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MODELLING THE BEHAVIOUR OF CARTON BOARD FOR IMPROVED MACHINE AND PROCESS DESIGN

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Abstract

Modelling machine and material with a common approach is a difficult task. This work deals with the design of high speed packaging machinery and in particular carton erection. An overall methodology is discussed and its application to the design of machinery for the erection of cartons is described in detail. The work demonstrates a model that allows the machine system, process and behaviour of the product to be considered within a single environment. The ability to consider machine-material interaction enables the identification of the limiting factors of current machine systems and provides a platform for the generation of design rules governing machinery that deals with a particular packaging operation and material. These design rules facilitate the development of the next generation of packaging machinery and materials for improved processability.

Keywords: systems modelling, product modelling, simulation in product design

1 Introduction

Global competition combined with legislative demands through the European Packaging Waste Directive are forcing the producers of fast moving consumer goods (FMCG) to use thinner, lighter weight and recycled packaging materials to convey their goods to the consumer. The behaviour of such materials when used with present designs of packaging machinery is less predictable [1]. This may result in lower operating efficiencies and reduced quality which is unacceptable to the machine users and their customers. Of increasing importance are what can be thought of as the qualitative aspects of the carton. These include package alignment and symmetry, the appearance, print finish and surface finish of the carton. These aspects can considerably alter the mechanical properties of the carton, such as slip coefficient and bending stiffness. All of which frustrate the ability to reliably predict the interaction between product (package) and machine system for different types of material.

In some areas of the packaging industry such variations in the properties of packaging material combined with the desire to accommodate larger variances in product attributes and higher speeds make the design of reliable mechanisms and operations particularly difficult. This is certainly the case in the area of cartoning and for the erection of skillets. In this work a skillet is a side-seamed carton with open ends, effectively forming a rectangular sleeve. This type of packaging is very common for snack foods, such as Easter eggs, pizzas and ready meals. Skillets are typically designed, printed, cut and creased at a supplier and then flat packed for transport to the converter or end user. These skillets are erected on site so that the product may be placed into the carton. Many of the current mechanisms for opening the skillets experience a high number of failures. These failures generally occur when the skillet either fails to open resulting in the take-up of an overall mode of buckling rather than separation, or when a false crease line is created and the skillet deforms. The prediction of such behaviour is very complicated because of not only the material properties but factors such as the point of applied loading, rate of loading (speed), aerodynamic and vacuum effects, and the design of the carton itself (number and position of creases and the aspect ratio of the sides of the carton).

This paper aims to address these issues through the creation of a simulation model for both machine system and the skillet during the erection process. This simulation model can be used to identify the performance bounds of a particular machine system and package, with a given set of material properties and attributes. The results can be used as a design tool for both machines with improved performance capabilities, and for the reverse engineering of pack design and materials for improved processibility.

2 Understanding machine-material interaction

The work described in this paper is part of a larger programme of research aimed at improving the design of packaging machinery. The aim of the programme is to research and validate a methodology for understanding and evaluating the interactions between packaging material and packaging machines. This methodology can then to be used to facilitate the understanding and modelling of machine-material interaction for the optimisation of machine design and material specification concurrently. In this paper the case of skillet erection is considered. A brief overview of the full methodology is presented. This is shown in figure 1 and the key phases are discussed in the following sections. The application of the methodology to the specific case of carton erection is described in detail in section 3.

2.1 Evaluation of machine system

This first phase of the methodology (figure 1) involves the evaluation of the machine system, the product and the process. In particular, the aim of this phase is to identify the key interactions that occur between the machine system and product during the process. An interaction occurs where part or the entire product is in contact with a component of the machine system in order to achieve, or support the undertaking of a particular function. For example, a number of interactions may occur during product transport, manipulation, filling, opening or sealing. For each interaction that occurs it is necessary to identify the properties or attributes that impact or influence the behaviour/success of the operation. These properties or attributes are related to either the pack, the material, environmental conditions, machine operations or individual machine components/effectors. This can be undertaken for the complete process, an individual operation or part of the process.

2.2 Investigation of relationships

The second phase of the methodology involves the investigation of the relationships between the various properties of the pack, material, environmental conditions, machine system and effector during interaction. These relationships can be investigated through experimental trials, theoretical modelling and empirical studies. The objective is to be able to quantify the permissible range of values within which it is possible to achieve successful undertaking of the process operation. Successful undertaking of the process means that an acceptable performance is achieved, that is to say that products fall within acceptable quality limits and there are no adverse effects for other operations.

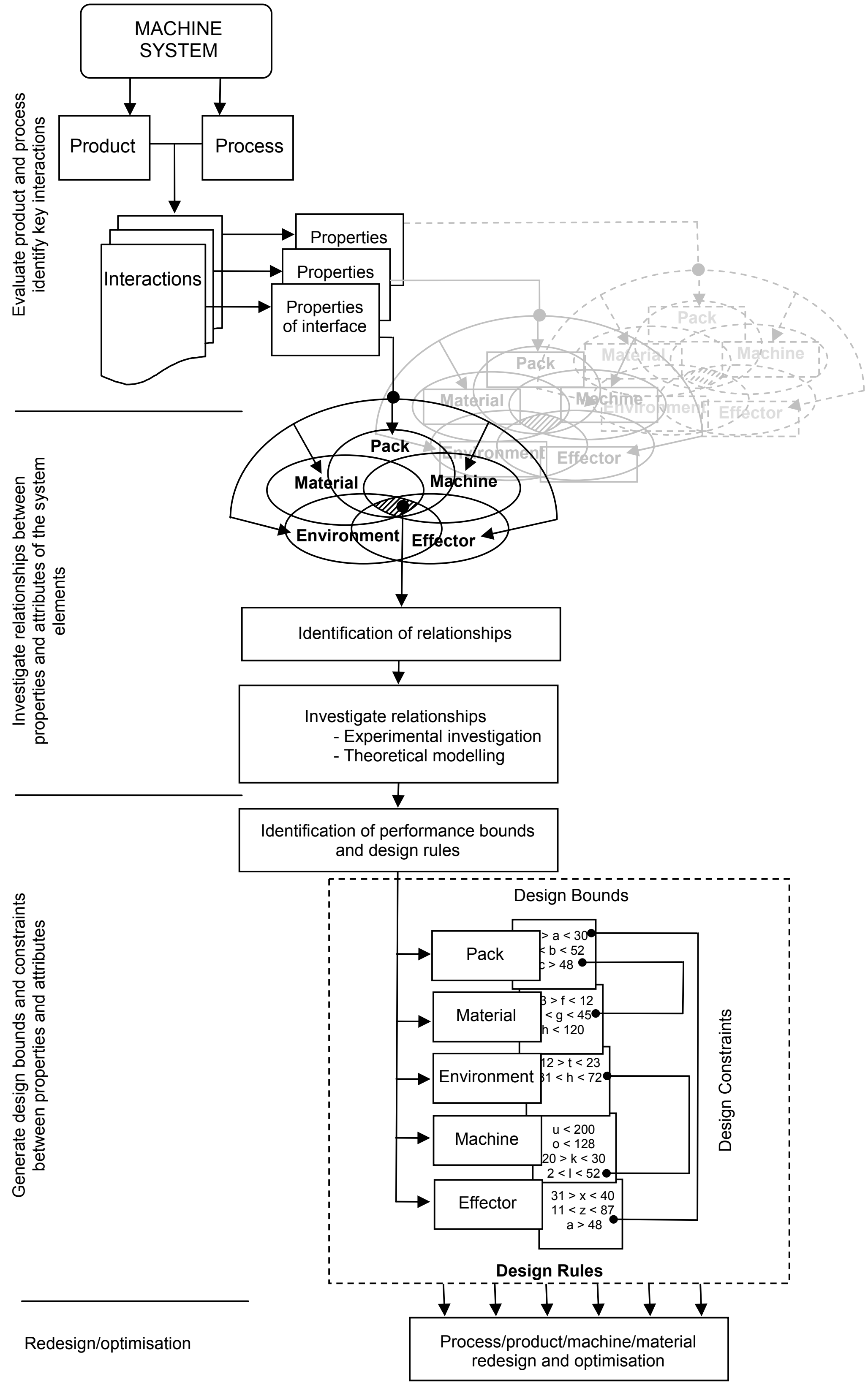


Figure 1 – Methodology for understanding machine-material interaction

In figure 1, this region is the intersection of the five sets and is denoted by the hatched lines. Such relationships may be dependent upon factors such as speed, load distribution, point of application or material compliance. During this phase it is also important that dependencies between properties/attributes are identified across the five elements; pack, material, environment, machine and end-effector. The outcome of this phase of the methodology is the establishment and quantification of relationships that govern the machine-material interaction.

2.3 Generation of design rules

The third phase of the methodology involves the generation of what can be thought of as design rules. These design rules are a collection of bounded parameters and constraints that describe the relationship necessary for successful processing. The design rules define the influence of the pack attributes, the material, the environment, the machine system and the end-effector upon the success of a particular operation. These rules are necessary to provide an understanding of the interaction and are critical for the task of redesign and optimization of a machine system.

2.4 Redesign/optimization

The design rules generated during the third phase of the methodology define bounds on performance and physical aspects of the machine system which must be satisfied. These rules can be used to redesign the machine, refine the process, alter the material specification, modify the environmental conditions or even change the pack design. All of these aspects may be altered to improve processablity. During the task of redesign these rules can be used to continually test a redesign concept. Or in the case of optimizing an existing machine system the design rules can be used to formulate the objective function(s) to be satisfied by the optimiser.

3 Industrial case study (skillet erection)

This section discusses the application of the proposed methodology to an industrial case study. The problem dealt with is the erection of cartons and, in particular, the case of skillet erection. As previously discussed the skillet is usually flat packed and transported to a converter or end user where it is then erected ready to receive product. The erection process is illustrated in figure 2. A common method of opening or erecting skillets is to apply a controlled displacement or end shortening to the free end of the skillet. For the case considered in figure 2, this is on the right-hand side of the skillet. As the displacement increases the skillet begins to open, and when an end shortening equal to the height of the carton has been applied the skillet is fully opened.

As the design of cartons becomes more complicated, with the inclusion of extreme aspect ratios, new materials and board types, and the introduction of features such as film windows, many existing processes perform less well. In fact, current machines exhibit a large number of failures and as a consequence are revised through costly trial-and-error approaches. This is primarily because of the lack of an understanding of the behaviour of carton board during the erection process. It is therefore difficult to determine whether current machine designs can cope with the changes or whether alterations to the machine, product or packaging material are necessary in order to improve process efficiency.

The aim of the case study is therefore to establish a model of the behaviour of carton board and a skillet during the erection process. This model may then be used to investigate the capability of the machine system to cope with a particular pack and material. The application of the methodology and various activities are described in the next sections.

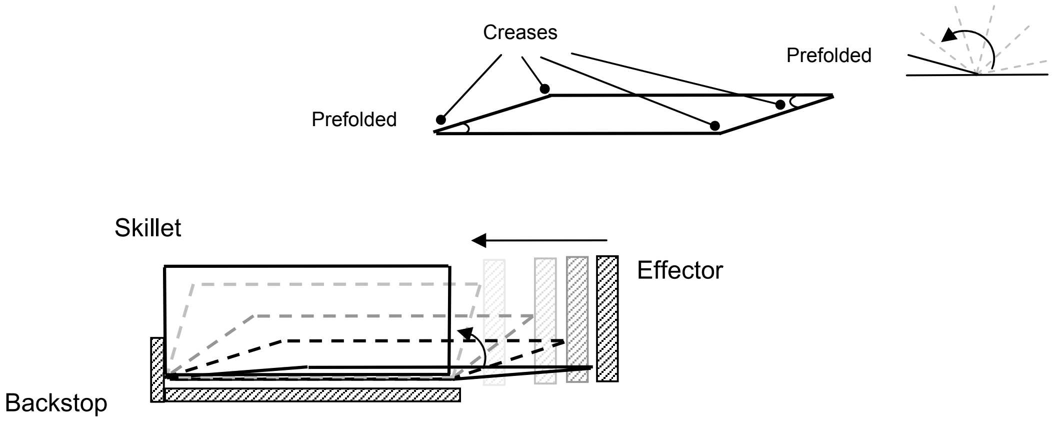


Figure 2 – Process overview of skillet erection

3.1 Evaluating machine system

Through an evaluation of the current machine system a number of key interactions have been identified. The physical interactions between the pack, the end effector, and the machine system are particularly important. These interactions are governed by the profile and magnitude of the applied displacement and the level of support for the skillet. The success of the process is also highly dependent upon the interaction of the four crease lines during erection, shown in figure 2. The impact of the environmental conditions on the performance of these creases is also an issue and is currently being investigated. Furthermore, the rate of displacement also influences the magnitude of the aerodynamic effects exerted upon the skillet during opening.

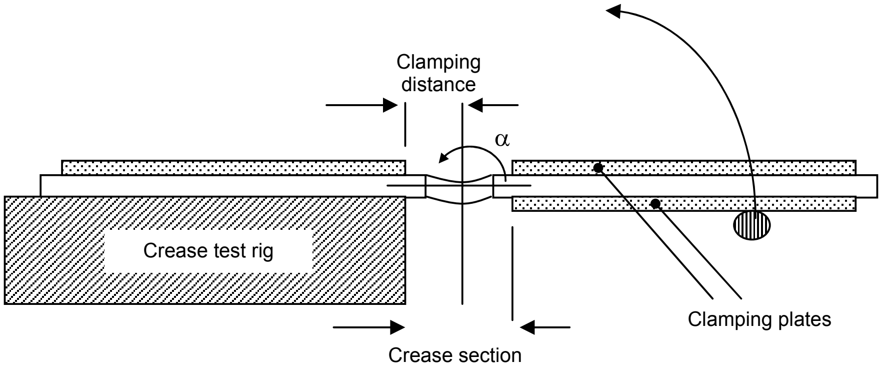
3.2 Investigation of relationships

The investigation of the relationships between the five system elements (Figure 1) can be conducted by either experimental investigation or theoretical modelling. For the case considered experimental investigation was undertaken to establish the localized behaviour of creases. The results were then incorporated into a theoretical model of the pack and process. The experimental study and the modelling are discussed in the following sections.

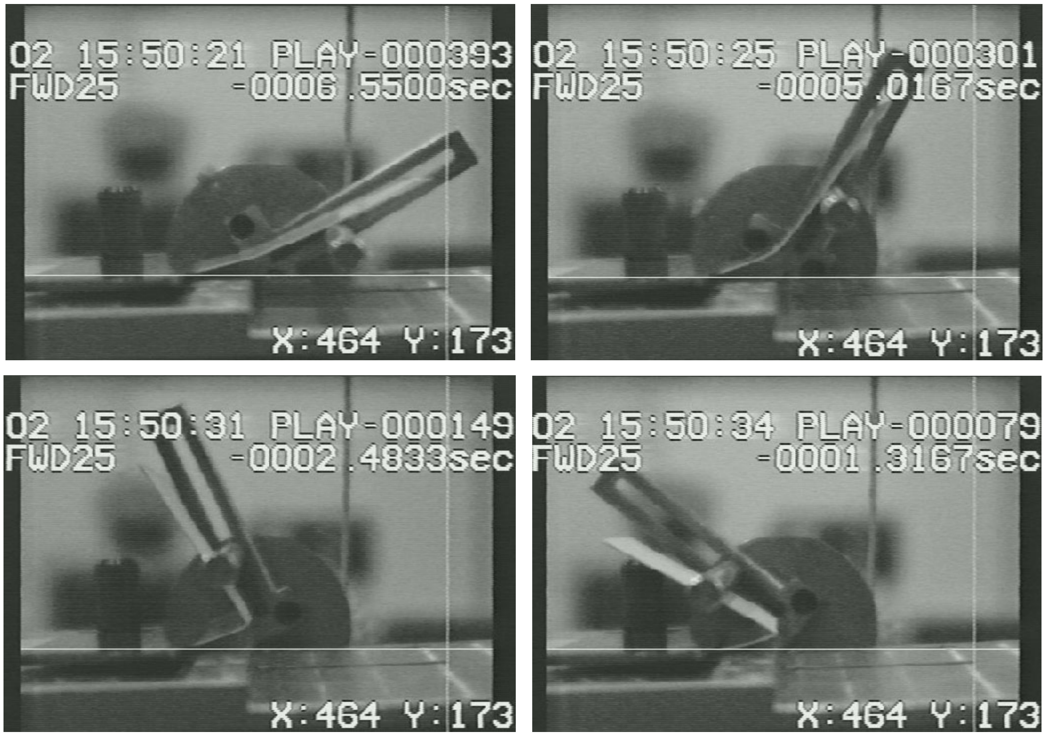
3.2.1 Experimental investigation

The aim of the experimental investigation is to establish a model that represents the variation in localised bending stiffness of a crease. This model must represent the change in properties of a crease during folding, opening after prefolding, and as a result of environmental conditions. It is necessary to consider both the folding and the opening because two opposing creases of the skillet are prefolded during construction, as shown in figure 2.

In order to undertake the experimental trials, a rig was devised, illustrated in part (a) of figure 3. Samples of carton board are held rigidly about either side of the crease. A tensile tester and processing unit are calibrated to allow for the additional mass of the clamping plates. The objective of rigidly supporting the carton about the crease is to provide a means for directly measuring the change in properties of the crease during folding and opening. The tensile tester accurately measures the load necessary to achieve a desired angular displacement and a high speed motion analyser is used to obtain video footage, shown in part (b) of figure 3.



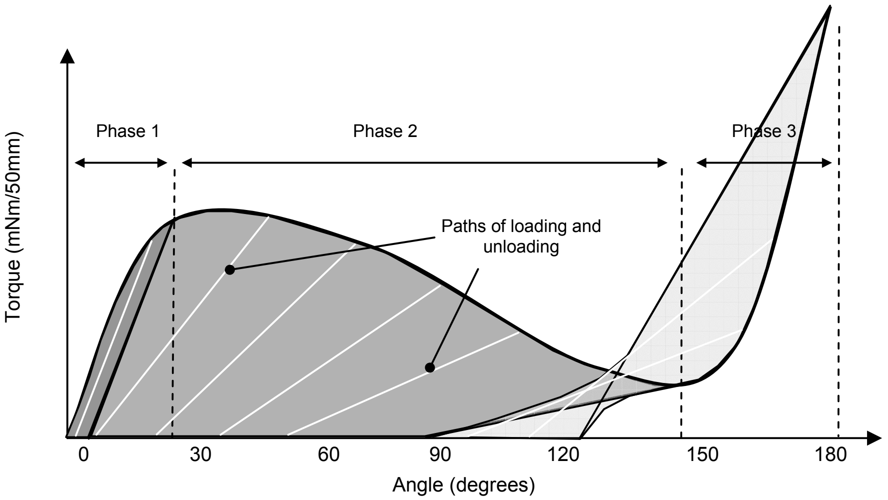
Part (a)



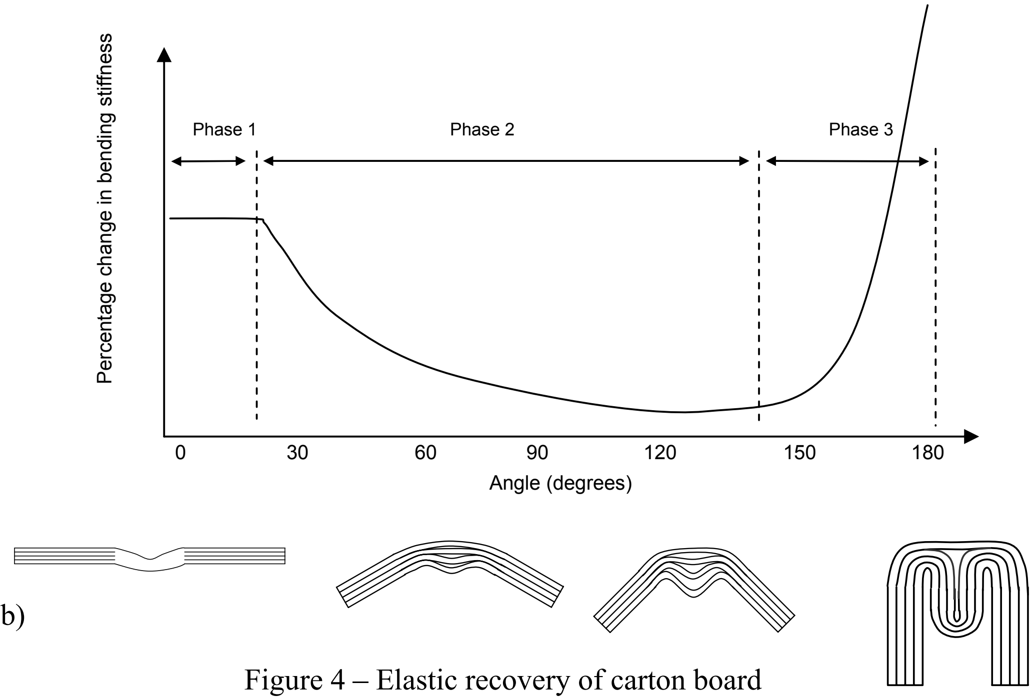
Part (b)

Figure 3 – Experimental rig

Creased carton board exhibits a partially elastic response when loaded. The load displacement characteristic, part (a) of figure 4 shows that the creased carton board exhibits an elastic response between 0 and 20 degrees of folding, a partially plastic region occurs between 20 degrees and 140 degrees, and beyond 140 degrees the creased board exhibits behaviour similar to strain hardening. This is because the plies within the board are effectively locking together. Applied loading beyond 180 degrees compresses the 'bead' directly and in this work it is assumed that at 180 degrees the stiffness of the crease is much greater than the stiffness of the carton board. The various states of the crease section during folding are shown in the lower portion of part (b) of figure 4. The implications of a partially elastic response are that a material follows a different load-displacement characteristic during unloading than that observed during loading. These loading and unloading paths are shown in part (a) and can be calculated from the experimental results. The gradients of these paths represent the bending stiffness of the carton board. The variation in bending stiffness over the complete folding cycle is shown in part (b) of figure 4 and shows three phases of response. The first phase occurs between 0 and 20 degrees, during which the stiffness is constant and equal to the initial stiffness of the crease. The second phase occurs between 20 and 140 degrees where the stiffness reduces in an approximately exponential manner. During the final stage of the response the stiffness rises exponentially. In order to represent the complete response polynomial curves are fitted to the data. This produces a parameterised model of the response (bending stiffness) of creased carton board during folding. The process is repeated for the opening of prefolded carton board.



Part (a)



Part (b)

Figure 4 – Elastic recovery of carton board

The resulting parametric models are expressed in terms of the percentage variation in bending stiffness with respect to the initial state for folding and the final state for opening. In turn these states can be related to the bending stiffness of the board. In this manner, the response of a particular board type during opening and folding can be derived from a single value.

3.2.2 Theoretical modelling

The modelling phase of this work aims to create a model of the behaviour of the skillet during erection. In order to achieve this, the work combines a minimum energy approach [2] with a constraint modelling environment. The constraint modelling environment is reported elsewhere [3, 4] and has been used successfully for the design and synthesis of machine systems based on kinematic rules and motion constraints. The energy method used in this work considers a section of carton board as a system of elements connected serially. These elements are rigid linkages connected to each other by mass less nodes that incorporate a bending stiffness. In this work, only bending stiffness is considered as it is assumed that negligible levels of through-thickness and laminar shear occur during skillet erection. In order to represent a skillet, nodes that correspond to a crease section are assigned a governing parametric model of either a crease or a prefolded crease.

In order to determine the response of the system two criteria are considered: the internal energy of the system and the position of the free end. The model aims to minimise the internal energy of the system, given by the sum of the energy due to bending at each node while satisfying the end conditions (applied displacements). The end conditions are expressed in terms of a penalty function, which is a measure of the difference between the calculated end conditions and the applied displacements. The modelling approach uses the syntax and constraint resolution algorithm implemented in the constraint modelling environment. In this manner, it is possible to consider the behaviour of the skillet, the machine system and the end-effector concurrently. Figure 5 shows a two-dimensional model of the response of a skillet during opening. The model allows the properties of the material (stiffness), the machine setup, the pack geometry, the profile of the applied displacement and the initial conditions to be altered. In figure 6 two modelling episodes are conducted with skillets that possess aspect ratios of 2:1 and 1:1 respectively.

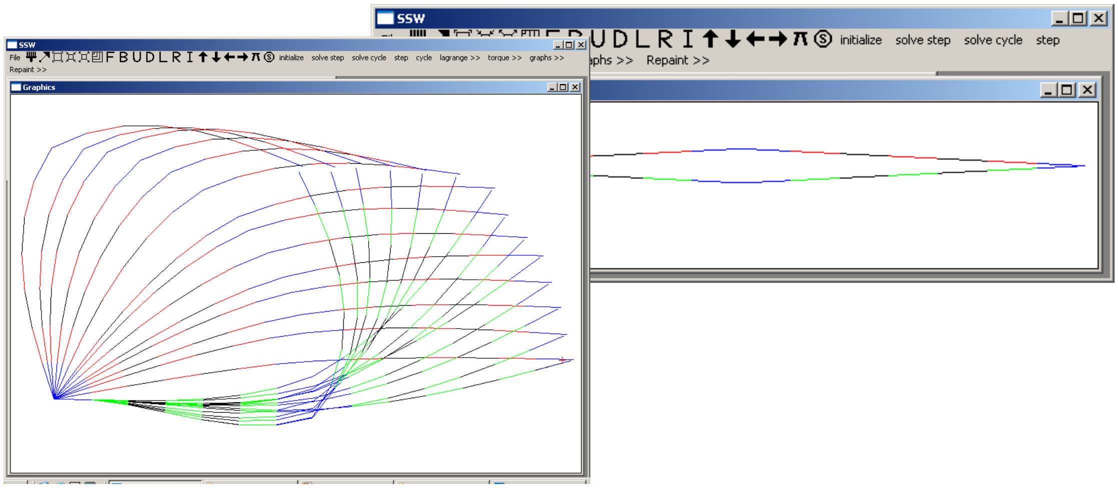


Figure 5 – Two-dimensional model of a skillet during opening

3.3 Generation of design rules

The combination of the experimental investigation and the theoretical modelling enable the behaviour of the skillet during erection to be represented. In this manner, the effect of changes in machine setup, pack geometry, material specification, and initial conditions (which are dependent upon environmental conditions and transport/handling) can be investigated. For example figure 7 shows a modelling episode where the process has failed and the skillet has taken up an overall mode of buckling. Through a series of successive modelling episodes it is possible to investigate the relationships between the various properties or attributes that govern the interactions between material and machine. For example, the speed of opening, crease stiffness, material stiffness and geometry of the skillet have been investigated. In this work, the design bounds are determined by success or failure of the skillet to open. For example, at higher opening speeds, and for high aspect ratio cartons the aerodynamic and vacuum effects prevent the skillet from opening. In addition to this, it is possible to generate an indication of the maximum amount of material that can be removed in order to accommodate features such as a film window before the process fails.

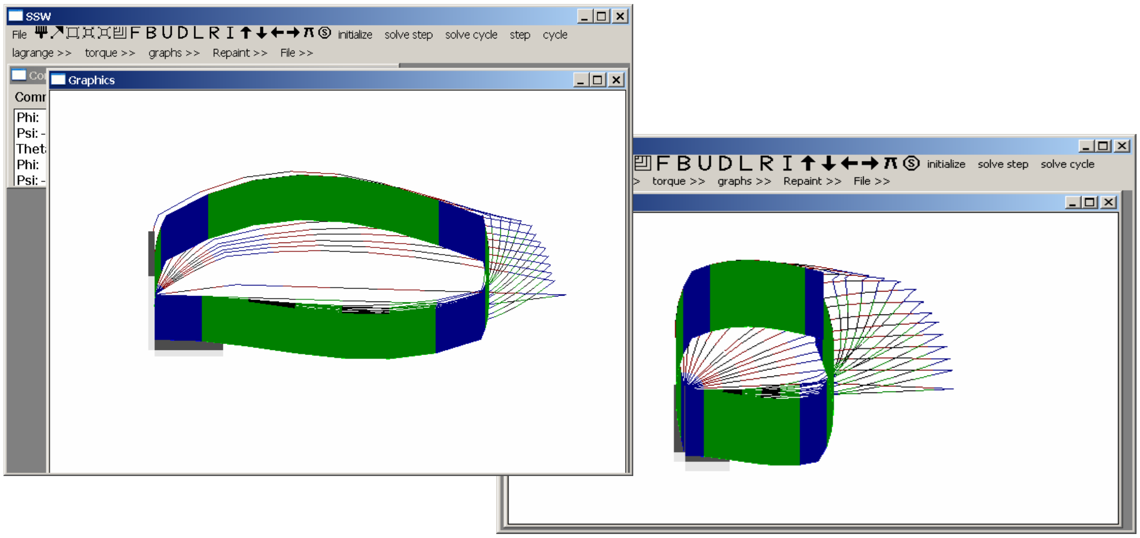


Figure 6 – Three-dimensional model cartons with different aspect ratios

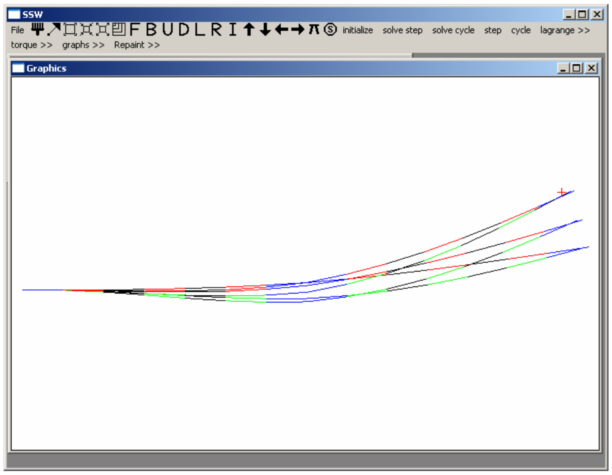


Figure 7 – Failure overall mode of buckling

These design bounds and associated constraints provide the understanding necessary to enable the flexible and responsive optimisation of machinery and where appropriate materials or pack design. For the case considered, the limits of performance for the current machine can be established and its capability to handle different pack configurations and materials can be investigated. In this manner, it is possible to ensure that the process is operated within these limits so as to maintain high levels of operating efficiency. In addition to this, because the materials and machinery are described in a common model, design changes and optimisation of machine components, such as the profile of the applied displacement, can be investigated.

4 Conclusions

Modelling machine and material interaction within a single environment is a difficult task. This work deals with the design of high speed packaging machinery and in particular carton erection. The work forms part of a larger programme of research which aims to create a methodology for understanding and evaluating the interactions between packaging machines and packaging materials. An outline of the methodology is provided and its application to an industrial case is discussed in detail.

The case of skillet erection is considered and modelled. The properties of the carton are measured experimentally and a simulation model is created for a particular carton design and erection process. Simulation episodes with variations in the product attributes highlight the limiting properties of the material, pack geometry and operating speeds for which the process is likely to fail. The simulation also allows for the optimal machine operation to be developed. In this case the path and velocity of the opening mechanism.

The approach demonstrates a model that allows the machine system, process and behaviour of the product to be considered concurrently. The ability to consider machine-material interaction enables the identification of the limiting factors of current machinery, and the creation of an understanding of the design rules governing packaging machinery for a particular operation and material type. These design rules facilitate the development of the next generation of packaging machinery and materials for improved processability.

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