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DEVELOPMENT OF THE NOTCHED SHEAR TEST

Mikael Nygårds[1,2], Christer Fellers[2] and Sören Östlund[1]

[1]KTH, Department of Solid Mechanics, SE-100 44 Stockholm, Sweden
[2]Innventia, Box 5604, SE-114 86, Stockolm, Sweden

ABSTRACT

The notched shear test (NST) will be proposed to measure shear strength of paperboard by utilizing standard in-plane tensile testing equipment. The test is a further development of the double notch shear test specimen; where plastic lamination has been utilized. With the new test setup it becomes possible to measure shear strength profile in the thickness direction of paperboard. As a spin-off of the NST also the strip shear test (SST) was suggested. The SST test can be used as a quick measure of shear strength. It is shown that the SST measurement correlates well with the traditional rigid shear test (RST). In order to verify that the NST specimen failed due to shear stresses, finite element simulations were performed. The simulations showed that the shear zone had a uniform shear stress field at the time of failure. Moreover, with the finite element simulations it was also possible to predict the force-displacement curve.

1. INTRODUCTION

For paper materials the out-of-plane direction is often referred to as the Z-direction (ZD), while the paper machine direction is referred to as MD, and the cross-machine direction is referred to as CD. The out-of-plane material properties of paperboard play an important role for the mechanical behaviour of paper materials. In converting operations such as creasing and subsequent folding of paperboard the governing mechanisms for good converting behaviour are deformation and damage in the out-of-plane direction. In the creasing operation the dominating deformation mechanisms is shear deformation of the fibres and joints [1]. In printing applications, paper materials exhibit a risk of ZD failure due to ink tack. In off-set printing the paper has a tendency to stick to the printing cylinder when exiting the printing nip, while the web tension still acts in the MD direction. Hence, the paper becomes loaded in the ZD direction, which increases the risk of delamination. In many other operations, such as embossing, package forming, etc. knowledge about the out-of-plane properties are important to increase the paper performance. For paperboard multiply structures are manufactured commercially. The multiply structure enables maintained or improved bending stiffness with less fibres, but it also offers the possibility to engineer profiles of properties in the thickness direction for different applications. With the possibility to engineer papers in the thickness direction the need to characterize such properties has also increased. Characterization becomes an important tool to verify that correct processing strategies are implemented.

From general mechanical point of view the out-of-plane behaviour can be divided into tension/compression and shear. In traditional shear testing of paper materials samples are glued to some kind of rigid supports, as schematically illustrated in Figure 1. In the literature this has been done in by for example the Arcan device [2, 3] the Rigid block method [4–6] and the Iosipescu method [7]. The fact that paper samples need to be glued to a rigid substrate leads to problem when testing thin papers, normally only paper materials with basis weights above approximately 60 g/m^2 can be tested in the out-of-plane direction [8].

In the composite literature double notch tests are common to evaluate shear properties. An ASTM standard exists, which utilize the double notch

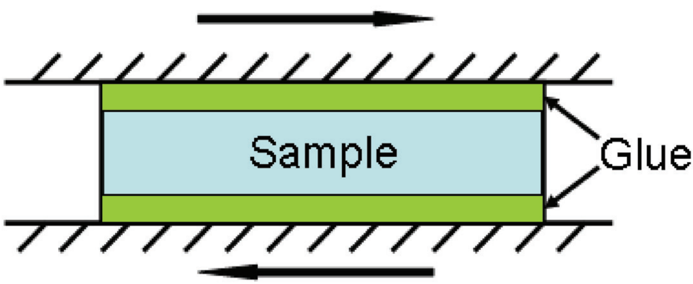


Figure 1. Schematic of rigid support shear methods; samples are glued.

compression test [9]. For this test finite element simulations have been performed in order to ensure that a uniform shear strain field is measured, c.f. [10–11]. Moreover, experiments and simulations have been performed in order to suggest improvements of the standard, c.f. [11].

Recently Nygårds *et al.* [6] proposed the double notch shear (DNS) test for shear testing of paperboard. This test has the advantage that it does not rely on gluing. Instead, notches are fabricated, and a predominantly shear failure occurs between the notches upon tensile loading of the specimen. Due to the notches the DNS test has one major disadvantage; tensile failure can be induced by the notches when the shear zone is too large. This limits the types of paper that can be tested. Therefore, in this work a modified test specimen is proposed, the notched shear test (NST). The test specimen will be improved by the utilization of plastic lamination, which will greatly improve the applicability of the test method. With the laminated test specimen tensile failure can be avoided. Moreover, the effect of notch depth will be investigated. As an extreme case the strip shear test (SST), *i.e.* when the notches go through the whole board will be investigated. This test resembles the rigid support shear methods, which therefore will be used as a comparative verification of the two former test specimens. When the experimental data has been presented, numerical finite element simulations will be used to show the stress distributions along the shear zone in the NST specimen. In order to perform realistic simulations of the stresses in the specimen the paperboard elastic-plastic properties need to be characterised, and fitted to an adequate material model, which also will be presented.

2. EXPERIMENTAL SETUP

Three shear tests will be presented. The first two tests originate from the DNS specimen [6], which has been improved by plastic lamination. The third test is the RST that was used as a comparison and verification of the other two tests. To test the different methods a commercial multiply paperboard was used. The paperboard was recently characterized by Nygårds [13] and its behavior is therefore well known.

2.1 Characterization of elastic-plastic properties

Four experimental techniques were used to characterize the elastic-plastic material properties of the paperboard. To evaluate the properties as functions of paperboard thickness the different plies were separated by grinding, and the bottom, middle and top plies were tested separately, as described by

Nygårds [13]. Each ply was characterized with respect to in-plane tension, cyclic ZD tension, cyclic ZD compression and out-of-plane shear. These tests were chosen since they are easily interpreted in term of stresses and strains, and give a good set of elastic-plastic material properties that are needed to describe the mechanical behaviour of the material.

For the ZD tension and ZD compression tests several loading/unloading cycles were used in order to evaluate how the elastic modulus evolves as a function of deformation.

2.2 Notched shear test (NST)

The notched shear test (NST) specimen was manufactured by using grinding and plastic lamination. The manufacturing of the specimen started with an A4 sized paperboard with thickness *h*. In Figure 2 the manufacturing and testing of one specimen is illustrated. In reality several specimens were manufactured from each sheet. Hence, the four stages of the manufacturing and testing procedure were:

1. The A4 sheet was ground by a 15 mm wide porous grinding wheel. Two grooves were ground on each sheet, one from each side, and 15 mm apart. With reference to the top surface the grooves were ground down a distance *d*. Hence, the groove from the bottom side were ground a depth *h-d*, such that the grooves met at the same thickness position.
2. Two pre-cut plastic sheets (Perfex gloss 250 (175/75), GMP Co. LTD.) were then positioned such that the cuts were aligned along the inner groove edges on both sides. To simplify the positioning of the plastic sheets double sided tape was used to fasten the plastic sheets locally. Thereafter the sandwich consisting of plastic sheet/paperboard/plastic sheet was put into an office laminator (Lamiart 320I).
3. The laminated sheet was cut into 15 mm wide strips. From each A4 sheet at least 10 samples were made for each thickness position.
4. All samples were tested separately in a tensile testing machine (Lorentzen & Wettre Alwetron TH1), following the standard for tensile testing [14]. At peak load failure occurred between the two grooves.

It was observed that the plastic foil used in the experiments was sufficiently strong to prevent in-plane failure, caused by the notches, during testing. This plastic strength reinforcement has two aspects of major interest. First of all, it was possible to notch the paperboard not just to the middle but also to other positions in the thickness direction in order to measure the out-of-plane shear strength in different plies or along the interfaces. In principle any notch

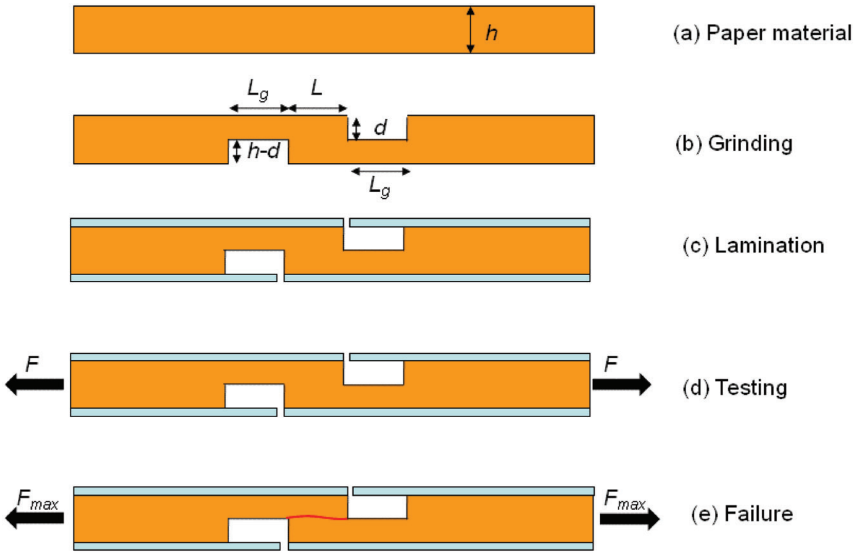


Figure 2. The manufacturing and testing procedure for the notched shear test (NST). (a) A paperboard with thickness h was the starting point, (b) two grooves were ground, (c) the paperboard was laminated with plastic, (d) the sample was tested in a tensile testing machine, (e) failure occurred between the two grooves.

depth $0 < d < h$ could be tested. In Figure 2 the special case $d = h/2$ is shown. In this work, shear strength profiles in the thickness direction will be measured. The second improvement due to the plastic reinforcement was that it enabled us to test longer shear zones. In fact with the tested paperboard and the proposed geometrical parameters all specimens failed in shear.

2.3 Strip shear test (SST)

As a new complementary test also completely cut laminated paperboards were tested. Then the paperboard samples were laminated with notched plastic sheets, according to the previous procedure. In Figure 3 a schematic illustration of this test can be seen. Since this test will load the whole paperboard, its failure will involve the weakest position in the thickness direction. Therefore this test procedure should act as a reference and verification of the NST procedure.

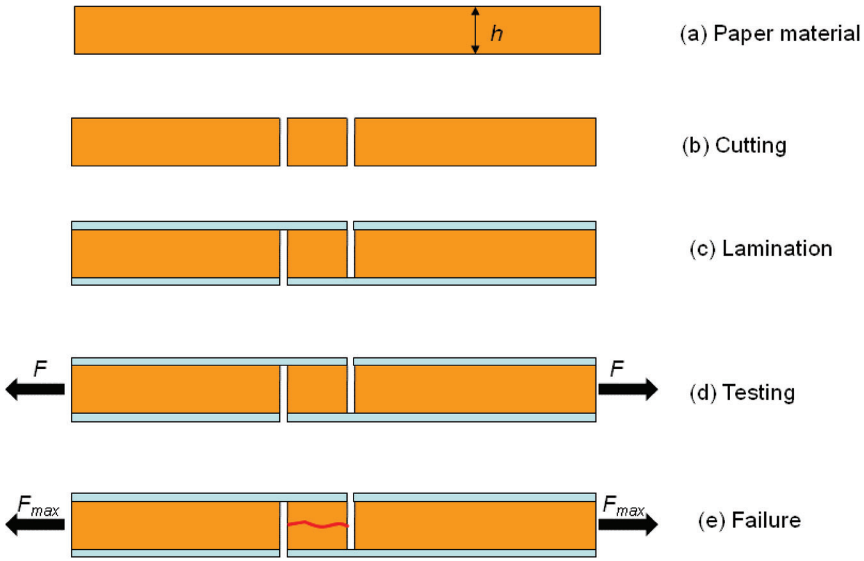


Figure 3. The manufacturing and testing procedure for the strip shear test (SST). (a) A paperboard with thickness *h* was the starting point, (b) two cuts were made, (c) the paperboard was laminated with plastic, (d) the sample was tested in a tensile testing machine, (e) failure occurred somewhere between the two cuts.

2.4 Rigid shear test (RST)

In the rigid block shear test the paperboard was glued to metal blocks with photo mounting tissue (Bienfang, ColorMount Dry Mounting Adhesive), c.f. Figure 4. The adhesive must be heated to 92°C in order to melt. If the adhesive does not melt the interface against the paperboard will not be strong enough. On the other hand if the adhesive was heated more than necessary it would penetrate more easily into the paperboard. Glue penetration will however not be an issue here since paperboard is tested; Girlanda and Fellers [8] have shown that papers down to 60 g/m^2 can be tested with this glue. However, to deal with these two conditions an empirical procedure was developed that heated the glue enough, but did not heat the paperboard more than necessary. The specimen preparation procedure that worked best followed:

1. The metal block was heated to 110°C.
2. After heating the metal blocks was placed in a purpose-made rig to ensure alignment during the gluing and reconditioning.

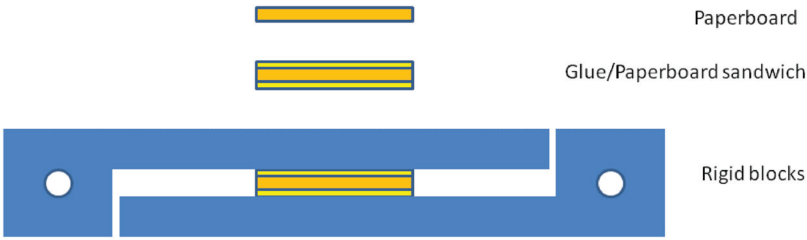


Figure 4. Schematic illustration of the manufacturing process of a rigid shear test (RST) specimen.

3. A sandwich consisting of two glue layers and one paperboard specimen was centred between the loading points on the metal blocks.
4. A compressive load was applied over the specimen to enhance adhesion.
5. The specimen was conditioned for at least 24 hours before the normal pressure was removed and the specimen was tested.

The shear specimens were tested in an MTS system with displacement control and a loading rate of 0.0025 mm/s. In RST the load was applied in tension by a system of links that minimizes the risk of misalignment.

2.5 Shear stress

For all tests the force, F, was measured and the maximum shear strength was calculated as the maximum force divided by the area of the shear zone. For NST and SST specimens the area of the shear zone was the distance between the notches multiplied by the width, i.e. 15 mm × 15 mm. For the RST specimens had width 20 mm and length 20 mm.

3. EXPERIMENTAL RESULTS

The SST and RST both provided a numerical value of the shear strength. The shear strength for paperboard previously characterized by Nygårds [13] was used to measured shear strength both in MD and CD and the average results are tabulated in Figure 5.

In Figure 5, box plots were used to illustrate the results. The box gives the 75% confidence interval for a normal distribution. The line in the box is the median value, and the star is the mean value. The dashed bars represent the 95% confidence interval. The plus signs outside the boxes represent

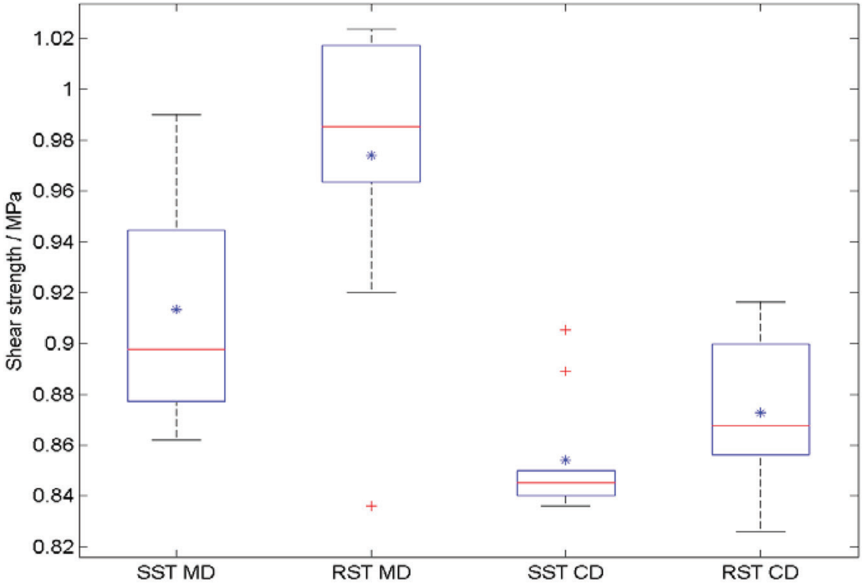
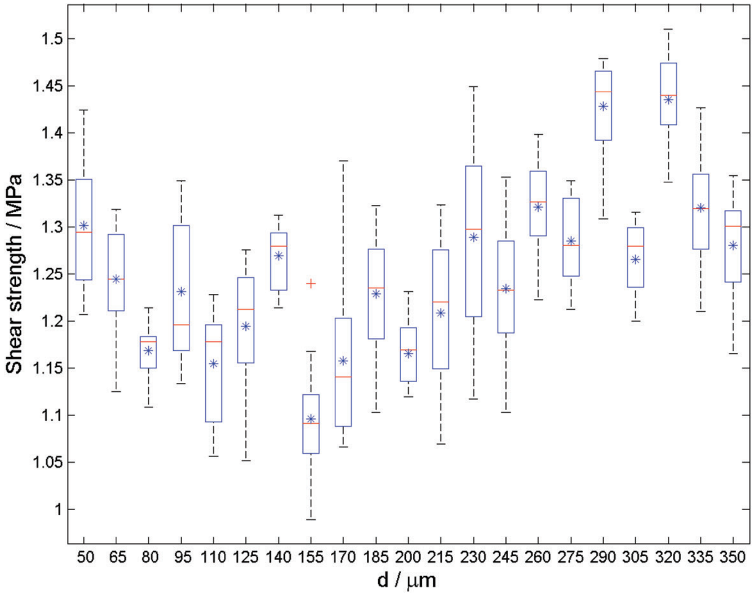


Figure 5. Measured shear strengths in MD and CD with SST and RST.

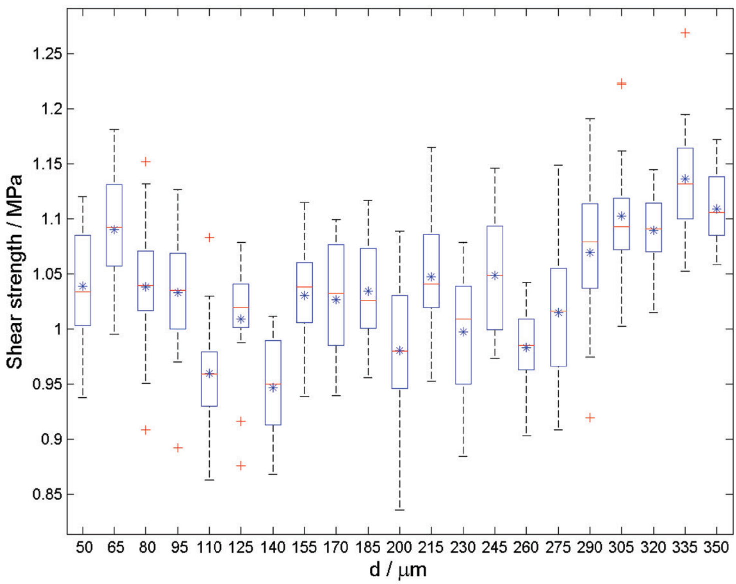
measurements that were not considered in the normal distribution. It was observed that both tests gave a higher value in MD than in CD. The similarity between the results for the two test methods is noteworthy. For both RST and SST ten samples were tested in each direction. It was noted that the scatter within each measurement series was about the same as the scatter between the methods.

NST measures the shear strength locally in the thickness direction, while SST and RST test a whole volume. Therefore, the NST was used to measure shear strength profiles in the ZD direction. Samples with different notch depths, d, but all with shear zone length, $L = 15$ mm were tested. The shear strength was measured in both MD and CD, for notch depths between $d = 50$ µm and $d = 350$ µm at intervals of 15 µm, as seen in Figure 6. From the shear strength profiles in Figure 6 it can be observed that the shear strengths in the MD in general were 10–20% higher than the measurements in the CD, which also was in accordance with the measurements by the SST and RST tests in Table 1.

It shall, however, be noted that the shear strengths measured by the NST were higher than the SST and RST measurements, therefore the effect of notch depth, d, was investigated to understand this observation. The results



(a)



(b)

Figure 6. Measured shear strength profiles in (a) MD and (b) CD.

for the NST specimen was sensitive to the accuracy of the notch positioning, since the two notches are assumed to end at the same position in the ZD, but from opposite sides of the specimen. To study the influence of the notch positioning, a special case with two notches of the same depth, $d = d_1 = d_2$, measured from the different surfaces, as illustrated in Figure 7a, were tested.

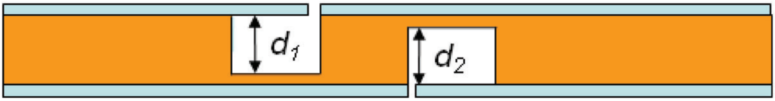
In Figure 7, the NST specimen corresponds to $d = 200$ µm, while the other test were used to investigate the sensitivity of the notch positioning. When $d = 140$ µm and 170 µm the shear strengths were higher than when $d = 200$ µm. In these cases there were "continuous" material through the shear zone; therefore the measured maximum load naturally goes up since fibres must be torn off or be pulled out of the fibre network. When d was increased to $d = 230$ µm, it was encouraging to see that the shear strengths in both MD and CD were similar to the shear strengths for $d = 200$ µm. Hence, it was better if the notches went deeper than the intended thickness position, and thereby overlapped; compared to if the notches did reach the intended thickness direction. However, as the notch depth was increased further the shear strength dropped, and approached the SST values. With deep notches, a larger amount of the fibre networks was loaded in shear, and failure could be activated at several through-thickness positions simultaneously. It can be observed in that the shear strength in MD dropped when the notch depth exceeded $d = 330$ µm. At this position both notches ended up in the bottom and top plies, respectively.

4. NUMERICAL VERIFICATION

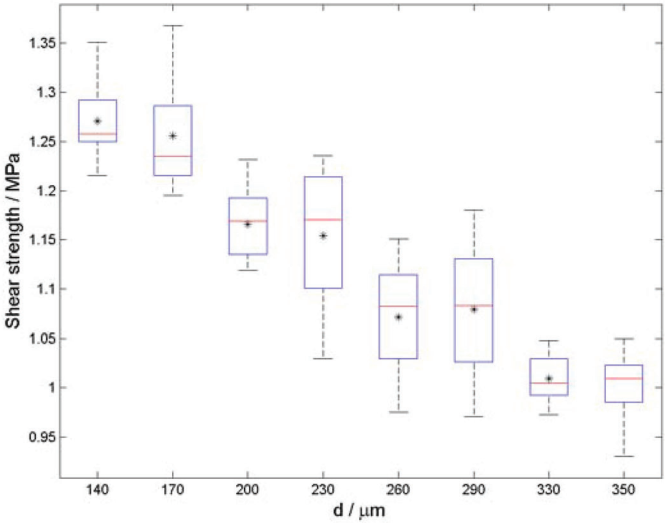
Numerical finite element simulations were used to ensure that a uniform shear stress field was generated along the anticipated shear zone. For this purpose a finite element mesh representing the NST specimen where the notches met in the middle of the paperboard, i.e. $d = 200$ µm, was generated. First only continuum elements were used, secondly also elements enabling interface failure was incorporated between the notches in the middle of the paperboard.

4.1 Geometrical model

To represent paperboard a combination of continuum and interface models was used. Each ply was represented by continuum elements, while the interface behaviour was represented by cohesive elements. This approach was proposed by Xia [15], and has previously been used by Nygårds *et al.* [1]. Due to the division into continuum and interface models the experimental



(a)



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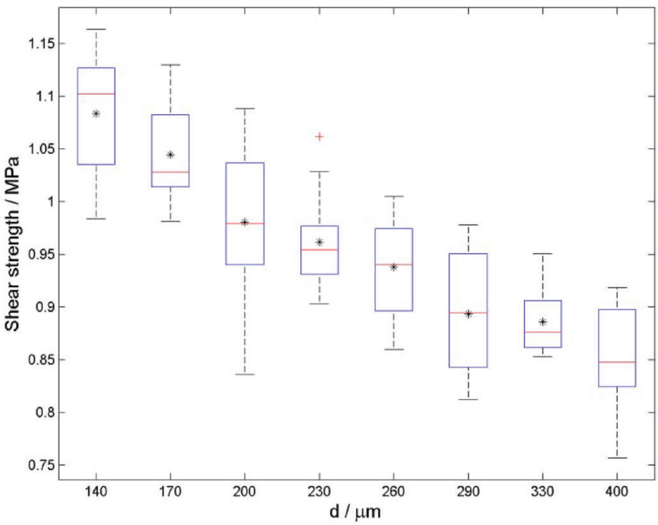

(c)

Figure 7. Investigation of notch positioning for the (a) NST for the special case $d = d_1 = d_2$ and the corresponding measured shear strengths as function of d in (b) MD and (c) CD.

characterization data also need to be divided into continuum and interface behaviour. Hence, it was assumed that the elastic-plastic behaviour was captured by the continuum elements, and the softening behaviour in ZD was captured by the cohesive interface elements. Therefore, the elastic stiffness components in the interface model were sufficiently stiffer than the corresponding continuum stiffness.

To represent the NST specimen a three dimensional mesh consisting of continuum elements was created in Abaqus [15]. The model was however only 0.1 mm deep in the CD direction, and a plane strain condition was applied in this direction. In the CD direction two layers of elements were used throughout the model. From a continuum mechanics viewpoint the model could as well have been two dimensional, but experiences showed that the two dimensional interface models in Abaqus [12] caused numerical problems with the material properties for paperboard. The mesh was finer in the areas where deformation could be expected, i.e. in the anticipated shear zone between the notches, as seen in Figure 8 for the right notch.

The elements representing the paperboard were divided into sets representing the bottom, middle and top plies. The paperboard was 0.400 mm thick, where the bottom and top plies were assumed to be 0.090 mm. Outside the paperboard a plastic layer with thickness 0.250 was applied one each side. In Figure 8 the mesh around one of the notches can be seen, where the different sets have been marked. To account for the delamination behaviour in the finite element model cohesive elements were inserted between the notches, i.e. in the middle of the paperboard, as shown in Figure 8.

4.2 Material models

The continuum behaviour of the paperboard was represented by an anisotropic elastic model, which is developed by Nygårds [17] and Nygårds *et al.* [1] based on the observations from the experimental characterization. In the continuum model it was assumed that the in-plane and out-of-plane models were uncoupled.

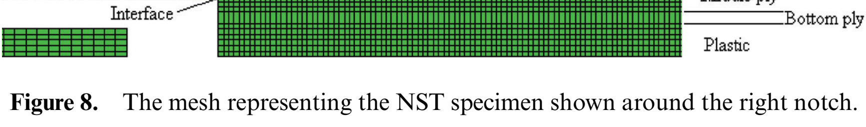

Figure 8. The mesh representing the NST specimen shown around the right notch.

4.2.1 In-plane model

In the in-plane model a concept proposed by Xia *et al.* [18] consisting of five yield planes, in MD tension, CD tension, in-plane shear, MD compression and CD compression with normal components N^I (I = 1–5) was used to construct the yield surface, $f^{\,in\text{-}plane}$, as seen in Table 2. The elastic material constants E_x, E_y *and* G_{xy} in the in-plane model were determined by least square fits to the experimental [13]. The hardening associated with each plane was controlled by yield stress components, σ_s^I, where σ_{s0}^I, A^I, B^I and C^I were material constants that were fitted to the plastic part of the in-plane tension curves in [13]. In the simulations it was assumed that hardening in compression was equivalent to hardening in tension.

4.2.2 Out-of-plane model

In the out-of-plane model the plastic behavior was divided into two parts; one yield surface for compression, $f^{\,comp}$, and one yield surface for shear, $f^{\,shear}$, as seen in Table 1. The compressive behavior was assumed to be uncoupled from the shear behavior, while a normal component, σ_{zz}, was incorporated in the yield stress in shear, τ_s. In the out-of-plane model the elastic material constants E_z, E_c, E_{xz} and G_{yz} were all determined by least square fits to the data in [13].

All material constants in Table 1 were determined from the experimental characterization by Nygårds [13]. More details on the determination of constitutive parameters can be found in [1, 13, 18].

The plastic foil used for lamination was assumed to be elastic isotropic with $E = 3800$ MPa and $\nu = 0.3$. The notches, whose geometry can be seen in Figure 2, were also represented by elements, although those have been removed in Figure 8. This approach made the model more stable, compared to if the specimen would have been meshed around the notches. The notch "material" was assumed to be elastic isotropic with $E = 0.1$ MPa and $\nu = 0.0$.

4.2.3 Cohesive properties

The interface behaviour of the paperboard was represented by an elastic-plastic cohesive behaviour that was available in Abaqus [16]. The initial thickness of the cohesive elements was zero. Therefore, the constitutive equations for this model were expressed in tractions and displacements. The elastic stiffness components in MD, CD and ZD were evaluated from the ZD tension and MD and CD shear tests, respectively. In order to make the interface stiffer than that of the continuum plies, the stiffness components were

Table 1. Continuum model used in the simulations. The in-plane and out-of-plane models were uncoupled. When the model is used for commercial paper materials the *x-y-z* system should be interpreted as a *MD-CD-ZD* system, i.e. $x = MD$, $y = CD$ and $z = ZD$.

In-plane model	Out-of-plane model
Elastic behaviour	
$\sigma_{xx} = E_x \varepsilon_x$ $\sigma_{yy} = E_y \varepsilon_y$ $\tau_{xy} = G_{xy} \gamma_{xy}$	$\sigma_{zz} = \begin{cases} E_z \varepsilon_{zz}^e & \text{if } \varepsilon_{zz}^e > 0 \\ E_c \left(1 - e^{-C_c \varepsilon_{zz}^e}\right) & \text{otherwise} \end{cases}$ $\tau_{xz} = G_{xz} \gamma_{xz}$ $\tau_{yz} = G_{yz} \gamma_{yz}$
Yield surfaces	
$f^{in-plane} = \sum_{I=1}^{5} \chi_I \left(\dfrac{\sigma : N^I}{\sigma_s^I} \right)^{2k} - 1$ $\chi_I = \begin{cases} 1 \text{ if } \sigma : N^I > 0 \\ 0 \quad \text{otherwise} \end{cases}$	$f^{comp} = -\sigma_{zz} - \sigma_s$ $f^{shear} = \sqrt{\tau_{xz}^2 + \tau_{yz}^2} - \tau_s$
Plastic hardening	
$\sigma_s^I = \sigma_{s0}^I + A^I \tanh\left(B^I \varepsilon_{eff}^p\right) + C^I \varepsilon_{eff}^p$ $\varepsilon_{eff}^p = \sqrt{\left(\varepsilon_{xx}^p\right)^2 + \left(\varepsilon_{yy}^p\right)^2 + \left(\dfrac{\gamma_{xx}^p}{2}\right)^2}$	$\sigma_s = B_p \left(e^{C_p \varepsilon_{zz}^p} - 1\right)$ $\tau_s = \tau_0 + \left(A_\tau - \sigma_{zz} B_\tau\right) \gamma^p$ $\gamma^p = \sqrt{\left(\gamma_{xz}^p\right)^2 + \left(\gamma_{xz}^p\right)^2}$

multiplied by a factor five before they were used in the model. The initiation of cohesive damage was controlled by a maximum traction criteria, as seen in Table 3, where t_{ZD}^0 is the ZD tension peak load, t_{ZD}^0 is the MD shear peak load and t_{ZD} and t_{MD} were the traction components in the model. The notation < > indicates that only positive traction components were considered. Strength degradation of all traction components was controlled by a damage parameter, D, as seen in Table 2, where α and δ_f were material constants that were fitted to the softening behaviour after the peak load in ZD tension.

4.3 Numerical results

The aim of the numerical simulations was twofold. Firstly, the finite element simulations were used to verify that the experimentally determined force displacement curves could be predicted by the numerical model. Secondly, the stress distributions between the two notches were analysed in order to gain further understanding of the failure mechanism.

Table 2. The constitutive equations used in the interface model, which were expressed in terms of tractions, t_{ZD}, t_{MD}, and t_{CD}, and displacements, δ_{ZD}, δ_{MD} and δ_{CD}

Elastic behaviour
$t_{ZD} = K_{ZD}\delta_{ZD}$ $t_{MD} = K_{MD}\delta_{MD}$ $t_{CD} = K_{CD}\delta_{CD}$
Criterion for initiation of cohesive damage
$\left(\frac{\langle t_{ZD}\rangle}{t_{ZD}^{0}}\right)^2 + \left(\frac{t_{MD}}{t_{MD}^{0}}\right)^2 + \left(\frac{t_{CD}}{t_{CD}^{0}}\right)^2 = 1$
Damage degradation
$t_{ZD} = \begin{cases} (1-D)t_{ZD}, & t_{ZD} \geq 0 \\ t_{ZD}, & \text{otherwise} \end{cases}$ $t_{MD} = (1-D)t_{MD}$ $t_{CD} = (1-D)t_{CD}$ $D = 1 - \frac{\delta_m^0}{\delta_m^{\max}}\left(1 - \frac{1 - e^{-\alpha\left(\frac{\delta_m^{\max} - \delta_m^0}{\delta_m^f - \delta_m^0}\right)}}{1 - e^{-\alpha}}\right)$

In Figure 9 the experimental force displacement curves from ten specimens with $d = 200$ µm are shown together with the result from two numerical simulations. In the first simulation only continuum elements were used. In the second simulation cohesive elements were inserted in the plane between the notch tips. The cohesive elements will in this case account for delamination damage in the paperboard model. It is observed in Figure 9 that the continuum model captured the experimental force-displacement curves well, but since no delamination behaviour were present in the model, the failure could not be predicted. However, when the cohesive elements had been inserted the same initial behaviour was achieved. But when the model was loaded to an elongation of about 0.5 mm, the cohesive elements started to open up, and the model became slightly more compliant. When the model was loaded to about 0.64 mm it failed, and a peak load was reached. Thereafter the force dropped in a manner similar to the experimental curves.

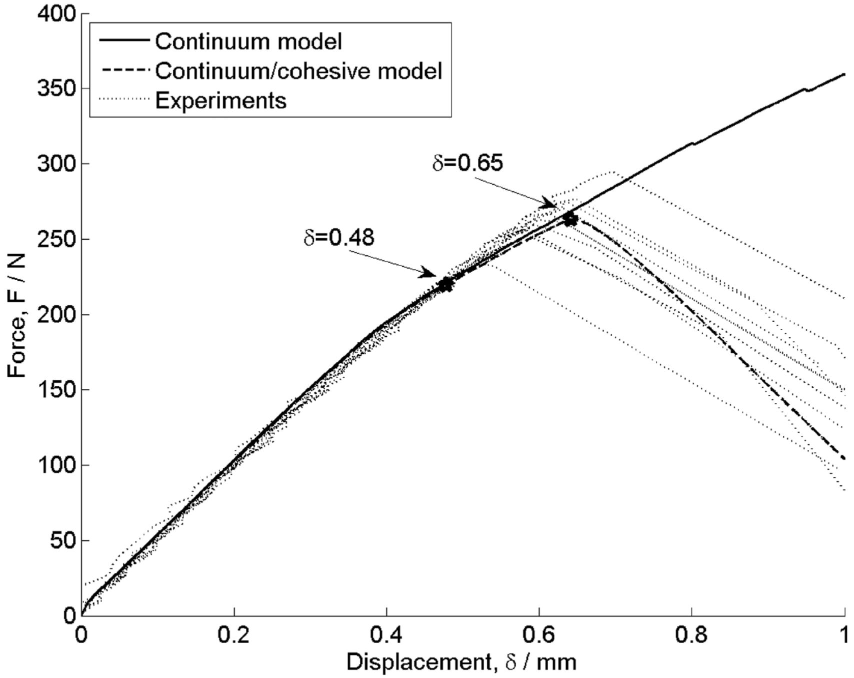

Figure 9. Force-displacement curves from the experimental and numerical tests of the NST specimen.

In Figure 10 the normalized shear traction component, t_{MD}/t^0_{MD}, and the normalized normal traction component t_{ZD}/t^0_{ZD}, in the cohesive elements have been plotted along the shear zone. The traction components have dimension pressure in the model and shall be interpreted as stress components. The stress distribution in Figure 14 have been plotted at two different displacements, $\delta = 0.48$ mm and $\delta = 0.64$ mm, as indicated in Figure 9. At $\delta = 0.48$ mm the deviation of the continuum/cohesive model from the continuum model was initiated. In Figure 10a it is observed that at the left notch deformation in the cohesive model had been initiated by the normal stress component, since $t_{ZD}/t^0_{ZD} = 1$. However, this was only observed in the element closest to the notch on the left side, but not on the right side. Instead the shear stress component, t_{MD}/t^0_{MD}, dominate along the rest of the shear zone. In Figure 10a it was also observed that only the elements closest to the notches started to open up when $\delta = 0.48$, but this without specimen failure. Hence, the flexibility of the continuum/cohesive model cancelled any existing stress

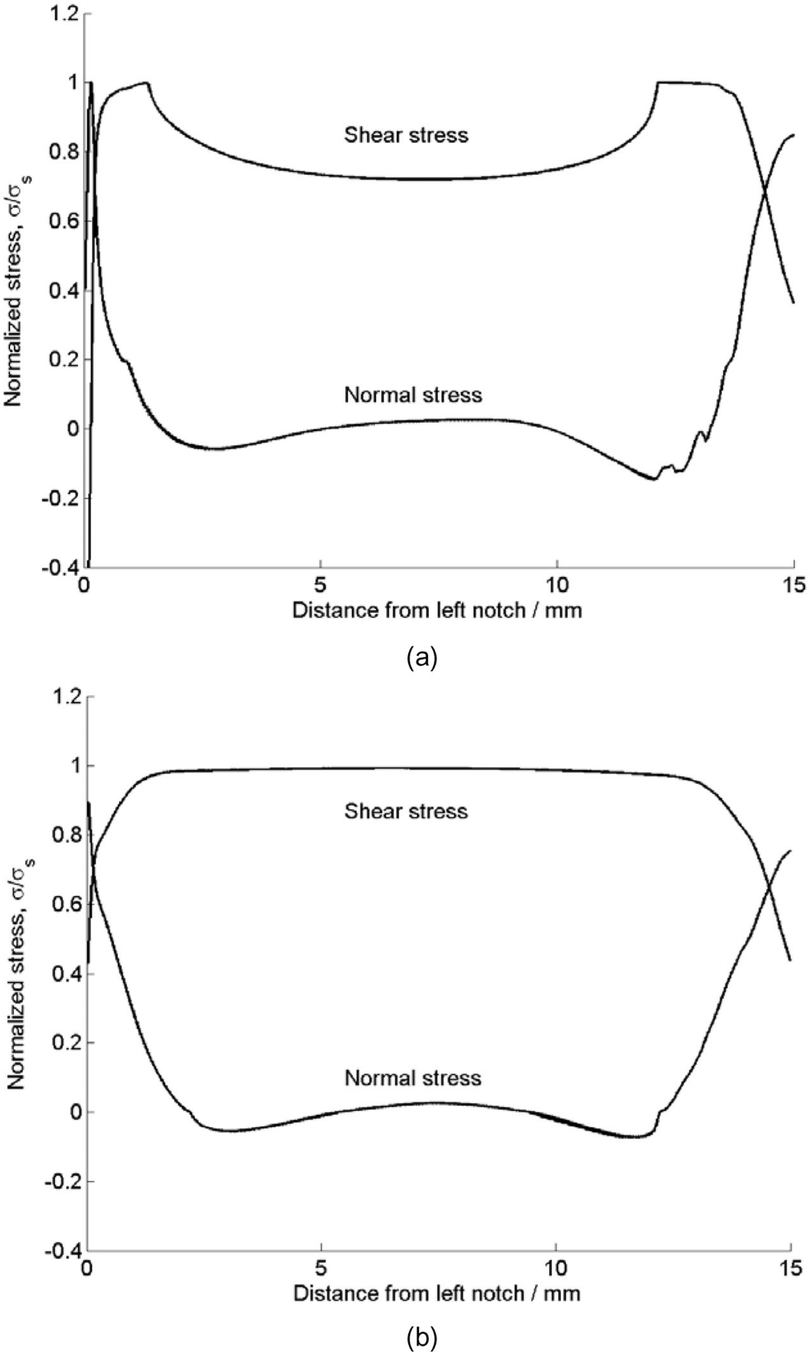

Figure 10. Stress components along the NST shear zone at different positions along the force-displacement curve at δ = 0.48 mm (a) and δ = 0.64 mm(b), as indicated in Figure 13.

concentrations. Instead a uniform shear stress distribution was present at specimen failure, as seen in Figure 10b. Therefore the failure was clearly shear dominated.

5. DISCUSSION

The development of the NST has been a journey where different specimen setups have been tested. Originally the idea of a double notch shear specimen came up when considering the work of Pettersson and Neumeister [12]. Thereafter, Nygårds *et al.* [6] proposed the double notch shear test for testing of paperboard. This test worked fine, but the size of the shear zone was limited due to the risk of tensile failure. Therefore the concept of plastic lamination was investigated. This enabled us to test shear zones that were as large as 15×15 mm^2. The major advantage with the plastic lamination was however the possibility to investigate through thickness shear strength profiles. As the test now is designed shear strength profiles can easily be determined, as shown in Figure 7. Hence the test can both be used as an industrial quality control measure, and in materials design to correlate process changes to their influence on the properties in the thickness direction of paperboard. The latter can be particular important for multiply structures since different plies and interfaces can be altered independently. The shear strength profiles can therefore be used in optimisation of the paperboard design for different applications.

Different producers manufacture paperboards that can have similar values of quality control measures in the out-of-plane direction, such as ZD tension and Scott bond. However, due to different process strategies the paperboards can behave differently in converting operations. This is due to the fact that the through-thickness profiles of the quality measures differ. In Figure 6, the profiles for a multiply paperboard are shown in MD and CD, respectively, and it is shown that this particular board has its weakest points in the interval 100–150 µm from the top surface, while the bottom interface and bottom ply shows higher shear strength. If the producer chooses to make weaker and better defined interfaces, and also strengthens the middle ply, a more pronounced profile would be observed. In creasing and folding operations this would be advantageous since the repeatability of the operation would increase and delamination would primarily occur at the interfaces.

The shear strengths obtained with different methods showed that the RST and SST tests gave the same results. Both these tests prescribe a displacement at the surfaces of the material; therefore a larger material volume in the thickness direction will be loaded. In these tests delamination can be initiated in multiple positions, both along the interfaces and within the different plies. It therefore comes natural that paperboard failure involves the weakest link. With the NST specimen, the failure location was instead prescribed due to the positioning of the notches. This was the concept that enabled us to measure profiles. As a consequence of this approach the measurements at the different positions in the thickness direction will be higher than the RST and SST measurements. There are two reasons for this. Firstly, the positions we use for NST measurements are discrete, here they were 15 μm apart, and hence we cannot ensure that we hit the weakest link of the paperboard. Secondly, in the NST specimen there will be only one shear damage site, while RST and SST can initiate shear damage in multiple positions.

To verify that the NST was a shear test, finite element simulations of the loaded specimen were conducted. To enable the simulations both geometrical and material models were needed. The geometrical model was straightforward to generate, since the specimen had been tested and improved experimentally. The choice of material model was, however trickier, since appropriate paper material models are not in general available in commercial finite element software. Our choice instead fell on a continuum model proposed by Nygårds *et al.* [1], which was used together with a built-in interface model in Abaqus [16]. The continuum model is experimentally verified for creasing operations with good predictability [1]. Therefore, we relied on its accuracy also for this work, and the comparison between numerical and experimental results in this work also showed a very good agreement, which strengthen our trust in the model.

6. CONCLUSIONS

A notched shear test (NST) has been proposed, and as a spin-off from this test also the strip shear test (SST) was suggested. The NST test can be used to measure shear strength profiles in the thickness direction of paperboard, while the SST test can be used as a quick measure of shear strength. The SST measurement correlates well with the rigid shear test (RST), which is a traditional shear test.

Finite element simulations were performed in order to show that the force-displacement behaviour from the experiments could be predicted. The finite elements simulations were also used to ensure that the NST specimen had a uniform shear stress distribution between the notches at the time of failure.

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Transcription of Discussion

DEVELOPMENT OF THE NOTCHED SHEAR TEST

Mikael Nygårds,[1,2] *Christer Fellers*[2] and *Sören Östlund*[1]

[1]KTH, Department of Solid Mechanics, SE-100 44 Stockholm, Sweden
[2]Innventia, Box 5604, SE-114 86, Stockholm, Sweden

Mark Kortschot University of Toronto

Very interesting paper. I just wondered, have you ever considered using an energy-based failure criterion, instead of a stress-based criterion? I do some work with composite delamination and one of the things that the composite guys do is to worry about the mode of delamination. What occurs to me is that in the creasing operation, you have pretty clear Mode II delamination. In fact, it looks a lot like the test that is used for Mode II in composite materials, which is a bending test. But in the new test that you devised, any rotation would lead to a kind of opening mode, which would be expected to actually change the delamination energy. So it is a long question, but I guess the first part of it is: have you considered energy-based failure criteria rather than stress-based criteria, or yield-envelope criteria? And could you tell me a little bit about the difference in mode between the creasing operation you are interested in and the test?

Mikael Nygårds

We have not considered energy-based criteria for the reason that we like stress-strain based constitutive models. It is not a problem to do this, but what you try to work with, in general, is an interpretation of experimental data and you try to translate that to numerical models. Working a lot with verification to see what is happening or not, we believe it works well in that respect. Maybe it could work also with an energy-based criterion. Going into the question that there is shearing: yes, creasing is mode 2, but there is also an opening mode. So there is a combination in there as well, so it is not a pure mode 2, I do not know which one is best.

Discussion

Mark Kortschot

Okay! Thank you.

Jean-Claude Roux University of Grenoble

In your presentation, the distance, *L*, between the two notches seems to have an importance. Can you comment on this? What would be an adequate distance, according to your experience, in a test?

Mikael Nygårds

We are using 15 mm, so we are testing an area which is 15 mm × 15 mm. That is given in the paper. First of all, we chose that because we are going to have a distance that is comparable with previous testing methods. Also, the idea of laminating it first, enabled us to go up in distance, because, if we do not laminate, the testing distance has to be very small. Yes, the strength goes down if you increase the length. My interpretation is that, if you have a crack going between the notches, the length of the path it can take will increase with increased length, so it will go more and more towards the normal shear test where it is following the weakest link; it has a tendency to jump up to the interface. And so, with this one, we believe that it is working quite well and *L* is longer than the fibre length. It is getting reproducible data, but it is not 30 mm. Also shear testing of very large shear zones creates a lot of elastic energy in that zone so you will have more rapid, or more brittle failure at that point, so it seems convenient from the testing.

Jean-Claude Roux

Thank you!