Simulating pull-out fracture in particleboard

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Abstract

Pull-out forces of screws and connectors in particleboard are particularly important when designing for strength and, or assembly in the furniture industry. The aim of this thesis was to develop a simulation model of particleboard that can predict pull-out forces of screws better than the currently used simulation model at IKEA of Sweden. The developed model was validated against experimental results from pull-out tests carried out by IKEA.

Material properties for particleboard are determined from experiments previously carried out at IKEA test labs unless stated otherwise in the report. The authors did not carry out any tests. In order to simulate the pull-out forces of a screw, the finite element method was employed, simulation models from three different material models selected from the Finite Element Analysis (FEA) software LS-DYNA. The first material model considered Mat_143, a wood material model based on the Hashin failure criterion and used to develop simulation model 1. The second material considered, Mat_122 3D, based on Hill’s plasticity theory, was used with Mat_Add_Generalised_Damage to allow for incremental damage accumulation and failure. This was simulation model 2. The third one, Mat_221 which represents an orthotropic material with simplified damage, was used to develop simulation model 3.

Experimental test results for tensile test, bending test, shear test and, finally, the screw pull-out test was used to validate the simulation models. Before the scale validation, a single hexahedral element was simulated to evaluate the accuracy of the simulation models and to get a better understanding of the limitations of the material models. A mesh type and convergence study was carried out where it was concluded that the first- and second-order hexahedral and tetrahedral elements could be employed for the full model simulations, giving a sufficiently accurate result, i.e. matching the experimental results by at least 86%. An element size range of 1-3 mm was enough for quasi-static load cases and while an element size range 0.15-3 mm was relevant for dynamic load cases. Model 1 was abandoned when it was discovered the material model was not suitable for predicting material behaviour other than that of wood for a large mesh.

The remaining two simulation models were evaluated for tensile, shear and bending load cases. Simulation model 2 predicted both tensile and bending forces with an accuracy of 99% or higher, and predicted shear forces with an accuracy of 86%. Simulation model 3 predicts both tensile and shear forces with an accuracy of 98% or higher and predicted bending forces with an accuracy of 86%.

For the screw pull-out test, simulation models 2 and 3 under-predicted the pull-out forces significantly due to premature shear failure.
The currently used particleboard simulation model is referred to as simulation model 4 throughout the report. Simulation model 4 was the most accurate simulation model for predicting pull-out forces in particleboard.

**KEYWORDS:** transversely isotropic material, orthotropic material, particleboard, finite element analysis, material model
Acknowledgement

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Abbreviations

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<tr>
<td>CAE</td>
<td>Computer-Aided Engineering</td>
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<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>GISSMO</td>
<td>Generalised incremental stress-state dependent</td>
</tr>
<tr>
<td></td>
<td>damage model</td>
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<tr>
<td>MAGD</td>
<td>Mat_Add_Generalised_Damage</td>
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<td>IoS</td>
<td>IKEA of Sweden</td>
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Symbols

<table>
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<th>Symbol</th>
<th>Full-Form</th>
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<tbody>
<tr>
<td>𝐸_{𝑖}</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>𝜈_{𝑖𝑗}</td>
<td>Poisson’s ratio</td>
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<td>𝐺_{𝑖𝑗}</td>
<td>Shear modulus</td>
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<tr>
<td>𝜎_{𝑖}</td>
<td>Normal stress component</td>
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<tr>
<td>𝜏_{𝑖}</td>
<td>Shear stress component</td>
</tr>
<tr>
<td>𝜀_{𝑖}</td>
<td>Strain component</td>
</tr>
<tr>
<td>𝐶_{𝑖𝑗}</td>
<td>Constitutive matrix</td>
</tr>
<tr>
<td>𝜎̅_{𝑖𝑗}</td>
<td>Stress tensor of undamaged material</td>
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<tr>
<td>𝜎_{𝑖𝑗}</td>
<td>Stress tensor of damaged material</td>
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<tr>
<td>𝐒_{𝑑𝑎𝑚}</td>
<td>Damaged Flexibility matrix</td>
</tr>
<tr>
<td>𝑑</td>
<td>Damage variable</td>
</tr>
<tr>
<td>𝜀^{�}_{𝑖}</td>
<td>Damage threshold</td>
</tr>
<tr>
<td>𝜀^{𝑐}_{𝑖}</td>
<td>Critical damage threshold</td>
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Introduction

1.1 Screw withdrawal capacity

Withdrawal resistance of screws is of great importance to designers and furniture constructors as it is decisive for the strength and durability of furniture and wood structures. Most dismountable joints in contemporary furniture production are made with screws or screw driving assemblies. Furthermore, a large part of functional fittings such as sliding doors and recliners are connected by screws to the structural elements.

The withdrawal capacity of screws in wood-based materials depends on the type of material used in the construction and on the direction of the axes of the joining elements relative to the plane of the board and wood, as well as the diameter of the screws, the diameter of the screws pilot hole and screw thread parameters, the degree of alignment of the joining element and the direction of the loading. Finally, in a testing context, the test method and the preparation of the test samples are also factors that influence the withdrawal capacity of the screws [1].

IKEA of Sweden which is a furniture manufacturer, carried out tests to gather information on how much force the screw and the particleboard are exerted to during screw withdrawal. Furthermore, the distance of the screw from the edge of the board and the distance between the screws were varied in order to see how the pull-out strength was affected by these factors. The Platsa, Euro and Assembly screws and an 18mm thick particleboard were used for the tests. The method of using a tensile test machine and measuring the displacement and the global force directly from equipment was applied with the mean value and standard deviation being recorded.

It was observed that there is a critical distance from the edge of the particleboard beyond which the screw withdrawal strength would not be affected. There is also a critical distance between the screws beyond
which they do not affect each other. This information is crucial when designing for strength.

1.2 CAE driven product development

Significant developments in the prediction of structural behaviour have been achieved in the past decades through deterministic analysis using simulation tools (e.g., Finite Element Analysis) and experimental methods. Implementation of Computer-Aided Engineering (CAE) tools has assisted in simulating the dynamics of a system and analysing potential and existing problems to obtain an understanding and to develop solutions. CAE has facilitated in verifying the design by performing analyse on virtual models thus lowering the costs of physical prototypes used for testing. Deterministic analysis methods such as Finite Element Methods can be employed in different design stages in several iterations of the process. Instigation of CAE tools early in the design process makes the design and experimental validation cycle shorter by assisting in the identification of errors at an early stage and at a faster rate, thereby allowing more exploration of the design space.

Since particleboard is the most used bulk material to produce furniture by IKEA, they initiated research on developing a simulation material model for particleboard. This can at an early design and development phase allow finalising engineering decisions by prediction of material behaviour in the vicinity of connectors and screws. However, in order to simulate load bearing capacities for different products, it is imperative to have a sufficiently accurate simulation model. It is also important that the material properties used to define particleboard are sufficiently accurate. These material properties are attained from experimental tests.

The process of product development is shown in Figure 1
Product development without CAE

Concept → Design → Experimental Validation → Production

Product development aided by CAE

Concept → Design with CAE for verification and testing → Experimental Validation → Production

- Design time increases to add CAE
- Validation time reduces significantly with fewer physical prototypes
- Overall time saving
- Significant cost saving

*Figure 1 CAE driven product development at Volvo [2].*

1.3 Problem formulation and thesis goal

In order to predict deformation and remaining bearing capacity in particleboards when subjected to static loads transferred via the connectors, nonlinear deformation behaviour and appropriate fracture mechanisms must be considered. This is because the mechanical tests performed by Hagman [3] showed a clear non-linear behaviour of the material under tensile loads load in the symmetry plane due to damage, or nonlinear elasticity, or a combination of both.

Simulation model 4, previously developed by Hagman [3], over-predicts the failure stresses and strains under tensile loads by a factor 2 when the material coordinate system is not aligned with the global coordinate system. It may also over-predict pull-out forces by 15%.

The goal of this thesis work is to develop a robust simulation model in finite element tool LS-DYNA for particleboard [4]. The simulation model should be able to:

- Accurately predict the pull-out forces of a screw in particleboard
- Accurately predict the failure force for the load cases bending, shearing and uniaxial tension.
1.4 Delimitations

i) Emphasis on the pull-out fracture of connectors in particleboard.

ii) Existing material data on particleboard will be used together with material data found from previously made experimental tests.

iii) Focus only on orthotropic and transversely isotropic material models.

iv) One type of connector to be considered, in this case, the Euro screw.

v) Focus on failure criteria for transversely isotropic materials.

vi) Effects from temperature variations and moisture variations will not be considered.

1.5 Tasks involved

The organisation of this thesis is as follows:

- Literature study on suitable material models in LS-DYNA and failure criteria for simulating the transversely isotropic material behaviour of particleboard.
- Determining particleboard material parameters from experimental test results.
- Finite element analysis of selected load cases for a single hexahedral element to validate the simulation models against experimental results.
- Finite element analysis of selected load cases for test specimen models to validate the simulation models against experimental results.
- Finite element analysis results of screw pull-out against experimental results to determine the most accurate and robust simulation model.

1.6 Ethical and environmental considerations

The work does not raise any questions regarding gender, age, ethnicity, sexual identification or religious belonging. Furthermore, no sustainability or related questions are in focus in this work, even though particleboard has many positive qualities in that aspect.
2 Literature study

In this section, the literature studied for this thesis is reviewed. The background of wood which is also transverse isotropic, and particleboard is presented. Material models in LS-DYNA which were selected as being suitable to predict the deformation and failure behaviour of particleboard are also presented.

2.1 What is particleboard?

Whilst wood is a versatile, durable and renewable material, it has variations in its chemical, physical and anatomical compositions between species and within species. Some wood uses may be limited by dimensions, anisotropy and defects [5]. To minimise these limitations, wood-based products with properties which are significantly different from solid wood, such as particleboard, emerged.

Wood is a composite material with properties that are much desired in the furniture and construction industry. It generally has a high strength-to-weight ratio and is strong and stiff when loaded parallel to the grain, but flexible when loaded perpendicular to the grain [6]. By defining the tangential (T) and radial (R) directions transverse to the fibre direction, and the longitudinal (L) direction parallel to the fibre direction [7], see Figure 2a, the tangential and radial planes have small differences between their material properties compared to the difference between the tangential and longitudinal properties. For simplification on orthotropic material properties, wood can be considered as a transversely isotropic material [8]. Throughout the report, the in plane is defined as x-y plane in Figure 2b and out of plane is defined as the normal vector to the x-y plane in Figure 2b.
Particleboard consists of a mix of wood waste material and an adhesive. The wood waste can be all from mechanically produced wood chips and sawdust to planer shavings. The bark is not used as it is seen as an impurity in the final product, instead, it can be used as energy for the process. For an overview of the production process, the reader is referred to the work of Rivela, Hospido and Feijoo [11], who studied the environmental aspect of the life-cycle of particleboard.

Particleboard can have different configurations. It can consist of either a single layer with the same density throughout the layer or, it can consist of several distinct layers with each layer having the same density. It can also consist of several layers with different densities that are growing into each other [12]. Smaller particles are used on both surfaces to get smooth surfaces and larger particles are used in the middle to give the board strength [11]. In this work, the focus will be on particleboard with several distinctive layers. The board in focus is considered to have five different layers with varying in density, see Figure 3.
Another advantage of particleboard is that it can be made from many types of wood. A lot of research is currently being made to see if it is possible to manufacture particleboards with more unusual materials like bamboo [14].

Particleboard is, like wood, considered to be transversely isotropic. The board is isotropic within the layers where the density varies slightly, in that layer. Research made by Eslah, Enayati, Tajvidi and Faezipour [15] and Svensson [13] shows that the mechanical properties are dependent on the density.

### 2.2 Mechanical properties

The mechanical properties of particleboard are greatly influenced by many factors. Eslah and his colleagues [15] showed through experimental testing on chipboards with different densities and resin content, that the mechanical properties such as Modulus of Rupture and Modulus of Elasticity increased with the increase of the density of the board and the amount of resin it contains. The research also suggests that the internal bonding strength is promoted with increasing resin content. According to Kalaycioglu, Deniz and Hiziroglu [16] it is important to have similar pH values of the wood particles and resin. Similar pH values create good bonding between the particles and resin which enhances both the physical and mechanical properties. Another influencing factor on the mechanical properties is the pressing time, the longer it is the stronger the chipboard produced.

Eckelman [17] also performed a test to determine the screw withdrawal capacity of particleboards with different densities. A screw was placed in the centre of the chipboard and another one close to the edge. The tests show that the screw
withdrawal strength is dependent on the density of the board and where on the board the screw is placed [17]. As expected, chipboards with higher densities give a higher screw withdrawal strength. Screws placed in the centre of the board showed higher screw withdrawal strength than screws placed close to the edge with a factor of 1.5-1.6. Eckelman [17] also suggests that a screw that goes through the board have, on average, 16% higher withdrawal capacity than a screw that is not going through the board.

Studies made by Nemli, Aydin and Zekovic [18] shows that the amount of wood dust present in the particleboard affects the mechanical properties significantly. Usage between 5-20% of wood dust showed an increased internal bonding strength but a decrease in modulus of rupture and modulus of elasticity. However, usage of over 20% of wood dust decreased the internal bond strength. Usage of more resin and longer pressing time showed an improvement of the mechanical properties. By increasing the level of moisture from 9% to 13%, the board’s modulus of rupture and modulus of elasticity were increased. But at a higher moisture level, 17%, the bending properties decreased.

2.3 Fracture propagation

The failure of particleboard happens rapidly through micro-cracking. However, bridging can be seen behind the crack tip. Bridging is when, behind the crack tip, there are still fibres that are connecting the fracture surfaces, see Figure 4. Failure does not occur until the fracture surfaces are completely separated. The strength of particleboard is reduced due to microcracking in the frontal process-zone, an illustration of this can be seen in Figure 4.

*Figure 4 Crack propagation in particleboard [19].*

Ehart et al [19] investigated how the fracture energy could be used to determine the fracture propagation in particleboard when a crack already is formed in the material. They concluded that Linear Elastic Fracture Mechanics (LEFM) was not suitable to describe the fracture in particleboard and instead used an energy formulation. The fracture energy was calculated from a load-displacement plot
by taking the area under the curve and dividing it by the crack surface area. The fracture energies obtained were 2930 N/m for a crack out of plane and 240 N/m for a crack in plane, see Figure 5 [19]. Observe that in Figure 5b, three plates were glued together to be able to perform the experimental test.

![Figure 5](image1.png)

*Figure 5 Specimens tested by Ehart et al. a. out of plane failure, b. in plane failure [19].*

### 2.4 Pull-out forces of screws in particleboard

From the study carried out by Vassiliou and Barboutis [20], the correlation between density and the required pull-out force of a screw from particleboard is investigated. Boards from three different manufacturers and several different screws were tested.

The different fittings that the manufacturers use for their particleboard are shown in Figure 6.

![Figure 6](image2.png)

*Figure 6 Joint fittings used in the study by Barboutis [20].*

The density of the particleboard and the pull-out force show a relationship that is almost linear for screws without plastic sockets [20], see Figure 7.
The screw withdrawal capacity differs slightly between the three manufacturer’s particleboards but when plastic inserts are used there is a bigger difference as shown in Figure 8.

Vassiliou and Barboutis [20] show that there is a visible, linear relationship between the density and the pull-out force for a screw in particleboard. However, there is no such clear relation when plastic sockets are used, probably because the manufacturers are using different sockets [20]. The plastic socket which goes deeper through the thickness of the board also gives the biggest pull-out force.
2.5 Material modelling

In the following section, a brief introduction will be given into the material model used to describe particleboard in LS-DYNA. More information about the material model can be found in the Appendix.

As the goal of the work presented here is to be able to accurately predict a screw pull-out from the face of particleboard, the material models chosen need to give the ability to:

- Describe the transverse isotropic and linear elastic behaviour of particleboard.
- Describe stress-strain softening behaviour of particleboard using separate damage and/or failure criteria for all orthogonal planes.

2.5.1 Linearly transversely isotropic material

Previous work done by Svensson [13] and research carried out by Hagman [3] suggest that particleboard can be modelled as a transversely isotropic material. For linear elasticity with transverse isotropy, the number of constitutive independent coefficients in the stiffness matrix can be reduced from 8 in the orthotropic case, to only 5 independent coefficients [21]. The stiffness matrix of an orthotropic material is shown in Voight notation, in Equation 1.

\[
[C] = \begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\
C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{55} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix}
\]  \quad (1)

The definition of transverse isotropy reads: “If there exists a plane, say S3, such that every plane perpendicular to it, is a plane of material symmetry, then the material is called transversely isotropic material” [21]. The material parameters from the more general orthotropic material can be reduced based on this definition. By expressing Equation 1 as:
\[
\begin{bmatrix}
\frac{1}{E_x} & -\frac{v_{yx}}{E_y} & -\frac{v_{zx}}{E_z} & 0 & 0 & 0 \\
-\frac{v_{xy}}{E_x} & \frac{1}{E_y} & -\frac{v_{zy}}{E_z} & 0 & 0 & 0 \\
-\frac{v_{xz}}{E_x} & -\frac{v_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}}
\end{bmatrix}
\]

where the xy plane is the plane of symmetry, then due to symmetry:

\[
\begin{align*}
\frac{v_{xy}}{E_x} &= \frac{v_{yx}}{E_y} \\
\frac{v_{zx}}{E_x} &= \frac{v_{xz}}{E_x} \\
\frac{v_{zy}}{E_y} &= \frac{v_{yz}}{E_y} \\
\end{align*}
\]

and due to transverse isotropy [22]

\[
\begin{align*}
E_x &= E_y & G_{yz} &= G_{zx} & v_{xy} &= v_{yx} & (4.a, b, c) \\
v_{xz} &= v_{yz} & v_{zx} &= v_{zy} & G_{xy} &= \frac{E_x}{2(1+v_{xy})} & (5.a, b, c)
\end{align*}
\]

The different material models studied in this work are listed below.

### 2.5.2 Material model 1

This material model Mat_143 - Wood available in LS-DYNA, was developed by Murray [23]. As the name suggests, it describes the behaviour of wood which is assumed transverse isotropic. This material model is based on the general constitutive relationship for an orthotropic material. Damage is based on the following damage formulation:

\[
\bar{\sigma}_{ij} = \sigma_{ij}/(1-d)
\]

where \(\bar{\sigma}_{ij}\) is the effective stress tensor of the damaged state, \(\sigma_{ij}\) is the stress tensor of the undamaged state and \(d\) is a damage parameter ranging between 0 and 1.

The damage parameter, \(d\), is related to two different failure modes [4]. The damage modes are based on the transverse isotropic directions, which is parallel modes and perpendicular modes. The parallel modes are damage within the isotropic plane and the perpendicular modes are damage perpendicular to the isotropic plane [23]. The failure criteria are explained in detail in Appendix 8.1.
2.5.3 Material model 2

The second material model evaluated is in LS-DYNA called Mat_221 - Orthotropic with simplified damage [4]. This material model is for an orthotropic material which is linearly elastic with an option for orthotropic simplified damage. The material model is based on the general constitutive relationship for an orthotropic material.

Damage is defined using the maximum strain criteria which are applied for tension, compression and shear in the orthotropic material directions. For damage two options are available, either the damage comes from tension only or from both tension and compression. Damage is applied to the elastic and shear modulus in all principle directions, $E_a$, $E_b$, $E_c$, $G_{ab}$, $G_{bc}$, $G_{ca}$ in Voight notation and damage only occurs when the critical damage threshold $\varepsilon^c$ is greater than the damage threshold $\varepsilon^s$, i.e. $\varepsilon^c > \varepsilon^s$ [4], and failure occurs when the failure strain is reached.

Damage can be defined using nine variables, three damage variables in each of the 3 orthotropic directions. The flexibility matrix when undergoing damage ($S_{dam}$) is described below in Equation 7 [4]:

$$
S_{dam} = \begin{bmatrix}
\frac{1}{E_a(1-d_{11})} & -\frac{v_{ba}}{E_b} & -\frac{v_{ca}}{E_c} & 0 & 0 & 0 \\
-\frac{v_{ba}}{E_b} & \frac{1}{E_b(1-d_{22})} & -\frac{v_{cb}}{E_c} & 0 & 0 & 0 \\
-\frac{v_{ca}}{E_c} & -\frac{v_{cb}}{E_c} & \frac{1}{E_c(1-d_{33})} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{ab}(1-d_{12})} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{bc}(1-d_{23})} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{ca}(1-d_{31})}
\end{bmatrix}
$$

(7)

where $E$ is the elastic modulus and $G$ is the shear modulus, $d$ is a damage parameter and $v$ is Poisson’s ratio.

$$
d = \max (d; D^c (\frac{\xi - \varepsilon^s}{\varepsilon^c - \varepsilon^s}) +)
$$

(8)

where $(\cdot)^+$ is the positive part $(\cdot)^+$ = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{if } x < 0 \end{cases}, \varepsilon$ are the current strains in each direction and $D^c$ is the critical damage [4].

When an element fails, it is optional to delete the element. If it is decided that the element should be deleted, the element can be deleted when either one, several or all integration points have failed.
2.5.4 Material model 3

The third material model evaluated is in LS-DYNA called Mat_122 – 3D Hill. This material model is based on Hill’s 1948 anisotropic plasticity theory [24], combined with orthotropic elastic behaviour. A more detailed description of the material model can be found in the LS-DYNA manual [7].

To describe the linear stress-strain relationship of particleboard with damage and failure, this material model is used together with another material model, Mat_Add_Generalised_Damage (MAGD).

MAGD which is also available in LS DYNA is then applied to the Hill material model and set such that no plasticity or hardening of the material is allowed, the material fails as soon as the elastic limit is reached. MAGD is only used together with material model 3.

The generalised damage is applied using several history variables as the damage driving quantities, simultaneously. GISSMO is one such damage model which can be used to obtain anisotropic damage behaviour or separate stress reduction for volumetric and deviatoric deformations. Only a maximum of three damage evolutions, i.e. definition of 3 history variables can be implemented at the same time [25]. Appendix 8.2 provides a detailed description of how this material model was used.
This section of the report covers the experimental testing carried out to obtain the material parameters for particleboard as well as the pull-out test. Some material parameters which were obtained from constitutive relationships and past research papers are also presented in this section. However, results from the tests plotted against density will not be presented as a request from IKEA to protect their data from competitors.

The tests carried out by Svensson [13] for his thesis were to study the correlation between mechanical properties and density in particleboard. Assuming particleboard to be homogeneous material, he carried out tensile and simple shear tests as well as a bending test. Since the stiffness varies in the particleboard, the bending test was performed to allow for an analysis of the stress distribution along the thickness direction [13].

The pull-out tests presented were previously carried out at IKEA test labs and not by the authors.

3.1 Density

Svensson [13] concluded in his work that density varies through the thickness of particleboard. He obtained an image of the density through the thickness of an 18mm particleboard using a 3D tomography X-ray machine, see Figure 9. The density is lowest in the middle part of the board due to the presence of larger chips and more air. The surface sections are most dense.

Using the results from this test, the density through the thickness can then be plotted. The particleboard density can vary between 610-850 kg/m$^3$ [13].
Svensson also carried out a compression test on the test piece with a force of 4000 N, see the result in Figure 9.

![Figure 9 Comparison of a specimen before and after compression in the out-of-plane direction. The left side is before and right side after compression of 4000 N.](image)

Figure 9 shows that when compressed, the wood chips and the glue in the board come together which could lead to an increase in stiffness [13].

### 3.2 Poisson’s ratio

Tests carried out by Svensson to obtain the Poisson’s ratio were inconclusive hence a literature study was carried out instead. Moarcas and Irle [26] determined Poisson’s ratio to be 0.17 from a 4 point bending test. This value is then used by the authors as the major Poisson’s ratio and it’s the same through the thickness of the board.

The minor Poisson’s ratio is then calculated from Equations 3(a,b,c) and 5(a,b,c) in Section 2.5.1.

### 3.3 In plane tensile test

A dumbbell shaped test specimen is employed for this test and it is optimised to avoid stress concentrations which would distort the results [13]. The test specimen is clamped on both ends for a depth of 60mm in a tensile test machine and subjected to a prescribed displacement of 1 mm/min.
Figure 10 Schematic of the dumbbell shape with dimensions used in Svensson’s in plane experimental test [13].

The results are presented in Figure 11. The ultimate tensile strength and failure strain are seen in Figure 11B and the force at failure can be seen in Figure 11A.

![Figure 11 A) Force-time curve measured for an in plane tensile test and b) in plane tensile stress-strain relationship. [13]](image)

As an average density is known for each distinctive layer, the stiffness can thus be calculated for each individual layer. To get the average stiffness of a complete 18 mm particleboard, using the stiffness found for each layer, Equation 9 is used.

\[
E = \frac{1}{t}(E_1 \cdot t_1 + E_2 \cdot t_2 + E_3 \cdot t_3) \text{ MPA}
\]  

(9)

where \( t \) is the total thickness of the board, \( E_x \) is the stiffness for a specific layer, \( t_x \) is the thickness of the specific layer, and \( x=1,2,3 \).

The stiffness of the 18mm particleboard specimen used in the in plane tensile test can be determined using the constitutive relationship in Equation 10 between the failure stress and strain.

\[
E = \frac{\sigma}{\varepsilon}
\]  

(10)
where $E$ is the stiffness of the board, $\sigma$ is the tensile stress and $\varepsilon$ is the tensile strain in the board.

The stiffness calculated in Equation 9 should match that in Equation 10, but in this case it did not. The stiffness for each layer needs to be reduced by 20% to match the stiffness of the board in the experimental test. By not reducing the stiffness by 20%, the total stiffness of the board would be too stiff compared to the stiffness found in the experimental test which would cause inaccurate results. The failure strain is assumed to be the same through the thickness of the board.

Particleboards created from paulownia have an elastic modulus of 2396 – 2780 MPa for densities 550-650 kg/m$^3$ [16], which relates well to the values obtained by the authors, see Table 1.

### 3.4 Out of plane tensile test

The stiffness of particleboard in the out of plane direction is found in experimental tests by Svensson [13] to be a lot weaker than the in plane stiffness as shown by the value of the force at failure in Figure 12. The test setup is similar to that of the out of plane shear test, see Figure 13, except for loading direction, i.e. the test piece is pulled apart instead of being sheared [13].

As no data with failure strains was presented for the out of plane tensile test in Svensson’s thesis, Equations 9 and 10 are employed again to obtain the corresponding parameters for each distinct layer.

![Out of plane tensile test](image)

*Figure 12 Force-time curve for an out of plane tensile test.*
3.5 In plane shear strength

With both the Young’s modulus and Poisson’s ratio known, the in plane shear modulus was calculated using Equation 5c.

3.6 Out of plane shear test

Svensson [13] carried out a simple shear test in the out of plane material direction. A particleboard sample with measurements 20x20x18 mm was used. In the test setup shown in Figure 13, two particleboard samples are glued to the metal bars. The metal holder in the centre is pulled upwards gradually with a prescribed motion of 1 mm/min whilst the outer metal holders are fixed.

![Experimental test setup for shear testing by Svensson [13].](image13)

Figure 13 Experimental test setup for shear testing by Svensson [13].

![Test piece being sheared in out of plane direction.](image14)

Figure 14 Test piece being sheared in out of plane direction.

The test results showed a linear relationship between the ultimate shear strength against density [13] and from this, the average strength of each
distinct layer can then be determined. The failure strains are calculated by the following relationship:

\[ \gamma = \frac{\tau}{G} \quad (11) \]

where \( \gamma \) is the shear strain, \( \tau \) is the shear stress and \( G \) is the shear modulus. The force at failure can be seen in Figure 15.

![Out of plane Shear test](image)

*Figure 15 Experimental force curve for a simple shear load case [13].*

### 3.7 Bending test

In order to obtain the in plane stiffness to density relationship for particleboard, Svensson [13] conducted a three-point bending test. The specimen used is the same as in the tensile test. The specimen is placed on two rolls while a round punch was pressing down in the middle of the board with a prescribed displacement of 2 mm/min. A simple schematic illustration of this test setup can be seen in Figure 16.

![Prescribed displacement 2 mm/min](image)

*Figure 16 Schematic illustration of the setup used in the experimental bending test.*

The result of the bending force at failure can be seen in Figure 17.
3.8 Compiled material parameters

The material properties found from the tests and research mentioned in this chapter are presented in Table 1. The three particleboard layers mentioned in Table 1 are shown in Figure 3. The failure strain and Poisson's ratio are the same through the thickness of the board.

Table 1 Particleboard material properties.

<table>
<thead>
<tr>
<th>Material property</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stiffness [MPa]:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In plane elastic modulus</td>
<td>3160</td>
<td>2240</td>
<td>1280</td>
</tr>
<tr>
<td>Out of plane elastic modulus</td>
<td>320</td>
<td>220</td>
<td>100</td>
</tr>
<tr>
<td>In plane shear modulus</td>
<td>1350</td>
<td>957</td>
<td>547</td>
</tr>
<tr>
<td>Out of plane shear modulus</td>
<td>620</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td><strong>Strength [MPa]:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In plane</td>
<td>8.53</td>
<td>6.04</td>
<td>3.45</td>
</tr>
<tr>
<td>Out of plane</td>
<td>2.50</td>
<td>1.61</td>
<td>0.69</td>
</tr>
<tr>
<td>In plane shear</td>
<td>4.27</td>
<td>3.02</td>
<td>1.73</td>
</tr>
<tr>
<td>Out of plane shear</td>
<td>4.27</td>
<td>3.10</td>
<td>1.87</td>
</tr>
<tr>
<td><strong>Poisson’s ratio:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minor</td>
<td>0.012</td>
<td>0.011</td>
<td>0.009</td>
</tr>
<tr>
<td>major</td>
<td></td>
<td></td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Failure strains:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In plane tension</td>
<td></td>
<td></td>
<td>0.0027</td>
</tr>
<tr>
<td>Out of plane tension</td>
<td></td>
<td></td>
<td>0.0073</td>
</tr>
<tr>
<td>In plane shear</td>
<td></td>
<td></td>
<td>0.0032</td>
</tr>
<tr>
<td>Out of plane shear</td>
<td></td>
<td></td>
<td>0.0730</td>
</tr>
</tbody>
</table>
3.9 Screw pull-out test

The screw pullout test setup is presented in Figure 18. As previously mentioned, testing was also done for the Assembly and Platsa screws but this study only focuses on the Euro screw.

An 80x80mm test piece is used as it is not too small such the edges may affect the result and also not too large that bending may occur due to the long distance between the edges. It is fixed on the edges by two jigs.

A hole of diameter 5mm is predrilled with a depth of 10mm whilst the screw depth is 7mm, see Figure 18b.

\[\text{Figure 18 a) Experimental setup, b) a section view describing the dimensions of the pre-drilled hole, dimensions in [mm].}\]

The screw is screwed flat to the surface of the jig, this is done carefully by hand to avoid damaging the predrilled hole. The screw is then extracted by a tensile machine at a rate of 10 mm/min.

An investigation is then carried out to see if there is any difference in pull-out force from a screw that is tightened with high torque or low torque. A torque of 3.5–4 Nm is considered as a high torque value for tensioning screws in this case. The result of the pull-out test on 7 test specimens can be seen in Figure 19.

\[\text{Table 2 Comparison of pull-out values with or without pre-tensions.}\]

<table>
<thead>
<tr>
<th>Screw</th>
<th>Pull-out values, not tightened</th>
<th>Pull-out values, tightened with 3.5–4 Nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro screw</td>
<td>370 N</td>
<td>420 N</td>
</tr>
</tbody>
</table>
A standard deviation of 50N was calculated [13] for the pull-out test results and the same deviation is considered for the simulation results. Specimens 1 to 4 were not tightened whilst specimen 5 to 7 were tightened with a torque of 3.5-4Nm.

![Test results for the EURO-screw pull-out test.](image)

*Figure 19 Test results for the EURO-screw pull-out test.*

The curves in figure 19 are shifted to the right the make the results more clear in the graph, otherwise in reality they all start at zero on the x-axis.
Single element simulations

Finite element analysis of a non-linear material as particleboard when approaching failure can be computationally expensive. Instead of wasting a huge amount of time analysing a fully meshed geometric model, simulation engineers use a single element analysis first for validation of the material model. After the single element has been validated, the same element type can then be employed in the full analyses.

4.1 Method

Particleboard is considered to be a heterogeneous material with three distinct layers, therefore only one layer will be analysed and validated in the following single element simulations. A single hexahedral element will be subjected to two load cases, a tensile test and a simple shear test.

In the tensile test, the simulation models are subjected to two different loads, one aligned to the material coordinate system and the second one at an angle of 45 degrees, see Figure 20. The global coordinate system is denoted as x, y and z while the material coordinate system is denoted as x’, y’ and z’, also see Figure 20.

The particleboard simulation model previously developed by Hagman [3], is unable to accurately predict forces, stresses and strains at failure within the isotropic plane. The isotropic plane in particleboard is defined as the x-y plane unless otherwise stated.
Two criteria will be used for verification, the first being that the simulation models need to accurately predict the stress-strain relationship for the tensile and simple shear load cases. To be considered accurate, a deviation of 10% compared to experimental results is allowed. The experimental results from Svensson’s thesis [13] are used for the verification.

The second criterion checks the simulation model’s ability to accurately predict, for a tensile test, the stress and strain at failure for any given loading angle within the isotropic plane thus validating transversely isotropic material behaviour. If the simulation model satisfies both criteria, then it will be evaluated for the full analyses.

All simulations are run explicitly with the simulation models set not to fail due to compression because Svensson [13] concluded particleboard has a high enough compressive strength that failure due to this load case could be neglected.

The material properties in Section 3.8 are used, and not modified, throughout all finite element analyses.

4.2 Boundary conditions
4.2.1 Tensile test analysis

The tensile finite element analysis (FEA) is conducted for two cases. In the first case, the material coordinate system is aligned to the global coordinate system, see Figure 20a. In the second case, the material coordinate system is at an
angle of 45 degrees to the global coordinate system within the isotropic plane, see Figure 20b.

Symmetry boundary conditions are applied on the three orthogonal faces and then a non-zero displacement is imposed on one of the free faces in the isotropic plane. A prescribed displacement of 1 mm/min is used.

4.2.2 Shear test analysis

The shearing analysis is carried out for both orthogonal planes, in plane and out of plane. Boundary conditions used can be seen in Figure 21. In the loading direction, a prescribed displacement of 1 mm/min and 0.5 mm/min is employed for the in and out of plane simulations respectively.

![Figure 21 Boundary conditions used in shear simulations.](image)

4.3 Results

In this section, the accuracy of the single element simulation models is presented. It is based on the comparison of the stress-strain relationship of particleboard at failure from experimental tests presented in Section 3 and the single element simulation results. The exact stress and strain values from single element simulation results are not presented, instead, the percentage accuracy of the simulation models is shown.

Since all three simulation models displayed transversely isotopic behaviour thus fulfilling the second selection criteria, the results of the first selection criteria are presented in Table 3.
4.3.1 Tensile and shear test accuracy of the simulation models

In Table 3, the accuracy of the simulation models can be seen.

Table 3 Accuracy of simulation models in tensile and shear tests.

<table>
<thead>
<tr>
<th>Case</th>
<th>Simulation model percentage accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 1</td>
</tr>
<tr>
<td>Tensile test in plane</td>
<td>97</td>
</tr>
<tr>
<td>Tensile test out of plane</td>
<td>99</td>
</tr>
<tr>
<td>Shear test in plane</td>
<td>98</td>
</tr>
<tr>
<td>Shear test out of plane</td>
<td>99</td>
</tr>
</tbody>
</table>

For all cases presented in Table 3, the simulation models are at least 90% accurate thus fulfilling the first selection criteria.

The particleboard simulation model created by Hagman [3] was analysed for the tensile tests and it did not show transversely isotropic behaviour. It accurately predicting stresses and strains with the load and material coordinate system aligned but giving more than double the failure values when the material coordinate system is at an angle to the load coordinate system in the isotropic plane. It also over-predicts the out of plane stress-strain values by about 8 times.
After the single element simulations, a better understanding of the simulation models’ behaviour was obtained and the full particleboard model was then considered. The experimental test results of an in plane tensile test, a bending test and an out of plane shear test presented in Section 3, are used to validate the simulation models. The simulation models were evaluated on their ability to accurately predict the failure force for the three mentioned load cases. An accuracy deviation of 15% was accepted. During a pull-out test it can be assumed that in the area in the vicinity of the screw, the board simultaneously experiences the mentioned load cases hence the developed simulation models were validated against the experimental test results.

A mesh type and convergence study were carried out first to ensure that neither mesh type nor element size significantly influenced the accuracy of the results. Simulation model 1 failed to converge for the full model simulations. This is found to be because the longitudinal properties have to be larger than the radial and tangential properties [27], which is not the case for particleboard material parameters used in this thesis, see Table 1. Thus, only the current simulation model developed by Hagman [3] along with simulation model 2 and 3 were evaluated in this section.

**Mesh type investigation**
Using an explicit solver and a comparison between first order hexahedral, first order tetrahedral and second order tetrahedral elements were carried out. Since explicit methods are only conditionally stable [28], mass scaling was employed.
Mass scaling was used to speed up the simulations and was observed not to affect the accuracy of the results.

A literature study was carried out where first-order hexahedral and first- and second-order tetrahedral elements were evaluated in both linear static and a non-linear elastoplastic bending case [29]. The results indicate that first-order tetrahedral elements are not able to accurately predict neither tip displacements nor stresses [29].

First order hexahedral and second order tetrahedral elements were able to accurately predict both stresses and tip displacements [29].

The authors considered the tensile test for the mesh type comparison for which all considered element types were able to predict the stresses and strain with an accuracy of more than 99% for all three FE simulation models.

**Mesh convergence investigation**

It is important to show that the chosen element size gives sufficiently accurate results, therefore a mesh convergence test was performed. Four different first order hexahedral element sizes are evaluated; 0.5 mm, 1 mm, 3 mm and 5 mm.

![Mesh convergence test](image)

*Figure 22 Result from a mesh convergence test with first order hexahedral element sizes: 0.5 mm, 1 mm, 3 mm and 5 mm.*

Since the ultimate tensile stress was 4.9 MPa for the experimental test, the results from Figure 22 show that 0.5 mm and 1 mm elements are 100% accurate and from there the accuracy decreased as the element size increased.

An optimal element size range of 1 – 2 mm was then considered to be accurate for the other quasi-static simulations i.e. the bending and shearing simulations. Results from a dynamic load case, the pull-out case, can be seen in Section 6.3.1.
5.1 Tensile test simulation

The in plane tensile test presented in Section 3.3 was simulated utilising the model presented in Figure 23.

The failure is expected to happen in the middle of the dumbbell where the cross-sectional area is the smallest. Thereby the model can be simplified by only considering the smallest area of the specimen and also by applying symmetry conditions, a quarter of the test specimen is considered. Only three layers instead of five are considered, the three different layers with different densities through the thickness are displayed in Figure 23 in 3 different colours i.e. green for the outer layer, yellow for the 2\textsuperscript{nd} layer and brown for the 3\textsuperscript{rd} layer.

Figure 23 Symmetry model with first order hexahedral elements used in plane tensile simulations.

5.2 Shear test simulation

The out of plane shear test presented in Section 3.6 was simulated utilising the model presented in Figure 24. In the experimental tests, two specimens were tested simultaneously but only one test specimen was considered after applying symmetry conditions.

The same size of the specimen, as well as the prescribed motion used during experimental testing, are used. Equal boundary conditions as used in single element simulations are implemented, see Figure 21.
5.3 Bending test simulation

Figure 25 shows a model of a quarter of the dumbbell test piece used in the bending test presented in Section 3.7. Only a quarter of the test specimen is considered after symmetry conditions are applied.

The supports used in the experimental tests are not modelled. Instead, a row of nodes is locked where the support would have been in contact with the specimen. The nodes are locked in such a way that the only movement in the bending direction for the specimen are allowed.

The punch used in experimental tests is not modelled. Instead, a row of nodes is given a prescribed displacement where the punch would have been in contact with the specimen. This can be seen in Figure 26.
5.4 Results

The results presented in this section show the accuracy of the three simulation models being evaluated. The accuracy was based on a comparison between the simulated force at failure and that from the experimental tests in Section 3, for the load cases mentioned in Table 4.

<table>
<thead>
<tr>
<th>Case</th>
<th>Simulation model percentage accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 2</td>
</tr>
<tr>
<td>Tensile test</td>
<td>99</td>
</tr>
<tr>
<td>Shear test</td>
<td>86</td>
</tr>
<tr>
<td>Bending test</td>
<td>100</td>
</tr>
</tbody>
</table>

5.5 Discussion

Here the results from Table 4 are discussed.

**Tensile test**
Simulation models 2 and 3 are accurate for the tensile test simulation with results almost identical to the experimental data at 99% accuracy. Simulation model 4 is 92% accurate which is also acceptable.

**Shear test**
Simulation models 2 and 3 are within the acceptable accuracy range as shown in Table 4. However, simulation model 4 over-predicted the failure force by more than three times and this was attributed to the material parameters used in the simulation model. Simulation model 4 does not accurately predict shear forces.
**Bending test**
Simulation model 2 matched with 100% of the bending force. This is because there is no shear failure through the thickness of the material under bending loads instead the elements are simultaneously being compressed and extended but can only fail due to tension. This accuracy also coincides with that of a pure tensile analysis for this model.

Simulation model 3 is 86% which is acceptable. However, it under predicts the failure force due to premature failure of the elements at the edge where the load is placed, see Figure 26.
Screw pull-out from particleboard

In this section, the three particleboard simulation models are evaluated for the pull-out load case. The simulation results are compared to the experimental results presented in Section 3.9.

As previously mentioned, only the Euro screw is modelled for the simulations and a standard deviation of 50N is allowed due to the difference in the torque used when tensioning the screws into the board, see Table 2. A drawing of the screw can be seen in Figure 27.

![Figure 27 Drawing of the screw used for the FEA validation test.](image-url)
6.1 Mesh type and convergence investigation

First-order hexahedral elements were selected over first and second order tetrahedral elements as they were more stable and less computationally expensive. A mesh convergence study was performed to see the mesh dependency in a more dynamic case than the static in-plane tensile case. Three different mesh sizes are considered; the coarsest mesh has an element size of 0.5 mm closest to the screw, the middle mesh size has an element size of 0.3 mm and the densest mesh has an element size of 0.15 mm closest to the screw. First order hexahedral elements are considered in the simulations.

6.2 Boundary conditions

Symmetry conditions are applied and only a quarter of the pull-out test setup is considered. The geometric test piece model of the particleboard had dimensions of 80x80mm and an 18mm thickness. The screw model is simplified by having the thread going around the screw, instead of, as in Figure 27, having the threads going in a spiral. In Figure 27 the thread is doing three laps around the centre, the same number of laps can be seen on the FEA screw model in Figure 28.

![Simplified threads of EURO screw.](image)

As can be seen in Figure 29, a crater is formed around the hole after the screw is pulled out. This leads to the assumption that the damage is only local around the screw. Thus, to save computational time, damage is only applied to the elements closest to the screw, this can be seen in Figure 30. The area closest to the screw, which has the colours red, blue and yellow have damage applied. In the rest of the area of the particleboard, only elasticity is applied meaning the elements cannot be eroded. Two different diameters of the failure area are tested to see how the size of the failure area affects the results, 18 mm and 40 mm.
Figure 29 Test pieces from experimental tests showing a crater around the hole after the screw is pulled out.

Figure 30 Finite element model of the particleboard and screw used in the pull-out test.

The particleboard is modelled around the screw in such way that it follows the threads of the screw, a surface to surface contact is applied between the screw and particleboard. When the screw starts to be pulled out, the surface to surface contact makes the elements closest to the thread follow the motion of the screw until they fail.

In the experimental tests, the screw was not tightened all the way down, but for the simulations, the screw was tightened all the way down, i.e. the top surface of the particleboard is level with the top of the screw head.

To replicate the clamps used in the experimental test, one of the surfaces on the side of the particleboard is fixed.
6.3 Pullout results

The pull-out force from the experimental tests was 370N which is a mean value, see Figure 19.

6.3.1 Mesh convergence results

The results show a mesh dependency as the results changed with different mesh size, see Figure 31. The failure developed in two different ways in the simulations. The failure progressed as shown in Figure 32 for the two smaller meshes, the elements are not able to transfer stresses and strains to the elements next to them.

The biggest mesh had a different failure propagation. Instead of deleting only the element closest to the screw, it developed outwards towards the damage radius, see Figure 33. This suggests that the elements are able to transfer stresses and strains to the elements near them.

![Mesh convergence test pull-out](image)

*Figure 31 Results from a mesh convergence test for the pull-out case.*
6.3.2 Pull-out result

Table 5 presents the pull-out failure forces together with the calculated accuracy for the evaluated simulation models. The smallest mesh size used are 0.15 mm which is the most dense mesh.
Table 5 Results from the pull-out simulations.

<table>
<thead>
<tr>
<th>Failure area</th>
<th>Simulation model failure force [N]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model 2</td>
<td>Model 3</td>
</tr>
<tr>
<td>Ø 18 mm</td>
<td>122</td>
<td>96</td>
</tr>
<tr>
<td>Ø 40 mm</td>
<td>122</td>
<td>96</td>
</tr>
</tbody>
</table>

Simulation model percentage accuracy

<table>
<thead>
<tr>
<th>Failure area</th>
<th>percentage accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 18 mm</td>
<td>33</td>
</tr>
<tr>
<td>Ø 40 mm</td>
<td>33</td>
</tr>
</tbody>
</table>

6.4 Pull-out discussion

Mesh convergence

Only the 0.3 mm element size obtained a failure force within the standard deviation from the experimental tests. Element size 0.5 mm obtains the lowest pull-out force, 200 N below the standard deviation.

The failure propagation for the densest mesh was unexpected, as previously, only the elements closest to the screw had been eroded for all other tested meshes. But for the bigger mesh, the cracks were climbing outwards towards the damage radius. This suggests that when the elements are small enough, they are able to transfer stresses and strains from element to element to distribute the damage over a larger area, creating a more realistic failure. As only the element size was changed, it implies that the mesh has a big impact on the pull-out force and the crack propagation.

By analysing the results from the mesh convergence test and discussions with simulation engineers [30] [31], the conclusion is that different pull-out forces will be obtained depending on how the model is modelled and what mesh size is used.

Simulation model 2

Simulation model 2 predicts the same pull-out force 96N for both the Ø18 mm and Ø40 mm damage areas which is an under-prediction of the pull-out forces by 75%, which is not acceptable. Looking at the deformed state, it was noted that just a few elements were deleted so there is no even stress distribution amongst the neighbouring elements. There is no failure propagation or visible crater after the screw pull-out simulation. In this case, the inaccuracy may also have been caused by the low out of plane shear strength parameters applied.
**Simulation model 3**
Simulation model 3 predicts the same pull-out force for both the ø18 mm and ø40 mm damage area pull-out models of 122N which is one third of the pull-out forces of the average experimental results, which is not acceptable. This simulation model is also load rate dependant. Its inaccuracy of the simulation model may have been caused by the low out of plane shear strength deduced from the inconsistent experimental test results from Svensson’s tests [13].

**Simulation model 4**
For the pull-out simulations, simulation model 4 gives results that match the experimental pull-out force very well. It was 99% accurate when the damage area is ø18 mm. However, when the damage area is increased from ø18mm to ø40mm the simulated pull-out force is 187N. This shows a dependency of the predicted pull-out force on the size of the damage area, which is not acceptable. This behaviour may be attributed to the conflicting material properties of the material model where it has a shear plane failure strain of 100%, this value is not from any experimental data, see Table 1. The material model is not load rate dependant as it gives identical results for various screw pull-out velocities.
Conclusion and Future work

7.1 Conclusion

The objective of this thesis work was to develop a simulation model in LS-DYNA that can adequately predict pull-out forces for screws in particleboard. No experimental testing was carried out and the material properties used for particleboard were deduced from previous experiments carried out at IKEA [13].

A literature study of wood, particleboard and screw pull-out tests was carried out. After the study it was concluded that particleboard exhibits transverse isotropic behaviour, then another literature study was conducted of available material models in LS-DYNA that can describe the transversely isotropic material behaviour.

The single hexagonal element which was first considered validated all 3 simulation models developed by the authors by comparing simulation results to that from a tensile and shear test, both in and out of plane, before moving on to the full model analyses.

For the full model tests validation was made against a tensile, out of place shear and bending. Simulation model 1 was eliminated due to instability issues which could not be resolved as confirmed by the FE-tool developer LS-DYNA. Simulation model 2 and 3 were both sufficiently accurate for these simulations but simulation model 4 over predicted the shear force at failure significantly, this simulation model should not be employed for a pure shear simulation.

Then, finally, for the pull-out test simulations, simulation models 2 and 3 under-predicted the failure force by more than 60% which is not acceptable. It was observed that the elements in the vicinity of the screw were failing prematurely.
where shear stresses were dominant. This led the authors to believe the shear properties implemented for the simulation models may have been understated. The experimental out of plane shear test results presented in Appendix 8.3 range from 500N to 1200N for 8 test specimens, see Figure 34. The inconsistency of these results suggest that the test method can be improved. Simulation model 4 particleboard predicted pull-out forces by the accuracy of 99% for a small damage area but as the damage area is increased, the simulation model’s accuracy decreased.

7.2 Future work

The shear properties are currently the ones that showed the largest deviations. The test pieces employed in the testing may have been too small according to Svensson [13] hence, size dependence should be factored in for experimental testing for this load case.
References


[31] J. Lindvall, Interviewee, FEA simulation engineer at IOS. [Interview]. 31 August 2018.


8.1 Mat 143 Wood damage and failure

This material model is based on the general constitutive relationship for an orthotropic material and was used to develop simulation model 1. Failure is described by a modified version of the Hashin criteria where the criterion is developed to predict the mode of failure.

Material model 1 offers usage of several ways to describe the material behaviour, it can be described by softening, hardening, viscoelasticity and Hashin composite damage failure criteria [4]. Only softening and failure criteria are used to describe the particleboard behaviour.

Softening is described by a degradation model and an energy-based damage model. The parallel and perpendicular damage parameters are recommended by [23] to be set to 0.9999 and 0.99 respectively, this activates failure in all orthotropic directions. The energy-based damage model is described by fracture energies together with a fitting parameter. The fracture energies are found from the work by [19]. The fitting parameter was found by comparing FEA results with experimental tests. The fitting parameter was determined when a satisfying comparison was found between the FEA results and experimental test results.

To describe the failure criteria, one needs to define material strength parameters. These parameters were found from experimental tests.

8.2 Mat_Add_Generalised_Damage (MAGD)

GISSMO and Damage implementation in MAGD

In MAGD, GISSMO was generalised in the sense that the user now has control over the damage driving quantities, i.e. the history variables [32]. In the case of
the author’s material model, mat_122 plus MAGD, this is done by splitting the effective plastic strain into 2 components, in plane and out of plane damage. The effective plastic strain grows whenever the material is actively yielding [33], that is when the stress is on Hill’s yield surface. To achieve in plane and out of plane damage two GISSMO models which must be identical are used.

Optionally, using MAGD with IFLAG 1=1 the components of the plastic strain rate tensor can be used as the incremental damage drivers [33]. The damage and failure criteria can then be defined using functions written in C programming language [34]. These functions call out the selected components of the plastic strain rate tensor which are defined in the material coordinate system [32]. This will then be a user defined history variable that has the dimension of a strain as the rate is computed internally in MAGD [4]. The functions that are presented below are not based on any failure criteria but rather being used to make sure that the compressive strength was 10 times that of the tensile strength.

These functions for the history variables are also used to define in plane and out of plane damage:

In plane: \( f_{\text{his1}}(exx,eyy,ezz,exy,eyz,ezx) = \max(((exx+eyy+exy)), -0.1*((exx+eyy+exy)) \)

Out of plane: \( f_{\text{his2}}(exx,eyy,ezz,exy,eyz,ezx) = \max(((ezz+ezx+eyz)), -0.1*((ezz+ezx+eyz)) \)

Then with IFLAG 2=1, the damage increment is defined to be driven by the plastic strain rate tensor components using the material coordinate system. With IFLAG 3= 0, element erosion occurs when the damage parameters computed d1, for in plane damage and d2, for out of plane damage, reach unity [4].

The relation between the nominal stresses \( \sigma_{ij} \), the effective stresses \( \tilde{\sigma}_{ij} \) and the damage tensor \( D_{ij} \) is defined by the following equation [4]:

\[
\sigma_{ij} = D_{ij}\tilde{\sigma}_{ij}
\]

The coefficients in the damage tensor \( D_{ij} \), are defined as a function of the damage parameters \( d_1 \) and \( d_2 \). For orthotropic damage in the principle system for in plane and out of plane damage driven by plastic strain the relationship in Equation 30 can be expressed as [4]:

\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{12} \\
\sigma_{23} \\
\sigma_{31}
\end{bmatrix} =
\begin{bmatrix}
1 - d_1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 - d_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 - d_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 - d_2 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 - d_1 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 - d_1
\end{bmatrix}
\begin{bmatrix}
\tilde{\sigma}_{11} \\
\tilde{\sigma}_{22} \\
\tilde{\sigma}_{33} \\
\tilde{\sigma}_{12} \\
\tilde{\sigma}_{23} \\
\tilde{\sigma}_{31}
\end{bmatrix}
\]

(15)
This means that in the material model, function 1 \(f_1(d_1,d_2,d_3)\) is defined for \(D_{11}, D_{22}, \) and \(D_{66}\), and function 2 \(f_2(d_1,d_2,d_3)\) for \(D_{33}, D_{44}, \) and \(D_{55}\). The functions are written as follows [32]:

\[
\begin{align*}
f_1(d_1,d_2,d_3) &= 1 - d_1 \\ f_2(d_1,d_2,d_3) &= 1 - d_2
\end{align*}
\]

Also, here it should be noted that since particleboard was made linearly elastic, the damage aspect of this material model was not utilised. To ensure that there would be no hardening for material model 3 after it reaches the yield stress, the damage threshold value was set to 0.0001.

The various ways in which MAGD can be used to date are discussed extensively in the report from the 14th German LS DYNA forum [32]. The GISSMO damage model is explained in more detail in the remarks section of MAT_ADD_EROSION of the LS DYNA manual [7], as well as in the material modelling section of Svensson’s thesis [13].

8.3 Out of plane shear force at failure for 10 test specimen.

![Figure 34 10 shear tests force time curves with deformation rate at 1 mm/min.](image)