	−33.8	−35.2	−37.2	−39.4
600 × 600 × 150	−18.0	−20.6	−23.5	−29.3	−33.4	−35.7	−37.8	−40.4	−43.7
600 × 600 × 300	−12.9	−15.0	−16.5	−23.1	−28.2	−30.8	−32.8	−36.1	−40.4
600 × 600 × 450	−11.1	−12.7	−14.9	−22.0	−26.6	−29.7	−31.6	−33.9	−38.3
600 × 600 × 600	−12.1	−14.0	−15.7	−22.6	−28.1	−30.7	−32.6	−34.7	−38.0

Table A4. The ΔBCT values for B-flute and diagonal overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−36.8	−38.6	−39.7	−43.8	−47.5	−50.6	−52.9	−56.7	−61.1
150 × 150 × 300	−37.0	−40.4	−42.0	−44.8	−50.2	−52.6	−55.5	−58.9	−62.9
150 × 150 × 450	−35.6	−39.8	−41.7	−45.1	−49.5	−52.7	−54.2	−58.5	−62.2
150 × 150 × 600	−34.9	−40.0	−41.7	−45.1	−49.2	−52.7	−55.0	−58.6	−63.1
300 × 150 × 150	−41.4	−42.9	−44.4	−47.9	−50.7	−53.5	−55.6	−60.2	−65.4
300 × 150 × 300	−37.5	−40.1	−41.8	−45.9	−49.5	−52.2	−54.1	−57.9	−62.6
300 × 150 × 450	−39.8	−42.0	−43.6	−46.8	−49.5	−53.3	−54.9	−59.2	−64.3
300 × 150 × 600	−38.9	−41.4	−42.8	−46.7	−49.6	−52.9	−54.8	−58.5	−62.9
300 × 300 × 150	−39.5	−41.3	−42.6	−47.7	−52.2	−54.9	−57.2	−60.9	−65.1
300 × 300 × 300	−37.0	−39.2	−40.7	−46.1	−50.3	−53.6	−55.8	−58.9	−62.3
300 × 300 × 450	−37.2	−39.6	−41.2	−46.6	−50.7	−53.8	−55.6	−59.0	−63.2
300 × 300 × 600	−36.1	−39.1	−41.3	−44.0	−51.7	−53.8	−56.6	−59.4	−62.7
450 × 150 × 150	−43.6	−45.5	−47.1	−50.1	−53.9	−55.9	−58.8	−62.8	−67.7
450 × 150 × 300	−38.7	−40.6	−42.2	−45.7	−49.3	−52.1	−54.3	−58.5	−63.9
450 × 150 × 450	−37.7	−40.3	−41.8	−46.5	−50.2	−53.1	−55.0	−58.4	−62.8
450 × 150 × 600	−38.8	−41.0	−42.6	−46.6	−49.6	−51.9	−55.0	−58.2	−64.0
450 × 300 × 150	−43.4	−44.8	−46.5	−50.4	−53.7	−56.4	−58.6	−62.1	−66.2
450 × 300 × 300	−37.0	−38.5	−39.7	−44.2	−47.9	−51.0	−53.4	−57.1	−61.8
450 × 300 × 450	−37.5	−39.8	−41.1	−46.9	−51.2	−54.1	−55.9	−59.2	−63.5
450 × 300 × 600	−38.0	−39.7	−41.1	−45.3	−49.5	−52.2	−54.5	−57.8	−62.3
450 × 450 × 150	−41.4	−43.3	−46.1	−51.5	−55.5	−58.8	−60.3	−63.6	−67.0
450 × 450 × 300	−36.1	−38.0	−39.8	−45.8	−50.6	−53.7	−55.8	−59.0	−63.2
450 × 450 × 450	−37.1	−39.1	−40.8	−47.2	−52.2	−55.1	−57.0	−59.4	−62.3
450 × 450 × 600	−36.2	−38.5	−40.5	−46.8	−51.4	−54.4	−55.7	−59.1	−62.9
600 × 150 × 150	−45.2	−47.0	−48.5	−52.2	−55.7	−58.0	−60.3	−64.1	−68.7
600 × 150 × 300	−39.9	−41.8	−43.7	−47.6	−50.7	−53.9	−55.9	−60.0	−65.3
600 × 150 × 450	−38.3	−40.2	−42.0	−46.0	−49.5	−52.9	−54.8	−58.3	−63.4
600 × 150 × 600	−37.3	−40.2	−41.8	−47.0	−50.3	−52.7	−55.6	−58.1	−63.1
600 × 300 × 150	−44.7	−45.9	−47.7	−51.7	−54.7	−57.2	−59.4	−62.9	−67.6
600 × 300 × 300	−38.9	−40.3	−42.1	−46.3	−49.7	−52.5	−54.5	−58.3	−63.0
600 × 300 × 450	−36.6	−38.0	−39.3	−43.5	−47.7	−50.5	−52.8	−56.2	−60.7
600 × 300 × 600	−36.7	−39.0	−40.7	−46.2	−50.7	−53.6	−54.7	−58.4	−61.7
600 × 450 × 150	−44.9	−46.5	−48.4	−52.8	−56.2	−58.7	−60.8	−64.1	−68.2
600 × 450 × 300	−38.6	−40.2	−42.2	−47.1	−51.1	−53.9	−56.2	−59.7	−64.2
600 × 450 × 450	−36.0	−37.8	−39.4	−44.5	−48.9	−52.3	−54.5	−57.7	−61.9
600 × 450 × 600	−37.6	−39.7	−41.2	−47.2	−51.4	−53.9	−56.2	−59.0	−62.4
600 × 600 × 150	−43.6	−45.8	−48.8	−54.4	−58.3	−60.8	−62.7	−65.5	−68.5
600 × 600 × 300	−37.7	−39.8	−41.5	−48.2	−53.3	−55.8	−57.8	−61.0	−65.1
600 × 600 × 450	−34.9	−37.3	−39.2	−46.1	−51.5	−54.6	−55.9	−59.1	−62.2
600 × 600 × 600	−36.2	−38.6	−40.5	−47.7	−52.7	−55.9	−57.6	−59.6	−61.9

Table A5. The ΔBCT values for C-flute and short-side overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−11.3	−13.0	−14.1	−17.7	−21.1	−24.4	−26.5	−31.1	−36.4
150 × 150 × 300	−11.8	−15.0	−16.7	−20.1	−24.2	−27.5	−29.9	−33.9	−38.4
150 × 150 × 450	−11.4	−15.6	−16.2	−19.7	−24.8	−26.8	−30.0	−33.6	−38.2
150 × 150 × 600	−9.8	−14.2	−16.2	−19.8	−23.6	−27.3	−29.7	−33.7	−39.0
300 × 150 × 150	−13.1	−14.8	−15.8	−20.1	−22.4	−25.5	−28.0	−33.9	−41.9
300 × 150 × 300	−5.7	−9.6	−11.4	−14.8	−18.0	−20.7	−23.7	−27.2	−35.2
300 × 150 × 450	−12.5	−14.8	−16.1	−18.5	−21.3	−23.7	−26.1	−31.3	−38.8
300 × 150 × 600	−10.1	−12.9	−14.1	−16.5	−19.1	−21.9	−24.3	−29.2	−36.0
300 × 300 × 150	−15.4	−17.1	−18.6	−23.1	−27.3	−30.2	−32.7	−36.6	−40.9
300 × 300 × 300	−11.2	−13.1	−14.4	−18.9	−23.3	−27.1	−28.9	−33.0	−37.9
300 × 300 × 450	−11.3	−14.4	−16.1	−20.1	−24.8	−27.2	−29.9	−33.4	−38.1
300 × 300 × 600	−10.5	−13.6	−16.8	−19.0	−26.2	−27.9	−31.2	−34.5	−37.8
450 × 150 × 150	−19.3	−22.5	−23.2	−23.4	−27.8	−28.3	−32.8	−37.7	−43.4
450 × 150 × 300	−15.2	−17.2	−18.1	−21.0	−22.8	−25.8	−26.7	−32.6	−38.7
450 × 150 × 450	−9.0	−12.1	−13.3	−15.6	−17.5	−20.6	−22.9	−27.8	−34.0
450 × 150 × 600	−12.5	−15.4	−16.6	−18.5	−20.2	−21.4	−25.3	−29.3	−36.7
450 × 300 × 150	−14.1	−14.8	−16.1	−19.2	−22.4	−25.5	−28.2	−33.1	−39.5
450 × 300 × 300	−9.5	−11.1	−11.8	−15.2	−17.7	−20.8	−23.5	−28.0	−34.5
450 × 300 × 450	−11.0	−12.7	−13.9	−17.4	−20.1	−23.2	−25.2	−29.1	−34.2
450 × 300 × 600	−9.4	−11.6	−12.6	−15.2	−18.7	−21.4	−24.4	−28.8	−34.3
450 × 450 × 150	−16.5	−18.4	−20.8	−26.0	−29.9	−33.9	−35.2	−38.1	−42.0
450 × 450 × 300	−11.1	−13.2	−14.8	−19.7	−24.3	−27.5	−29.8	−33.8	−37.7
450 × 450 × 450	−11.5	−13.5	−15.0	−20.5	−25.4	−29.0	−30.6	−34.0	−38.5
450 × 450 × 600	−11.3	−13.1	−15.5	−19.2	−23.2	−27.4	−28.6	−32.3	−37.3
600 × 150 × 150	−22.9	−25.4	−26.0	−27.4	−30.2	−30.6	−34.7	−39.2	−44.5
600 × 150 × 300	−16.5	−18.9	−19.7	−22.5	−22.8	−26.9	−28.8	−33.5	−39.1
600 × 150 × 450	−15.1	−18.0	−18.6	−20.8	−22.1	−25.1	−26.6	−29.7	−36.3
600 × 150 × 600	−10.3	−13.8	−14.9	−16.8	−18.5	−19.9	−23.5	−27.5	−34.6
600 × 300 × 150	−16.1	−16.6	−17.7	−20.9	−23.8	−26.8	−29.1	−35.3	−42.8
600 × 300 × 300	−11.0	−12.5	−13.4	−16.3	−18.7	−21.7	−24.0	−29.2	−35.7
600 × 300 × 450	−10.3	−11.6	−12.5	−14.3	−17.6	−19.7	−22.6	−27.0	−32.9
600 × 300 × 600	−11.4	−13.1	−13.8	−16.0	−19.5	−21.3	−24.2	−28.1	−34.3
600 × 450 × 150	−13.5	−14.7	−16.1	−20.2	−24.0	−27.1	−30.0	−34.9	−41.8
600 × 450 × 300	−10.8	−12.0	−13.3	−17.1	−20.7	−23.8	−26.6	−31.0	−36.2
600 × 450 × 450	−9.2	−10.3	−11.6	−15.4	−18.6	−21.9	−24.4	−29.0	−34.6
600 × 450 × 600	−10.8	−12.7	−14.0	−17.6	−20.8	−24.0	−26.0	−30.2	−35.0
600 × 600 × 150	−18.4	−21.1	−23.5	−29.0	−33.0	−35.5	−37.8	−40.4	−43.8
600 × 600 × 300	−12.9	−15.0	−16.7	−22.8	−27.6	−30.3	−32.4	−35.9	−39.9
600 × 600 × 450	−10.4	−12.4	−14.3	−20.6	−25.0	−28.2	−30.4	−33.3	−38.5
600 × 600 × 600	−11.6	−13.6	−15.3	−21.5	−26.9	−30.3	−31.7	−34.6	−38.7

Table A6. The ΔBCT values for C-flute and long-side overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−11.3	−13.0	−14.8	−18.3	−21.8	−23.8	−26.5	−31.1	−36.4
150 × 150 × 300	−11.8	−15.0	−16.7	−19.6	−24.2	−26.8	−29.9	−33.9	−38.1
150 × 150 × 450	−11.4	−15.6	−16.2	−20.2	−24.8	−26.8	−30.0	−33.6	−38.3
150 × 150 × 600	−9.8	−13.9	−15.8	−20.2	−23.6	−27.0	−29.8	−34.0	−38.4
300 × 150 × 150	−18.9	−21.3	−23.2	−26.0	−29.3	−33.0	−35.3	−37.6	−42.3
300 × 150 × 300	−18.0	−20.8	−22.1	−26.5	−30.3	−33.6	−34.6	−38.7	−41.2
300 × 150 × 450	−19.3	−21.3	−22.4	−26.9	−30.6	−33.1	−35.3	−38.4	−42.1
300 × 150 × 600	−16.9	−19.2	−20.7	−25.4	−29.2	−32.3	−34.2	−37.6	−41.2
300 × 300 × 150	−15.4	−17.1	−18.5	−23.1	−27.3	−30.1	−32.5	−36.3	−40.2
300 × 300 × 300	−11.2	−13.1	−14.4	−18.9	−23.3	−26.3	−28.9	−33.0	−37.9
300 × 300 × 450	−11.3	−14.4	−16.1	−20.1	−24.8	−27.2	−29.3	−33.4	−37.9
300 × 300 × 600	−10.5	−13.6	−16.0	−18.3	−25.1	−27.1	−30.6	−34.1	−37.5
450 × 150 × 150	−19.3	−21.0	−24.4	−27.9	−32.0	−34.8	−37.0	−39.9	−43.2
450 × 150 × 300	−13.6	−15.4	−16.9	−22.4	−26.2	−30.0	−32.5	−36.4	−40.8
450 × 150 × 450	−14.1	−16.7	−19.0	−25.4	−30.5	−33.3	−34.7	−38.4	−41.3
450 × 150 × 600	−13.1	−14.6	−16.4	−21.9	−26.9	−29.4	−32.1	−36.0	−39.9
450 × 300 × 150	−25.6	−26.9	−28.8	−32.5	−35.7	−38.1	−39.8	−42.3	−45.0
450 × 300 × 300	−15.6	−17.2	−18.9	−23.6	−27.8	−30.8	−32.9	−36.1	−39.9
450 × 300 × 450	−15.2	−17.1	−18.4	−23.7	−28.7	−32.0	−33.9	−37.3	−41.1
450 × 300 × 600	−16.1	−18.1	−19.7	−24.6	−28.8	−31.5	−33.5	−36.6	−40.5
450 × 450 × 150	−16.5	−18.4	−20.8	−26.0	−29.9	−33.7	−34.9	−38.1	−41.6
450 × 450 × 300	−11.1	−13.2	−14.8	−19.7	−24.3	−27.5	−29.8	−33.8	−38.7
450 × 450 × 450	−11.5	−13.5	−15.0	−20.5	−25.4	−28.3	−30.6	−34.0	−38.5
450 × 450 × 600	−12.3	−14.4	−15.5	−20.8	−24.9	−27.4	−29.6	−32.9	−37.3
600 × 150 × 150	−17.9	−21.6	−22.6	−28.4	−32.5	−35.4	−37.4	−40.4	−43.7
600 × 150 × 300	−11.1	−13.1	−16.5	−21.6	−27.0	−30.3	−32.9	−36.8	−40.0
600 × 150 × 450	−9.1	−11.1	−13.8	−19.8	−25.3	−28.9	−31.3	−35.0	−39.5
600 × 150 × 600	−12.0	−14.7	−16.7	−24.6	−30.2	−33.1	−35.1	−37.9	−41.7
600 × 300 × 150	−26.7	−28.1	−29.6	−33.9	−37.4	−39.0	−40.6	−42.9	−45.4
600 × 300 × 300	−18.5	−20.2	−22.4	−27.2	−31.1	−33.8	−35.8	−38.9	−42.7
600 × 300 × 450	−15.0	−17.5	−18.2	−23.5	−29.4	−31.7	−33.9	−37.1	−41.2
600 × 300 × 600	−16.6	−18.6	−19.3	−26.2	−31.3	−34.2	−36.0	−38.1	−41.2
600 × 450 × 150	−28.6	−29.5	−31.3	−35.0	−38.0	−39.9	−41.4	−43.8	−45.8
600 × 450 × 300	−18.1	−19.8	−22.1	−26.8	−30.7	−33.4	−35.5	−38.5	−41.9
600 × 450 × 450	−13.7	−15.6	−17.3	−22.9	−27.8	−30.9	−32.9	−35.7	−39.1
600 × 450 × 600	−14.8	−16.9	−18.4	−24.9	−30.0	−32.8	−34.4	−36.8	−39.7
600 × 600 × 150	−18.4	−21.1	−23.5	−29.0	−33.0	−35.5	−37.5	−40.4	−43.6
600 × 600 × 300	−12.9	−15.0	−16.6	−22.4	−27.6	−30.0	−32.3	−36.2	−40.6
600 × 600 × 450	−10.4	−12.4	−14.3	−20.6	−25.0	−28.2	−30.4	−33.3	−38.5
600 × 600 × 600	−11.6	−13.6	−15.3	−21.5	−26.9	−29.6	−31.7	−34.6	−38.7

Table A7. The ΔBCT values for C-flute and diagonal overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−35.9	−37.9	−38.9	−42.6	−46.0	−49.1	−51.5	−55.5	−60.4
150 × 150 × 300	−36.7	−40.3	−42.1	−44.8	−49.6	−52.2	−55.2	−59.0	−63.3
150 × 150 × 450	−35.3	−39.7	−41.5	−44.8	−49.0	−52.1	−54.0	−58.6	−62.6
150 × 150 × 600	−34.6	−39.8	−41.6	−45.0	−48.8	−52.2	−54.6	−58.6	−63.2
300 × 150 × 150	−41.3	−43.0	−45.2	−48.5	−51.3	−54.3	−56.6	−61.3	−67.1
300 × 150 × 300	−35.7	−39.4	−41.4	−45.8	−49.1	−52.1	−53.5	−58.7	−63.2
300 × 150 × 450	−40.2	−42.7	−44.0	−47.4	−50.3	−53.4	−55.5	−59.8	−65.4
300 × 150 × 600	−37.8	−40.8	−42.3	−46.1	−49.1	−52.2	−54.3	−58.4	−63.5
300 × 300 × 150	−40.5	−42.3	−43.5	−48.1	−52.4	−55.1	−57.6	−61.5	−65.5
300 × 300 × 300	−35.6	−38.1	−39.6	−44.3	−48.3	−51.7	−54.2	−57.9	−61.9
300 × 300 × 450	−36.2	−39.2	−40.8	−45.6	−49.5	−52.8	−54.8	−58.8	−63.2
300 × 300 × 600	−35.4	−39.2	−41.2	−43.9	−50.7	−53.0	−56.0	−59.4	−63.2
450 × 150 × 150	−44.2	−46.8	−48.3	−50.6	−55.0	−56.5	−60.0	−64.0	−68.3
450 × 150 × 300	−38.5	−40.8	−42.4	−46.2	−49.5	−52.4	−54.6	−59.0	−64.6
450 × 150 × 450	−36.4	−39.6	−41.3	−45.7	−49.2	−52.1	−54.5	−58.1	−63.0
450 × 150 × 600	−37.6	−40.4	−41.7	−45.6	−48.8	−51.0	−54.1	−57.8	−63.8
450 × 300 × 150	−44.5	−45.7	−47.3	−50.8	−53.9	−56.7	−58.9	−62.6	−67.3
450 × 300 × 300	−37.5	−39.0	−40.1	−44.1	−47.5	−50.6	−53.1	−57.3	−62.3
450 × 300 × 450	−38.1	−39.9	−41.0	−45.5	−49.4	−52.6	−54.6	−58.3	−62.7
450 × 300 × 600	−37.7	−39.9	−41.2	−45.1	−48.9	−51.8	−54.1	−58.0	−62.8
450 × 450 × 150	−42.3	−44.1	−46.6	−51.5	−55.3	−58.8	−60.4	−63.7	−67.2
450 × 450 × 300	−35.9	−38.0	−39.6	−44.9	−49.5	−52.6	−54.9	−58.7	−63.2
450 × 450 × 450	−36.1	−38.3	−40.0	−45.7	−50.6	−53.7	−55.9	−58.9	−62.4
450 × 450 × 600	−35.9	−38.3	−39.8	−44.9	−49.2	−52.2	−53.9	−58.1	−62.3
600 × 150 × 150	−46.2	−48.0	−49.4	−52.9	−56.4	−58.0	−61.1	−64.9	−69.1
600 × 150 × 300	−38.9	−41.2	−43.0	−47.2	−49.9	−53.5	−55.7	−60.0	−64.9
600 × 150 × 450	−36.8	−39.3	−41.1	−44.9	−48.4	−51.8	−53.8	−57.5	−62.9
600 × 150 × 600	−35.7	−39.0	−40.8	−45.9	−49.4	−51.9	−54.6	−57.7	−63.2
600 × 300 × 150	−46.1	−47.2	−48.8	−52.4	−55.4	−58.0	−59.9	−64.2	−69.1
600 × 300 × 300	−39.7	−41.3	−42.8	−46.7	−49.8	−52.7	−54.9	−59.2	−64.2
600 × 300 × 450	−37.4	−38.9	−40.1	−43.7	−47.8	−50.6	−53.1	−57.1	−62.0
600 × 300 × 600	−37.9	−40.0	−41.3	−45.4	−49.8	−52.7	−54.2	−58.3	−62.1
600 × 450 × 150	−45.7	−47.2	−48.8	−52.7	−56.1	−58.6	−60.8	−64.2	−68.8
600 × 450 × 300	−39.3	−40.8	−42.6	−46.9	−50.7	−53.6	−56.0	−59.8	−64.3
600 × 450 × 450	−35.8	−37.7	−39.1	−43.7	−47.9	−51.3	−53.6	−57.4	−62.1
600 × 450 × 600	−37.0	−39.2	−40.7	−46.0	−50.2	−52.9	−55.3	−58.7	−62.7
600 × 600 × 150	−44.6	−46.5	−49.1	−54.2	−58.1	−60.7	−62.6	−65.5	−68.7
600 × 600 × 300	−37.9	−40.0	−41.6	−47.5	−52.4	−55.1	−57.3	−61.0	−65.2
600 × 600 × 450	−34.5	−37.0	−38.8	−44.9	−50.0	−53.2	−54.8	−58.6	−62.4
600 × 600 × 600	−35.8	−38.3	−40.2	−46.7	−51.6	−54.9	−56.8	−59.4	−62.5

Table A8. The ΔBCT values for EB-flute and short-side overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−11.3	−13.0	−14.1	−17.7	−21.1	−24.4	−26.5	−31.1	−36.4
150 × 150 × 300	−11.8	−15.0	−16.7	−20.1	−24.2	−27.5	−29.9	−33.9	−38.4
150 × 150 × 450	−11.4	−15.6	−16.2	−19.7	−24.8	−26.8	−30.0	−33.6	−38.2
150 × 150 × 600	−9.8	−14.2	−16.2	−19.8	−23.6	−27.3	−29.7	−33.7	−39.0
300 × 150 × 150	−13.1	−14.8	−15.8	−20.1	−22.4	−25.5	−28.0	−33.9	−41.9
300 × 150 × 300	−5.7	−9.6	−11.4	−14.8	−18.0	−20.7	−23.7	−27.2	−35.2
300 × 150 × 450	−12.5	−14.8	−16.1	−18.5	−21.3	−23.7	−26.1	−31.3	−38.8
300 × 150 × 600	−10.1	−12.9	−14.1	−16.5	−19.1	−21.9	−24.3	−29.2	−36.0
300 × 300 × 150	−15.4	−17.1	−18.6	−23.1	−27.3	−30.2	−32.7	−36.6	−40.9
300 × 300 × 300	−11.2	−13.1	−14.4	−18.9	−23.3	−27.1	−28.9	−33.0	−37.9
300 × 300 × 450	−11.3	−14.4	−16.1	−20.1	−24.8	−27.2	−29.9	−33.4	−38.1
300 × 300 × 600	−10.5	−13.6	−16.8	−19.0	−26.2	−27.9	−31.2	−34.5	−37.8
450 × 150 × 150	−19.3	−22.5	−23.2	−23.4	−27.8	−28.3	−32.8	−37.7	−43.4
450 × 150 × 300	−15.2	−17.2	−18.1	−21.0	−22.8	−25.8	−26.7	−32.6	−38.7
450 × 150 × 450	−9.0	−12.1	−13.3	−15.6	−17.5	−20.6	−22.9	−27.8	−34.0
450 × 150 × 600	−12.5	−15.4	−16.6	−18.5	−20.2	−21.4	−25.3	−29.3	−36.7
450 × 300 × 150	−14.1	−14.8	−16.1	−19.2	−22.4	−25.5	−28.2	−33.1	−39.5
450 × 300 × 300	−9.5	−11.1	−11.8	−15.2	−17.7	−20.8	−23.5	−28.0	−34.5
450 × 300 × 450	−11.0	−12.7	−13.9	−17.4	−20.1	−23.2	−25.2	−29.1	−34.2
450 × 300 × 600	−9.4	−11.6	−12.6	−15.2	−18.7	−21.4	−24.4	−28.8	−34.3
450 × 450 × 150	−16.5	−18.4	−20.8	−26.0	−29.9	−33.9	−35.2	−38.1	−42.0
450 × 450 × 300	−11.1	−13.2	−14.8	−19.7	−24.3	−27.5	−29.8	−33.8	−37.7
450 × 450 × 450	−11.5	−13.5	−15.0	−20.5	−25.4	−29.0	−30.6	−34.0	−38.5
450 × 450 × 600	−11.3	−13.1	−15.5	−19.2	−23.2	−27.4	−28.6	−32.3	−37.3
600 × 150 × 150	−22.9	−25.4	−26.0	−27.4	−30.2	−30.6	−34.7	−39.2	−44.5
600 × 150 × 300	−16.5	−18.9	−19.7	−22.5	−22.8	−26.9	−28.8	−33.5	−39.1
600 × 150 × 450	−15.1	−18.0	−18.6	−20.8	−22.1	−25.1	−26.6	−29.7	−36.3
600 × 150 × 600	−10.3	−13.8	−14.9	−16.8	−18.5	−19.9	−23.5	−27.5	−34.6
600 × 300 × 150	−16.1	−16.6	−17.7	−20.9	−23.8	−26.8	−29.1	−35.3	−42.8
600 × 300 × 300	−11.0	−12.5	−13.4	−16.3	−18.7	−21.7	−24.0	−29.2	−35.7
600 × 300 × 450	−10.3	−11.6	−12.5	−14.3	−17.6	−19.7	−22.6	−27.0	−32.9
600 × 300 × 600	−11.4	−13.1	−13.8	−16.0	−19.5	−21.3	−24.2	−28.1	−34.3
600 × 450 × 150	−13.5	−14.7	−16.1	−20.2	−24.0	−27.1	−30.0	−34.9	−41.8
600 × 450 × 300	−10.8	−12.0	−13.3	−17.1	−20.7	−23.8	−26.6	−31.0	−36.2
600 × 450 × 450	−9.2	−10.3	−11.6	−15.4	−18.6	−21.9	−24.4	−29.0	−34.6
600 × 450 × 600	−10.8	−12.7	−14.0	−17.6	−20.8	−24.0	−26.0	−30.2	−35.0
600 × 600 × 150	−18.4	−21.1	−23.5	−29.0	−33.0	−35.5	−37.8	−40.4	−43.8
600 × 600 × 300	−12.9	−15.0	−16.7	−22.8	−27.6	−30.3	−32.4	−35.9	−39.9
600 × 600 × 450	−10.4	−12.4	−14.3	−20.6	−25.0	−28.2	−30.4	−33.3	−38.5
600 × 600 × 600	−11.6	−13.6	−15.3	−21.5	−26.9	−30.3	−31.7	−34.6	−38.7

Table A9. The ΔBCT values for EB-flute and long-side overhanging.

Box	ΔBCT (%)								
	1%	3%	5%	10%	15%	20%	25%	35%	50%
150 × 150 × 150	−11.3	−13.0	−14.8	−18.3	−21.8	−23.8	−26.5	−31.1	−36.4
150 × 150 × 300	−11.8	−15.0	−16.7	−19.6	−24.2	−26.8	−29.9	−33.9	−38.1
150 × 150 × 450	−11.4	−15.6	−16.2	−20.2	−24.8	−26.8	−30.0	−33.6	−38.3
150 × 150 × 600	−9.8	−13.9	−15.8	−20.2	−23.6	−27.0	−29.8	−34.0	−38.4
300 × 150 × 150	−18.9	−21.3	−23.2	−26.0	−29.3	−33.0	−35.3	−37.6	−42.3
300 × 150 × 300	−18.0	−20.8	−22.1	−26.5	−30.3	−33.6	−34.6	−38.7	−41.2
300 × 150 × 450	−19.3	−21.3	−22.4	−26.9	−30.6	−33.1	−35.3	−38.4	−42.1
300 × 150 × 600	−16.9	−19.2	−20.7	−25.4	−29.2	−32.3	−34.2	−37.6	−41.2
300 × 300 × 150	−15.4	−17.1	−18.5	−23.1	−27.3	−30.1	−32.5	−36.3	−40.2
300 × 300 × 300	−11.2	−13.1	−14.4	−18.9	−23.3	−26.3	−28.9	−33.0	−37.9
300 × 300 × 450	−11.3	−14.4	−16.1	−20.1	−24.8	−27.2	−29.3	−33.4	−37.9
300 × 300 × 600	−10.5	−13.6	−16.0	−18.3	−25.1	−27.1	−30.6	−34.1	−37.5
450 × 150 × 150	−19.3	−21.0	−24.4	−27.9	−32.0	−34.8	−37.0	−39.9	−43.2
450 × 150 × 300	−13.6	−15.4	−16.9	−22.4	−26.2	−30.0	−32.5	−36.4	−40.8
450 × 150 × 450	−14.1	−16.7	−19.0	−25.4	−30.5	−33.3	−34.7	−38.4	−41.3
450 × 150 × 600	−13.1	−14.6	−16.4	−21.9	−26.9	−29.4	−32.1	−36.0	−39.9
450 × 300 × 150	−25.6	−26.9	−28.8	−32.5	−35.7	−38.1	−39.8	−42.3	−45.0
450 × 300 × 300	−15.6	−17.2	−18.9	−23.6	−27.8	−30.8	−32.9	−36.1	−39.9
450 × 300 × 450	−15.2	−17.1	−18.4	−23.7	−28.7	−32.0	−33.9	−37.3	−41.1
450 × 300 × 600	−16.1	−18.1	−19.7	−24.6	−28.8	−31.5	−33.5	−36.6	−40.5
450 × 450 × 150	−16.5	−18.4	−20.8	−26.0	−29.9	−33.7	−34.9	−38.1	−41.6
450 × 450 × 300	−11.1	−13.2	−14.8	−19.7	−24.3	−27.5	−29.8	−33.8	−38.7
450 × 450 × 450	−11.5	−13.5	−15.0	−20.5	−25.4	−28.3	−30.6	−34.0	−38.5
450 × 450 × 600	−12.3	−14.4	−15.5	−20.8	−24.9	−27.4	−29.6	−32.9	−37.3
600 × 150 × 150	−17.9	−21.6	−22.6	−28.4	−32.5	−35.4	−37.4	−40.4	−43.7
600 × 150 × 300	−11.1	−13.1	−16.5	−21.6	−27.0	−30.3	−32.9	−36.8	−40.0
600 × 150 × 450	−9.1	−11.1	−13.8	−19.8	−25.3	−28.9	−31.3	−35.0	−39.5
600 × 150 × 600	−12.0	−14.7	−16.7	−24.6	−30.2	−33.1	−35.1	−37.9	−41.7
600 × 300 × 150	−26.7	−28.1	−29.6	−33.9	−37.4	−39.0	−40.6	−42.9	−45.4
600 × 300 × 300	−18.5	−20.2	−22.4	−27.2	−31.1	−33.8	−35.8	−38.9	−42.7
600 × 300 × 450	−15.0	−17.5	−18.2	−23.5	−29.4	−31.7	−33.9	−37.1	−41.2
600 × 300 × 600	−16.6	−18.6	−19.3	−26.2	−31.3	−34.2	−36.0	−38.1	−41.2
600 × 450 × 150	−28.6	−29.5	−31.3	−35.0	−38.0	−39.9	−41.4	−43.8	−45.8
600 × 450 × 300	−18.1	−19.8	−22.1	−26.8	−30.7	−33.4	−35.5	−38.5	−41.9
600 × 450 × 450	−13.7	−15.6	−17.3	−22.9	−27.8	−30.9	−32.9	−35.7	−39.1
600 × 450 × 600	−14.8	−16.9	−18.4	−24.9	−30.0	−32.8	−34.4	−36.8	−39.7
600 × 600 × 150	−18.4	−21.1	−23.5	−29.0	−33.0	−35.5	−37.5	−40.4	−43.6
600 × 600 × 300	−12.9	−15.0	−16.6	−22.4	−27.6	−30.0	−32.3	−36.2	−40.6
600 × 600 × 450	−10.4	−12.4	−14.3	−20.6	−25.0	−28.2	−30.4	−33.3	−38.5
600 × 600 × 600	−11.6	−13.6	−15.3	−21.5	−26.9	−29.6	−31.7	−34.6	−38.7

Table A10. The ΔBCT values for EB-flute and diagonal overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−35.9	−37.9	−38.9	−42.6	−46.0	−49.1	−51.5	−55.5	−60.4
150 × 150 × 300	−36.7	−40.3	−42.1	−44.8	−49.6	−52.2	−55.2	−59.0	−63.3
150 × 150 × 450	−35.3	−39.7	−41.5	−44.8	−49.0	−52.1	−54.0	−58.6	−62.6
150 × 150 × 600	−34.6	−39.8	−41.6	−45.0	−48.8	−52.2	−54.6	−58.6	−63.2
300 × 150 × 150	−41.3	−43.0	−45.2	−48.5	−51.3	−54.3	−56.6	−61.3	−67.1
300 × 150 × 300	−35.7	−39.4	−41.4	−45.8	−49.1	−52.1	−53.5	−58.7	−63.2
300 × 150 × 450	−40.2	−42.7	−44.0	−47.4	−50.3	−53.4	−55.5	−59.8	−65.4
300 × 150 × 600	−37.8	−40.8	−42.3	−46.1	−49.1	−52.2	−54.3	−58.4	−63.5
300 × 300 × 150	−40.5	−42.3	−43.5	−48.1	−52.4	−55.1	−57.6	−61.5	−65.5
300 × 300 × 300	−35.6	−38.1	−39.6	−44.3	−48.3	−51.7	−54.2	−57.9	−61.9
300 × 300 × 450	−36.2	−39.2	−40.8	−45.6	−49.5	−52.8	−54.8	−58.8	−63.2
300 × 300 × 600	−35.4	−39.2	−41.2	−43.9	−50.7	−53.0	−56.0	−59.4	−63.2
450 × 150 × 150	−44.2	−46.8	−48.3	−50.6	−55.0	−56.5	−60.0	−64.0	−68.3
450 × 150 × 300	−38.5	−40.8	−42.4	−46.2	−49.5	−52.4	−54.6	−59.0	−64.6
450 × 150 × 450	−36.4	−39.6	−41.3	−45.7	−49.2	−52.1	−54.5	−58.1	−63.0
450 × 150 × 600	−37.6	−40.4	−41.7	−45.6	−48.8	−51.0	−54.1	−57.8	−63.8
450 × 300 × 150	−44.5	−45.7	−47.3	−50.8	−53.9	−56.7	−58.9	−62.6	−67.3
450 × 300 × 300	−37.5	−39.0	−40.1	−44.1	−47.5	−50.6	−53.1	−57.3	−62.3
450 × 300 × 450	−38.1	−39.9	−41.0	−45.5	−49.4	−52.6	−54.6	−58.3	−62.7
450 × 300 × 600	−37.7	−39.9	−41.2	−45.1	−48.9	−51.8	−54.1	−58.0	−62.8
450 × 450 × 150	−42.3	−44.1	−46.6	−51.5	−55.3	−58.8	−60.4	−63.7	−67.2
450 × 450 × 300	−35.9	−38.0	−39.6	−44.9	−49.5	−52.6	−54.9	−58.7	−63.2
450 × 450 × 450	−36.1	−38.3	−40.0	−45.7	−50.6	−53.7	−55.9	−58.9	−62.4
450 × 450 × 600	−35.9	−38.3	−39.8	−44.9	−49.2	−52.2	−53.9	−58.1	−62.3
600 × 150 × 150	−46.2	−48.0	−49.4	−52.9	−56.4	−58.0	−61.1	−64.9	−69.1
600 × 150 × 300	−38.9	−41.2	−43.0	−47.2	−49.9	−53.5	−55.7	−60.0	−64.9
600 × 150 × 450	−36.8	−39.3	−41.1	−44.9	−48.4	−51.8	−53.8	−57.5	−62.9
600 × 150 × 600	−35.7	−39.0	−40.8	−45.9	−49.4	−51.9	−54.6	−57.7	−63.2
600 × 300 × 150	−46.1	−47.2	−48.8	−52.4	−55.4	−58.0	−59.9	−64.2	−69.1
600 × 300 × 300	−39.7	−41.3	−42.8	−46.7	−49.8	−52.7	−54.9	−59.2	−64.2
600 × 300 × 450	−37.4	−38.9	−40.1	−43.7	−47.8	−50.6	−53.1	−57.1	−62.0
600 × 300 × 600	−37.9	−40.0	−41.3	−45.4	−49.8	−52.7	−54.2	−58.3	−62.1
600 × 450 × 150	−45.7	−47.2	−48.8	−52.7	−56.1	−58.6	−60.8	−64.2	−68.8
600 × 450 × 300	−39.3	−40.8	−42.6	−46.9	−50.7	−53.6	−56.0	−59.8	−64.3
600 × 450 × 450	−35.8	−37.7	−39.1	−43.7	−47.9	−51.3	−53.6	−57.4	−62.1
600 × 450 × 600	−37.0	−39.2	−40.7	−46.0	−50.2	−52.9	−55.3	−58.7	−62.7
600 × 600 × 150	−44.6	−46.5	−49.1	−54.2	−58.1	−60.7	−62.6	−65.5	−68.7
600 × 600 × 300	−37.9	−40.0	−41.6	−47.5	−52.4	−55.1	−57.3	−61.0	−65.2
600 × 600 × 450	−34.5	−37.0	−38.8	−44.9	−50.0	−53.2	−54.8	−58.6	−62.4
600 × 600 × 600	−35.8	−38.3	−40.2	−46.7	−51.6	−54.9	−56.8	−59.4	−62.5

Table A11. The ΔBCT values for BC-flute and short-side overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−12.0	−13.8	−14.9	−18.1	−21.0	−24.1	−26.4	−30.6	−34.8
150 × 150 × 300	−10.9	−14.3	−16.5	−20.5	−23.5	−26.8	−28.9	−33.0	−37.7
150 × 150 × 450	−11.2	−15.0	−16.2	−19.9	−24.4	−26.2	−29.4	−33.2	−37.7
150 × 150 × 600	−9.4	−13.1	−15.4	−20.5	−23.4	−26.7	−29.2	−33.1	−37.9
300 × 150 × 150	−14.9	−17.1	−18.2	−21.1	−23.3	−26.2	−31.0	−34.3	−44.1
300 × 150 × 300	−0.4	−5.4	−8.1	−14.1	−16.3	−19.9	−22.5	−31.7	−40.8
300 × 150 × 450	−12.7	−16.0	−17.7	−20.5	−23.0	−25.5	−26.1	−33.1	−39.0
300 × 150 × 600	−9.1	−12.6	−14.3	−17.3	−21.2	−22.4	−25.0	−30.0	−38.8
300 × 300 × 150	−16.7	−18.6	−19.8	−23.8	−27.6	−30.3	−32.9	−36.8	−41.0
300 × 300 × 300	−11.5	−13.6	−14.8	−18.7	−22.4	−25.2	−27.9	−32.2	−37.0
300 × 300 × 450	−11.1	−14.6	−16.4	−20.4	−23.9	−26.9	−29.0	−32.5	−37.3
300 × 300 × 600	−10.7	−14.2	−16.6	−19.8	−25.4	−27.3	−30.6	−34.2	−37.8
450 × 150 × 150	−21.5	−24.1	−27.2	−26.5	−31.4	−31.0	−35.8	−40.1	−44.8
450 × 150 × 300	−18.1	−20.5	−21.6	−23.5	−26.1	−28.0	−29.9	−34.4	−40.8
450 × 150 × 450	−8.0	−13.2	−13.7	−16.8	−21.0	−21.8	−24.4	−29.4	−37.9
450 × 150 × 600	−14.0	−17.2	−18.9	−21.1	−22.9	−25.5	−27.6	−31.6	−38.6
450 × 300 × 150	−15.1	−16.4	−17.4	−20.4	−23.4	−26.4	−29.2	−34.5	−42.7
450 × 300 × 300	−10.5	−12.4	−13.4	−16.5	−18.9	−21.9	−24.7	−29.5	−36.0
450 × 300 × 450	−10.8	−12.8	−13.7	−16.9	−19.3	−22.4	−24.6	−29.1	−35.1
450 × 300 × 600	−9.5	−12.4	−13.3	−15.9	−19.0	−21.7	−25.0	−29.5	−35.2
450 × 450 × 150	−17.7	−19.4	−21.6	−26.1	−29.8	−33.7	−35.0	−38.4	−42.1
450 × 450 × 300	−12.2	−14.4	−15.9	−20.2	−24.1	−27.2	−29.8	−33.5	−38.8
450 × 450 × 450	−11.6	−14.0	−15.3	−19.8	−24.0	−27.8	−29.4	−33.3	−38.1
450 × 450 × 600	−12.2	−14.4	−16.7	−19.6	−23.2	−27.1	−28.8	−32.8	−37.8
600 × 150 × 150	−23.3	−27.6	−28.2	−29.5	−32.0	−31.8	−36.0	−39.9	−44.2
600 × 150 × 300	−18.6	−21.3	−22.4	−24.2	−27.1	−28.4	−30.2	−34.5	−41.3
600 × 150 × 450	−17.7	−20.2	−21.5	−23.2	−24.5	−27.2	−28.7	−32.4	−37.9
600 × 150 × 600	−11.3	−14.6	−16.4	−18.8	−20.4	−22.1	−25.4	−29.5	−36.6
600 × 300 × 150	−19.8	−20.5	−21.4	−24.3	−27.1	−29.9	−31.3	−38.1	−45.0
600 × 300 × 300	−12.1	−14.1	−15.2	−18.0	−20.4	−23.4	−26.3	−31.3	−39.6
600 × 300 × 450	−11.3	−13.3	−14.3	−16.1	−19.3	−21.5	−24.6	−29.5	−36.4
600 × 300 × 600	−11.9	−14.1	−14.9	−17.0	−20.2	−22.3	−25.4	−29.6	−36.5
600 × 450 × 150	−15.4	−16.4	−17.6	−21.2	−24.5	−27.4	−30.3	−35.1	−42.7
600 × 450 × 300	−11.5	−13.5	−14.6	−18.1	−21.3	−24.3	−27.0	−31.2	−36.6
600 × 450 × 450	−9.4	−11.3	−12.5	−15.7	−18.6	−21.6	−24.2	−28.9	−34.4
600 × 450 × 600	−10.4	−12.6	−13.8	−17.2	−20.0	−23.1	−25.2	−29.7	−34.7
600 × 600 × 150	−19.3	−21.9	−23.8	−28.7	−32.4	−35.1	−37.2	−40.3	−43.8
600 × 600 × 300	−14.1	−16.4	−17.8	−22.7	−27.3	−29.9	−32.3	−36.2	−40.6
600 × 600 × 450	−11.0	−13.7	−15.2	−20.3	−23.9	−27.0	−29.4	−32.9	−38.4
600 × 600 × 600	−11.7	−14.1	−15.5	−20.6	−25.2	−28.8	−30.3	−33.8	−38.4

Table A12. The ΔBCT values for BC-flute and long-side overhanging.

Box	ΔBCT (%)								
	1%	3%	5%	10%	15%	20%	25%	35%	50%
150 × 150 × 150	−12.0	−13.8	−14.9	−18.1	−21.0	−23.6	−26.1	−30.3	−35.6
150 × 150 × 300	−10.9	−14.3	−16.5	−19.8	−23.5	−26.1	−28.9	−33.0	−37.3
150 × 150 × 450	−11.2	−15.0	−16.2	−19.9	−24.4	−26.2	−29.4	−33.2	−37.5
150 × 150 × 600	−9.4	−13.4	−16.0	−20.5	−22.9	−26.2	−29.0	−33.1	−38.2
300 × 150 × 150	−17.4	−18.8	−20.6	−25.7	−28.9	−31.6	−34.0	−37.8	−41.5
300 × 150 × 300	−17.6	−19.9	−21.2	−25.3	−28.6	−31.0	−32.9	−37.9	−41.7
300 × 150 × 450	−15.7	−16.8	−17.9	−22.8	−26.3	−28.0	−30.5	−35.1	−38.4
300 × 150 × 600	−16.1	−18.6	−20.1	−24.1	−27.4	−30.5	−32.5	−36.2	−40.2
300 × 300 × 150	−16.7	−18.6	−19.8	−23.8	−27.6	−30.2	−32.6	−36.4	−40.4
300 × 300 × 300	−11.5	−13.6	−14.8	−18.7	−22.4	−26.1	−27.9	−32.2	−37.0
300 × 300 × 450	−11.1	−14.6	−16.4	−20.4	−23.9	−26.9	−28.3	−32.5	−37.0
300 × 300 × 600	−10.7	−14.2	−16.6	−18.8	−24.3	−26.4	−29.9	−33.6	−37.3
450 × 150 × 150	−19.2	−19.4	−21.6	−26.0	−30.0	−33.0	−35.4	−38.9	−42.7
450 × 150 × 300	−12.1	−14.0	−15.9	−20.3	−24.3	−28.4	−31.0	−34.1	−40.0
450 × 150 × 450	−12.5	−15.6	−18.4	−23.0	−28.4	−30.1	−32.2	−35.6	−40.9
450 × 150 × 600	−11.5	−13.9	−14.7	−19.6	−24.5	−27.5	−29.6	−34.3	−38.3
450 × 300 × 150	−25.3	−26.0	−28.3	−31.6	−34.6	−37.0	−38.3	−41.6	−44.5
450 × 300 × 300	−17.6	−19.2	−20.4	−24.3	−27.8	−30.6	−32.8	−36.5	−40.7
450 × 300 × 450	−16.1	−17.7	−19.5	−24.0	−27.3	−30.3	−32.6	−36.3	−39.4
450 × 300 × 600	−16.9	−19.4	−20.7	−24.7	−28.2	−30.8	−32.9	−36.2	−40.2
450 × 450 × 150	−17.7	−19.4	−21.6	−26.1	−29.7	−33.4	−34.7	−38.4	−41.8
450 × 450 × 300	−12.2	−14.4	−15.9	−20.2	−24.1	−27.2	−29.8	−33.5	−37.8
450 × 450 × 450	−11.6	−14.0	−15.3	−19.8	−24.0	−26.9	−29.4	−33.3	−38.1
450 × 450 × 600	−12.2	−15.5	−16.7	−21.0	−24.6	−27.1	−29.5	−33.1	−37.5
600 × 150 × 150	−14.2	−16.6	−20.0	−25.4	−29.8	−33.0	−35.4	−37.9	−43.1
600 × 150 × 300	−9.6	−12.6	−15.2	−19.4	−24.8	−28.3	−31.1	−35.3	−39.9
600 × 150 × 450	−7.7	−9.6	−12.1	−17.3	−22.1	−25.7	−28.5	−32.8	−36.8
600 × 150 × 600	−9.8	−13.0	−15.8	−22.6	−27.8	−30.1	−32.3	−35.6	−39.7
600 × 300 × 150	−25.0	−27.2	−29.1	−32.3	−36.1	−37.7	−39.5	−42.9	−45.1
600 × 300 × 300	−19.0	−20.7	−22.9	−27.0	−30.5	−32.9	−35.3	−38.1	−42.3
600 × 300 × 450	−15.7	−17.5	−18.9	−23.4	−27.7	−30.4	−32.6	−35.8	−39.6
600 × 300 × 600	−16.3	−18.2	−19.9	−25.0	−28.9	−32.0	−34.2	−37.0	−41.4
600 × 450 × 150	−28.0	−29.1	−30.8	−34.1	−37.0	−39.1	−40.7	−43.1	−45.7
600 × 450 × 300	−20.0	−21.5	−23.5	−27.5	−30.9	−33.5	−35.6	−38.5	−41.8
600 × 450 × 450	−14.9	−16.9	−18.3	−22.9	−27.0	−29.9	−32.0	−35.1	−38.9
600 × 450 × 600	−15.2	−17.7	−19.0	−24.3	−28.5	−31.3	−33.1	−36.1	−39.4
600 × 600 × 150	−19.3	−21.9	−23.8	−28.7	−32.4	−35.1	−37.4	−40.3	−43.9
600 × 600 × 300	−14.1	−16.4	−18.0	−23.0	−27.1	−30.0	−32.3	−35.9	−39.8
600 × 600 × 450	−11.0	−13.7	−15.2	−20.3	−24.6	−27.5	−29.7	−32.9	−38.4
600 × 600 × 600	−11.7	−14.1	−15.5	−20.6	−25.2	−28.0	−30.3	−33.8	−38.4

Table A13. The ΔBCT values for BC-flute and diagonal overhanging.

Box	ΔBCT (%)								
	1%	**3%**	**5%**	**10%**	**15%**	**20%**	**25%**	**35%**	**50%**
150 × 150 × 150	−36.8	−38.8	−39.8	−43.1	−46.1	−48.9	−51.1	−55.0	−59.8
150 × 150 × 300	−36.6	−40.1	−42.1	−45.2	−49.1	−51.6	−54.4	−58.3	−62.7
150 × 150 × 450	−35.5	−39.3	−41.6	−45.2	−48.4	−51.4	−53.5	−58.0	−62.2
150 × 150 × 600	−34.7	−39.2	−41.5	−45.2	−48.3	−51.6	−54.0	−58.0	−62.7
300 × 150 × 150	−41.4	−43.5	−45.1	−48.3	−51.1	−53.9	−57.5	−60.9	−67.8
300 × 150 × 300	−30.5	−35.6	−38.7	−46.5	−47.2	−52.5	−53.7	−59.8	−64.4
300 × 150 × 450	−37.8	−40.9	−42.7	−45.4	−48.8	−51.4	−53.6	−58.4	−64.5
300 × 150 × 600	−36.5	−39.9	−41.8	−45.7	−49.2	−51.5	−53.9	−58.2	−64.5
300 × 300 × 150	−41.8	−43.7	−44.8	−48.8	−52.6	−55.3	−57.7	−61.6	−65.6
300 × 300 × 300	−36.1	−38.8	−40.1	−44.1	−47.5	−50.7	−53.2	−57.1	−61.1
300 × 300 × 450	−36.2	−39.5	−41.2	−45.2	−48.8	−51.8	−54.0	−58.0	−62.5
300 × 300 × 600	−35.8	−39.8	−41.9	−44.6	−49.9	−52.2	−55.3	−59.0	−63.0
450 × 150 × 150	−44.1	−46.7	−49.5	−51.2	−55.8	−57.0	−60.7	−64.6	−68.7
450 × 150 × 300	−39.4	−41.9	−43.6	−46.9	−50.0	−52.8	−55.5	−59.3	−65.2
450 × 150 × 450	−35.1	−38.7	−41.0	−45.9	−49.1	−52.1	−54.7	−58.8	−64.4
450 × 150 × 600	−37.5	−40.5	−41.9	−45.8	−49.2	−51.4	−54.2	−58.2	−64.1
450 × 300 × 150	−45.3	−46.5	−47.8	−51.0	−54.0	−56.7	−59.0	−63.0	−68.6
450 × 300 × 300	−38.8	−40.7	−41.9	−45.3	−48.3	−51.2	−53.7	−57.8	−63.3
450 × 300 × 450	−38.2	−40.5	−41.5	−45.5	−48.7	−51.7	−53.8	−57.9	−62.6
450 × 300 × 600	−37.8	−40.7	−42.1	−45.6	−48.9	−51.7	−54.0	−58.1	−63.3
450 × 450 × 150	−43.5	−45.2	−47.3	−51.6	−55.1	−58.5	−60.2	−63.7	−67.3
450 × 450 × 300	−37.2	−39.5	−40.9	−45.4	−49.3	−52.4	−54.8	−58.7	−63.3
450 × 450 × 450	−36.4	−39.1	−40.6	−45.3	−49.4	−52.3	−54.7	−58.3	−62.1
450 × 450 × 600	−36.7	−39.7	−41.1	−45.2	−49.0	−52.0	−53.9	−58.4	−62.8
600 × 150 × 150	−45.8	−47.8	−49.1	−52.5	−55.9	−58.4	−60.7	−64.5	−68.6
600 × 150 × 300	−39.1	−41.6	−43.5	−47.2	−50.8	−53.3	−55.6	−59.8	−65.0
600 × 150 × 450	−37.2	−39.7	−41.6	−45.3	−48.5	−51.7	−53.9	−57.5	−63.0
600 × 150 × 600	−35.1	−38.5	−40.7	−45.7	−49.4	−51.8	−54.4	−58.2	−63.5
600 × 300 × 150	−47.4	−48.5	−49.9	−53.3	−56.2	−58.8	−60.4	−65.1	−70.1
600 × 300 × 300	−40.5	−42.5	−44.1	−47.5	−50.5	−53.3	−55.8	−59.9	−65.9
600 × 300 × 450	−38.3	−40.3	−41.5	−44.7	−48.4	−51.0	−53.7	−57.9	−63.3
600 × 300 × 600	−38.5	−41.2	−42.5	−46.1	−49.9	−52.6	−54.2	−58.5	−63.3
600 × 450 × 150	−46.5	−47.8	−49.2	−52.7	−55.8	−58.3	−60.6	−64.1	−69.2
600 × 450 × 300	−40.7	−42.5	−44.0	−47.7	−51.0	−53.8	−56.3	−60.0	−64.5
600 × 450 × 450	−36.7	−38.9	−40.2	−44.1	−47.4	−50.7	−53.1	−57.1	−61.8
600 × 450 × 600	−37.3	−40.0	−41.3	−45.7	−49.2	−51.9	−54.3	−58.1	−62.4
600 × 600 × 150	−45.6	−47.3	−49.5	−53.9	−57.6	−60.2	−62.3	−65.3	−68.8
600 × 600 × 300	−39.2	−41.4	−42.9	−47.8	−52.2	−54.9	−57.3	−61.0	−65.2
600 × 600 × 450	−35.3	−38.2	−39.7	−44.7	−49.0	−52.1	−54.0	−58.1	−62.3
600 × 600 × 600	−35.9	−39.2	−40.8	−46.0	−50.2	−53.4	−55.6	−58.8	−62.4

References

1. Garbowski, T. Optimal corrugated board—What does it mean? *Przegląd Pap.* **2022**, *78*, 517–524. [CrossRef]
2. Garbowski, T. The most common mistakes when estimating the load-bearing capacity of corrugated board packaging. *Przegląd Pap.* **2023**, *79*, 485–488. [CrossRef]
3. Garbowski, T. Safety Factors in the Design of Corrugated Board Packaging. *Packag. Rev.* **2023**, *3*, 16–22.
4. Garbowski, T. The use of artificial intelligence for the optimal production of corrugated board. *Przegląd Pap.* **2023**, *79*, 279–288. [CrossRef]
5. FEMat Systems: BSE System. Available online: http://fematsystems.pl/bse-system_en/ (accessed on 18 December 2023).
6. Sohrabpour, V.; Hellström, D. M odels and software for corrugated board and box design. In Proceedings of the 18th International Conference on Engineering Design (ICED 11), Copenhagen, Denmark, 15–18 October 2011.
7. Kellicutt, K.; Landt, E. Development of design data for corrugated fiberboard shipping containers. *Tappi J.* **1952**, *35*, 398–402.
8. Maltenfort, G. Compression strength of corrugated containers. *Fibre Contain* **1956**, *41*, 106–121.
9. McKee, R.C.; Gander, J.W.; Wachuta, J.R. Compression strength formula for corrugated boxes. *Paperboard Packag.* **1963**, *48*, 149–159.
10. Allerby, I.M.; Laing, G.N.; Cardwell, R.D. Compressive strength—From components to corrugated containers. *Appita Conf. Notes* **1985**, *1*, 11.
11. Schrampfer, K.E.; Whitsitt, W.J.; Baum, G.A. *Combined Board Edge Crush (ECT) Technology*; Institute of Paper Chemistry: Appleton, WI, USA, 1987.
12. Batelka, J.J.; Smith, C.N. *Package Compression Model*; Institute of Paper Science and Technology: Atlanta, GA, USA, 1993.
13. Urbanik, T.J.; Frank, B. Box compression analysis of world-wide data spanning 46 years. *Wood Fiber Sci.* **2006**, *38*, 399–416.
14. Garbowski, T. Digitization of corrugated board. *Przegląd Pap.* **2022**, *78*, 683–686. [CrossRef]
15. Garbowski, T.; Gajewski, T.; Grabski, J.K. The role of buckling in the estimation of compressive strength of corrugated cardboard boxes. *Materials* **2020**, *13*, 4578. [CrossRef]
16. Urbanik, T.J.; Saliklis, E.P. Finite element corroboration of buckling phenomena observed in corrugated boxes. *Wood Fiber Sci.* **2003**, *35*, 322–333.
17. Nordstrand, T. Basic Testing and Strength Design of Corrugated Board and Containers. Ph.D. Thesis, Lund University, Lund, Sweden, 2003.
18. Suarez, B.; Muneta, M.L.M.; Sanz-Bobi, J.D.; Romero, G. Application of homogenization approaches to the numerical analysis of seating made of multi-wall corrugated cardboard. *Compos. Struct.* **2021**, *262*, 113642. [CrossRef]
19. Fadiji, T.; Ambaw, A.; Coetzee, C.J.; Berry, T.M.; Opara, U.L. Application of finite element analysis to predict the mechanical strength of ventilated corrugated paperboard packaging for handling fresh produce. *Biosyst. Eng.* **2018**, *174*, 260–281.
20. *ISO 12048:1994*; Packaging Complete, Filled Transport Packages. Compression and Stacking Tests Using a Compression Tester. ISO: Geneva, Switzerland, 1994.
21. *ISO 3037:2022*; Corrugated Fibreboard, Determination of Edgewise Crush Resistance (Non-Waxed Edge Method). ISO: Geneva, Switzerland, 2022.
22. Avilés, F.; Carlsson, L.A.; May-Pat, A. A shear-corrected formulation of the sandwich twist specimen. *Exp. Mech.* **2012**, *52*, 17–23. [CrossRef]
23. Garbowski, T.; Gajewski, T. Transverse shear modulus in corrugated materials. *Przegląd Pap.* **2020**, *76*, 103–108. [CrossRef]
24. Nordstrand, T.; Carlsson, L. Evaluation of transverse shear stiffness of structural core sandwich plates. *Comp. Struct.* **1997**, *37*, 145–153. [CrossRef]
25. Pozorski, Z.; Wojciechowski, S. The influence of symmetrical boundary conditions on the structural behaviour of sandwich panels subjected to torsion. *Symmetry* **2020**, *12*, 2093.
26. Yan, J.; Wang, G.; Li, Q.; Zhang, L.; Yan, J.D.; Chen, C.; Fang, Z. A comparative study on damage mechanism of sandwich structures with different core materials under lightning strikes. *Energies* **2017**, *10*, 1594. [CrossRef]
27. Zhang, X.; Jin, X.; Xie, G.; Yan, H. Thermo-fluidic comparison between sandwich panels with tetrahedral lattice cores fabricated by casting and metal sheet folding. *Energies* **2017**, *10*, 906.
28. Duan, Y.; Zhang, H.; Sfarra, S.; Avdelidis, N.P.; Loutas, T.H.; Sotiriadis, G.; Kostopoulos, V.; Fernandes, H.; Petrescu, F.I.; Ibarra-Castanedo, C.; et al. On the use of infrared thermography and acousto-ultrasonics NDT techniques for ceramic-coated sandwich structures. *Energies* **2019**, *12*, 2537. [CrossRef]
29. Hohe, J. A direct homogenization approach for determination of the stiffness matrix for microheterogeneous plates with application to sandwich panels. *Compos. Part B* **2003**, *34*, 615–626.
30. Buannic, N.; Cartraud, P.; Quesnel, T. Homogenization of corrugated core sandwich panels. *Comp. Struct.* **2003**, *59*, 299–312.
31. Biancolini, M.E. Evaluation of equivalent stiffness properties of corrugated board. *Comp. Struct.* **2005**, *69*, 322–328. [CrossRef]
32. Abbès, B.; Guo, Y.Q. Analytic homogenization for torsion of orthotropic sandwich plates: Application. *Comp. Struct.* **2010**, *92*, 699–706.
33. Marek, A.; Garbowski, T. Homogenization of sandwich panels. *Comput. Assist. Methods Eng. Sci.* **2015**, *22*, 39–50.
34. Garbowski, T.; Marek, A. Homogenization of corrugated boards through inverse analysis. In Proceedings of the 1st International Conference on Engineering and Applied Sciences Optimization, Kos Island, Greece, 4–6 June 2014; pp. 1751–1766.

35. Kim, S.; Horvath, L.; Molina, E.; Frank, B.; Johnson, S.; Johnson, A. Predicting the effect of pallet overhang on the box compression strength. *Packag. Technol. Sci.* **2023**, *36*, 927–939. [CrossRef]
36. *TAPPI T402 sp-21*; Standard Conditioning and Testing Atmospheres for Paper, Board, Pulp Handsheets, and Related Products, Test Method TAPPI/ANSI T 402 sp-21. TAPPI Press: Atlanta, GA, USA, 2021.
37. Abaqus Unified FEA®Software. Available online: https://www.3ds.com/products-services/simulia/products/abaqus (accessed on 18 December 2023).
38. Hill, R. A theory of the yielding and plastic flow in anisotropic metals. *Proc. R. Soc. London Ser. A Math. Phys. Sci.* **1948**, *193*, 281–297. [CrossRef]