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Validation of isotropic deformation theory of plasticity for fracture mechanics analysis of paper materials

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a report from STFI-Packforsk

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1 Summary

Seven different commercial grades of paper materials were investigated in this work. Tensile and fracture toughness testing according to standardised laboratory testing methods were performed for each of these paper materials. The tensile test data was used to calibrate an isotropic deformation theory of plasticity model and the fracture toughness test data was used to calibrate a fracture criterion based on a constant critical value of the *J*-integral. The calibrated material model and fracture criterion were then used in fracture mechanics analysis of large edge-cracked paper webs using the finite element method. The ultimate failure, in terms of critical load and critical elongation, was predicted. The predictions of ultimate failure were performed for various different crack sizes for each of the seven investigated paper materials.

Experiments on large edge-cracked paper webs were performed in order to validate the fracture mechanics predictions. The edge-cracks were made using a razor blade and the experiments were performed using a custom-built vertical tensile tester. The ultimate failure, in terms of critical load and critical elongation, was measured. The measurement of ultimate failure were performed for various different crack sizes for each of the investigated paper materials.

The results show that the predictions of ultimate failure are in excellent agreement with the measurements of ultimate failure and therefore imply that isotropic deformation theory of plasticity is a suitable modelling level for fracture mechanics analysis of paper materials.

Comparison of the seven different materials showed that the presence of a defect changed the ranking of their strength and stretchability. This result demonstrates that strength parameters determined by standard tensile testing, such as tensile strength and strain at break, may give misleading results when used for ranking of the runnability of paper materials in manufacturing, converting and end-use situations. The results in this work promotes the use of isotropic deformation theory of plasticity for material characterisation and fracture mechanics analysis for prediction of the ultimate strength of notched full-size structures in order to evaluate the defect-sensitivity.

2 Introduction

Previous experimental studies have shown that the fracture process zone in paper materials, i.e. the region where damage evolves and new traction-free crack surfaces are gradually formed, commonly become of significant size before ultimate structural collapse occurs (Tanaka 1998; Wiens, Göttsching et al. 1998; Hornatowska, Östlund et al. 1999; Wiens and Göttsching 1999). Under such large-scale damage evolution conditions, crack tip characterisation using a single parameter becomes questionable.

Other studies, however, show that a fracture criterion based on the *J*-integral appears to possess predictive capability of ultimate failure of paper materials (Gregersen 1998; Fellers, Melander et al. 1999; Mäkelä and Östlund 1999; Wellmar, Gregersen et al. 2000).

The applicability of the *J*-integral to paper materials was investigated in more detail by Mäkelä and Östlund, who formulated an incremental orthotropic elastic-plastic material model (Mäkelä and Östlund 2003) suitable for describing the material behaviour of paper materials. Based on this model, they developed a cohesive crack model suitable for analysing fracture processes of paper materials (Mäkelä and Östlund 2006). The proposed cohesive crack model, which accounts for characteristic types of material behaviour of paper materials, such as linear elasticity, plasticity, anisotropy, and damage evolution, was carefully calibrated for one paper grade. The accuracy of the failure predictions obtained by the calibrated cohesive crack model was then verified by comparisons to experiments on notched paper sheets.

The calibrated cohesive crack model was used to demonstrate that the *J*-integral can accurately be used to characterise the crack tip state in paper materials even when large-scale damage prevail. Furthermore, the cohesive crack model was used to study the transferability of the fracture process in paper materials. This study was performed by predicting ultimate failure of centre-cracked paper webs with various different characteristic dimensions. The results showed that the critical size of the damage region generally increases as result of increased characteristic dimensions of the structure, i.e. the stability of the damaged region is extended for structures with large dimensions. However, such differences in the stability of the damage zone had small influence on the load-carrying capacity and the critical strain of the structure. The study therefore showed that the *J*-integral approximately exhibits transferability, implying that a failure criterion based on a constant critical value of the *J*-integral can be used to obtain accurate engineering predictions of the ultimate failure of paper materials for a large range of structural dimensions.

In a recent investigation, the importance of modelling damage behaviour, plasticity, and anisotropy, respectively, for producing accurate fracture mechanics analysis of paper materials were studied (Mäkelä and Östlund 2007). Different levels of material models, ranging from cohesive crack models to linear elasticity, and their influence on the accuracy of failure predictions were investigated. The study showed that accurate modelling of the plasticity is highly important, especially when the treated material exhibits pronounced elastic-plastic material behaviour. Damage behaviour becomes important when structures with small characteristic dimensions are analysed, while the anisotropy has surprisingly small influence on fracture mechanics predictions.

The study specifically promotes isotropic deformation theory of plasticity as a suitable modelling level for fracture mechanics analysis of paper materials. This model appears to produce excellent predictions of ultimate failure in paper materials, independently of the degree of non-linearity and anisotropy of the treated paper material. Its only limitation appears to be when transferability becomes seriously violated, e.g. for crack sizes that are smaller than few millimetres.

The aim of this work was to verify the accuracy of using isotropic deformation theory of plasticity in fracture mechanics analysis for a selection of different commercial grades of paper materials.

3 Materials and Methods

3.1 Materials

Seven different commercial grades of paper materials, which were carefully selected in order to cover a wide field of end-use applications, were treated in this work. The common feature of these selected materials were that they all have demands on load-carrying capacity in converting or end-use situations. Otherwise, these materials covered papers that were made from different fibre types or combinations thereof, were produced using different papermaking strategies, and had different end-use applications. The selected paper materials comprised the following grades:

- Medium-weight coated paper (MWC)
- Testliner (Liner)
- Fluting paper (Fluting)
- Sackpaper (Sack)
- Newsprint (News)
- Supercalendered paper with 10 % addition of reinforcement fibres (SC10)
- Supercalendered paper with 20 % addition of reinforcement fibres (SC20)

All selected paper materials were supplied as wrapped wound rolls by six different European mills (the last two paper grades were supplied by the same mill). The length of the paper webs on the supplied rolls were in the range of 300-500 m, while the web width ranged between 0.95m and 1.1 m, except for the newsprint roll that had a width of 1.8 m. The newsprint roll was cut to a width of approximately 1.1 m using a bandsaw, in order to make it compatible with the available roll handling equipment.

The supplied rolls were unwrapped and stored in a standardised climate of 23 °C and 50 % relative humidity for minimum two weeks before further actions were taken, in order to allow the paper materials to reach moisture equilibrium.

3.2 Experiments

All experiments in this work were performed at the joint facilities of the Department of Chemical Engineering at Norwegian University of Science and Technology (NTNU) and the Paper and Fibre Research Institute (PFI). The experiments were performed in a controlled climate of 23 °C and 50 % relative humidity for each of the seven investigated paper materials.

3.2.1 Laboratory testing

Full-width paper samples were cut out from the paper rolls and the samples were stored in a controlled climate of 23 °C and 50 % relative humidity for an additional 24 hours prior to laboratory testing.

The grammage of the paper materials was evaluated using ISO 536:1995 and the structural thickness and structural density was determined using SCAN-P88:01. The paper samples for these measurements were cut out from different positions along the cross-machine direction (CD) of the paper webs in order to cover possible CD variations in these properties.

Tensile testing was performed in the machine direction (MD) according to ISO 1924-3:2005 and fracture toughness testing was performed in the MD according to SCAN-P77:95. The 15 mm wide MD tensile test pieces and the 50 mm wide MD fracture toughness test pieces were cut out alternately from one edge of the paper web to the other edge of it in order to cover possible CD variations of the material properties. A 20 mm symmetrically placed centre-crack, oriented along CD, was made in each fracture toughness test piece using a sharp razor blade. A L&W tensile tester and a clamping length of 100 mm was used in the tensile and fracture toughness tests. The out-of-plane buckling of the fracture toughness test pieces were prevented during the testing by the use of anti-buckling guides.

3.2.2 Determination of material parameters

The tensile test data was used to calibrate an isotropic deformation theory of plasticity model, which is expressed uniaxially as:

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{E_0}\right)^N \qquad (1)$$

The deformation plasticity model forms a one-to-one relation between strain, ε, and stress, σ, that is established by three material parameters: the tensile stiffness, E, the strain hardening modulus, E_0, and the strain hardening exponent, N. The tensile stiffness was determined according to ISO 1924-3:2005, while the strain hardening material parameters were evaluated by least-squares fitting of *Eq. 1* to the tensile test data.

The fracture toughness was determined by finite element (FE) analysis of the fracture toughness testing geometry as the value of the *J*-integral corresponding to the determined mean value of the failure load from the fracture toughness testing. In these analysis, the calibrated isotropic deformation theory of plasticity model was used to model the material behaviour. These analyses are described in more detail in the section “Numerical analysis”.

3.2.3 Tensile testing of large edge-cracked paper webs

The paper rolls were edge-trimmed and rewound on a metal core using an in-house rewinder equipped with sharp razor blades. The edge-trimming was performed in order to obtain the desired web width and to ensure that possible edge-damages of the paper webs from transport, handling and bandsawing were eliminated. The edge-trimmed paper webs were then continuously stored in a climate of 23 °C and 50 % relative humidity pending tensile testing.

An custom-built vertical tensile tester (see Figure 1), capable of testing paper webs with widths ranging up to 1000 mm, was used. The metal core with the rewound paper web was journalled in bearings of the pivot bar of the tensile tester, located in the top position of the tensile tester. The paper web was unwound from the metal core, thread over an upper high-friction roll and a lower stationary high-friction roll, before it was rewound on another metal core with rotational degree of freedom, located in the bottom position of the tensile tester. The paper web was allowed to align itself by the influence of gravidity during the unwinding and rewinding, and it was slightly stretched before the bearings of the metal cores were locked.

Figure 1. Vertical tensile tester for testing of large paper webs.

The high-friction rolls were used in order to prevent slippage of the paper web during tensile testing. The winding angle of the paper on the high-friction rolls was approximately 270°. Possible uneven CD tension profiles of the mounted paper web was corrected by the use of a horizontal straight smooth bar that was pressed against the paper web and fixed in a position that made the tension profile as even as possible.

The initial length of the mounted paper web was 1880 mm, measured as the web length between the top position of the upper high-friction roll and the bottom position of lower high-friction roll. Two chips of light-weight foam polystyrene were mounted with a vertical separation of 1350 mm along the centre line of the paper web using adhesive tape. The MD displacements of each of these chips were continuously measured by laser displacement sensors during testing. The elongation of the web was evaluated as the difference of these measured displacements and the strain was evaluated as this elongation divided by the initial separation of the chips.

The loading of the paper web was imposed by horizontal displacement of the upper high-friction roll. This prescribed deformation was supplied by a motor-driven spindle that controlled the pivoting bar where the top metal core and the upper high-friction roll were mounted. The force that was subjected to the paper web was continuously measured by a load cell during testing. After testing, the measured loads were corrected for the dead weight of the upper metal core with the rewound paper.

An edge crack was cut in the paper web before the testing was initiated. This man-made crack was produced using a sharp razor blade and its size was carefully measured using a digital slide calliper. Several different tests with different crack sizes were performed for each of the investigated materials.

The out-of-plane buckling of the paper web in the crack tip region was prevented during all tensile tests by the use of two smooth 200 mm high and 1300 mm wide plexiglass sheets. One of these sheets was stationary mounted behind the paper web and the other one was mounted in front of the paper web in such way that the whole width of the paper web was enclosed by the plexiglass sheets. Initial trials showed that the measured tensile behaviour of paper webs without man-made cracks were not affected by the plexiglass sheets, i.e. the possible influence of the plexiglass sheets on tensile test results due to friction were negligible.

Tests that exhibited slippage, non-uniform loading, poor crack quality or any other irregularities were rejected. After one test had been performed, the bearings of the metal cores were unlocked and new paper was unwound from the upper metal core. All paper that was affected by the previous test was cut loose before the preparation of the next test begun.

3.3 Numerical analysis

The commercial finite element code ABAQUS/Standard (2002) was used to perform all numerical analyses in this work. Two different types of fracture mechanics analyses were performed, determinations of fracture toughness based on laboratory test data and predictions of the ultimate failure of large paper webs.

The symmetries in geometry and loading of the fracture mechanics problems that were analysed were considered. The double-symmetry of the fracture toughness tests (uniaxially loaded centre-cracked geometry) was utilised to restrict the analysis to one quarter of the structure and the single-symmetry of the large paper webs (uniaxially loaded centre-cracked geometry) was utilised to restrict the analysis to one half of the structure. *Figure 2* shows an illustration of the type of finite element mesh that was used in the fracture mechanics analyses.

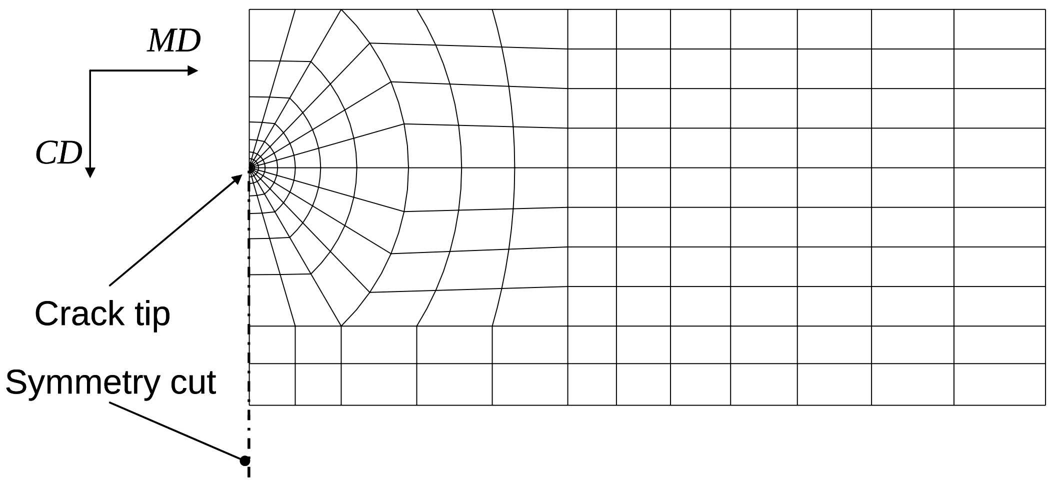

Figure 2. Illustration of the type of used FE-mesh in the numerical analyses (model of one half of an analysed edge-cracked structure, after symmetry considerations).

Quadratic eight-node isoparametric plane stress elements were used in all numerical analyses. The used material model, which constitutes a generalisation of the uniaxial deformation theory of plasticity model in *Eq. 1* to plane stress conditions, is given by,

$$\varepsilon_{ij} = C^{-1}_{ijkl}\sigma_{kl} + \frac{3}{2}\left(\frac{\sigma_{\mathrm{e}}}{E_0}\right)^N \frac{s_{ij}}{\sigma_{\mathrm{e}}} \qquad (2)$$

where the relation between the components of the strain tensor, ε_{ij}, and the components of the stress tensor, σ_{ij}, are established by the elastic material parameters of the compliance tensor, C^{-1}_{ijkl}, and the two strain hardening material parameters E_0 and N. The parameter σ_{e} is the von Mises effective stress, and s_{ij} denote the components of the deviatoric stress tensor. The Poisson's ratio was assumed to be 0.293 for all investigated materials.

The loading was applied as uniformly and monotonically increasing prescribed displacement in MD of the nodes located on the remote boundary from the cracked symmetry plane (cf. the nodes located on the right edge of the FE-mesh in *Fig. 2*), while the displacement in CD of these nodes were restricted. The *J*-integral was evaluated using the implemented domain integral formulation in ABAQUS/Standard.

The fracture toughness of the investigated materials were determined by fracture mechanics analysis of the fracture toughness testing geometry. The fracture toughness was evaluated as the value of the *J*-integral corresponding to the evaluated *mean failure load* from the fracture toughness testing.

The ultimate failure of the large edge-cracked paper webs were predicted by analysing the testing geometries of the large paper webs. The critical force and critical elongation was evaluated as the values of force and elongation corresponding to the fracture toughness of the material. These analyses were performed for various different crack sizes for each of the investigated materials.

The different paper materials had different widths, which makes it difficult to fairly compare the material performances from a fracture mechanics perspective due to geometrical factors. For this reason, some additional predictions of ultimate failures of the materials at equal web width was performed. In these analyses, a web length of 1880 mm and a web width of 1000 mm was analysed for all investigated materials. The critical force and critical elongation was determined for various different crack sizes in the same way as in the analysis of the tensile tests of the large edge-cracked paper webs

4 Results and discussion

4.1 Determined material properties

Table 1 summarises the evaluated structural parameters for the investigated materials. These results show that the materials spanned a large interval of grammages, thicknesses and densities.

Table 1. Summary of the measured structural parameters.

	MWC	Liner	Fluting	Sack	News	SC10	SC20
Grammage [g/m2]	90	100	111	79	45	51	52
Thickness [mm]	75.4	149.8	144.9	103.7	60.9	41.7	41.9
Rel. 95 % CI [%]	*3.0*	*5.7*	*5.4*	*6.1*	*6.0*	*6.0*	*5.8*
Structural density [kg/m3]	1194	668	766	762	739	1223	1241

The determined material parameters from the tensile testing, separated as parameters describing the constitutive behaviour and the strength of the investigated materials, respectively, are summarised in *Tables 2-3*. The results in *Table 2* show that the fluting exhibited highest tensile stiffness index, followed by the sack paper and the newsprint, while the stiffness of the other four materials were surprisingly similar. *Table 3* further shows that the fluting exhibited the highest specific strength among the investigated materials, followed by the sack paper. The most stretchable material was the sack paper followed by the fluting and the testliner. The only two materials that showed an overall similar performance were the two supercalendered paper grades, of which the most reinforced one (SC20) had slightly higher stiffness, strength and strain at break than the less reinforced one (SC10).

Table 2. Summary of the determined constitutive parameters.

	MWC	Liner	Fluting	Sack	News	SC10	SC20
Tensile stiffness index [MNm/kg]	7.52	7.61	11.98	10.41	9.77	7.27	7.69
Rel. 95 % CI [%]	*1.1*	*2.1*	*1.6*	*2.8*	*1.6*	*1.3*	*1.3*
Hardening modulus index [kNm/kg]	228.9	188.4	519.2	370.1	236.3	196.2	196.3
Hardening exponent	3.55	4.19	3.29	3.46	4.36	3.89	3.98

Table 3. Summary of the determined strength parameters.

	MWC	Liner	Fluting	Sack	News	SC10	SC20
Tensile strength index [kNm/kg]	54.5	61.4	124.1	107.4	66.0	47.0	49.6
Rel. 95 % CI [%]	*1.7*	*2.0*	*2.5*	*3.4*	*2.3*	*1.7*	*2.6*
Strain at break [%]	1.34	1.72	1.94	2.39	1.07	1.05	1.08
Rel. 95 % CI [%]	*3.1*	*4.2*	*3.7*	*3.6*	*4.7*	*2.9*	*4.7*
Tensile energy absorption index [J/kg]	463	705	1499	1684	438	306	337
Rel. 95 % CI [%]	*5.1*	*6.1*	*5.8*	*5.7*	*7.6*	*4.8*	*8.1*

Figure 3 shows the stress-strain curves from the tensile testing. The tensile stress-strain curves of all investigated materials were excellently modelled by the deformation plasticity model in Eq. 1, when calibrated by the determined constitutive parameters in *Table 2*.

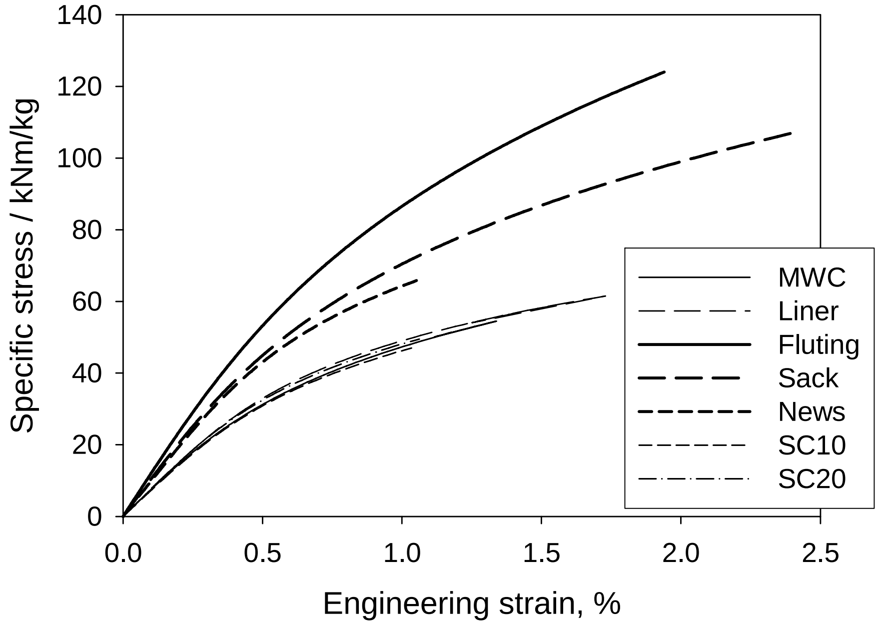

Figure 3. Summary of stress-strain curves from the tensile testing. Each curve is based on the mean value from ten tensile tests.

Table 4 summarises the determined material data from the fracture toughness testing of the 50 mm wide MD test pieces with man-made 20 mm centre cracks. The apparent strength index and apparent strain at break express the specific strength and strain at break, respectively, of the fracture toughness test pieces without regarding the presence of the centre-cracks in the test pieces. The fracture toughness index, which was determined numerically by FE-analysis of the fracture toughness test geometry for each material, expresses the ability of the material to sustain stress concentrations. The sackpaper exhibited highest strength and stretchability at presence of a defect and the highest fracture toughness among the investigated materials.

Table 4. Summary of the determined material data from the fracture toughness testing.

	MWC	**Liner**	**Fluting**	**Sack**	**News**	**SC10**	**SC20**
Apparent strength index [kNm/kg]	23.58	26.98	39.21	46.64	27.23	19.40	20.98
Rel. 95 % CI [%]	*2.1*	*2.6*	*1.7*	*2.0*	*2.8*	*1.5*	*2.6*
Apparent strain at break [%]	0.52	0.59	0.48	0.82	0.43	0.42	0.44
Rel. 95 % CI [%]	*2.6*	*2.6*	*2.4*	*3.5*	*4.4*	*3.4*	*4.6*
Fracture toughness index [Jm/kg]	4.14	5.60	6.25	13.80	3.61	2.54	2.89

4.2 Measured and predicted strength of large edge-cracked paper webs

The tensile testing of the large paper webs were performed for 1000 mm wide webs, with three exceptions: the width of the MWC paper web was 950 mm and the widths of the fluting paper and the sackpaper webs were 800 mm. In the former case, the choice of a smaller width was due to that the web width on the supplied roll was 1000 mm, wherefore the width after edge-trimming became lower, and in the latter case the smaller width was chosen to ensure that the load cell of the tensile tester was not overloaded. The results from these tensile tests are shown in *Figures 4-10*, where each experimental point corresponds to the measured force at break or elongation at break from one test versus the size of the man-made edge-crack in the test.

Furthermore, the force at break and elongation at break for the investigated large edge-cracked paper webs were predicted using fracture mechanics analysis. These analyses were performed based on isotropic deformation theory of plasticity and a failure criterion based on a critical constant value of the *J*-integral. The isotropic deformation theory of plasticity model (see *Eq. 2*) was calibrated by the determined constitutive parameters of the materials (see grey fields in *Table 2*) and the determined fracture toughness index of the materials were used as the critical value of *J* (see grey fields in *Table 4*). The predictions of ultimate failure are shown as solid lines in *Figures 4-10*. These results show that the predictions of ultimate failure are in excellent agreement with the experimental results and therefore imply that isotropic deformation theory of plasticity is a suitable model for fracture mechanics analysis of paper materials.

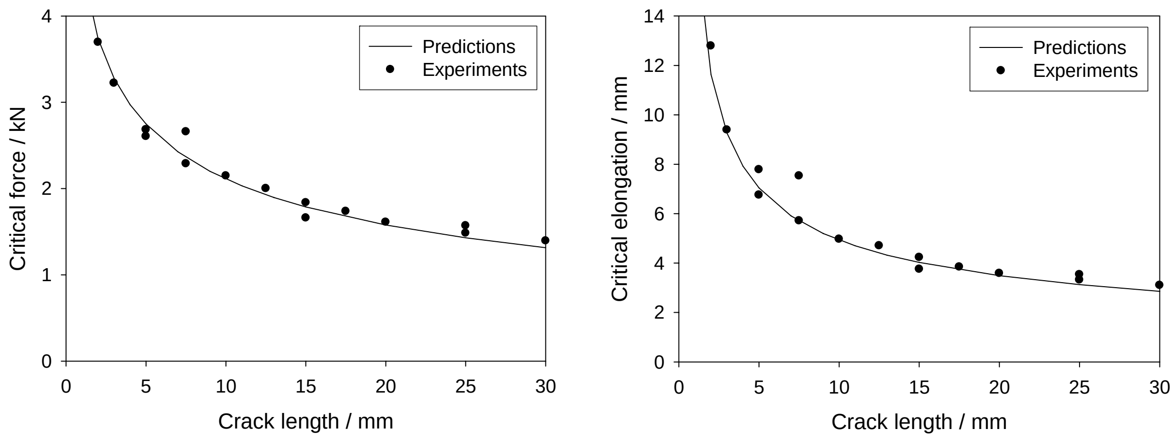

Figure 4. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **MWC** paper webs (Length 1880 mm, Width 950 mm).

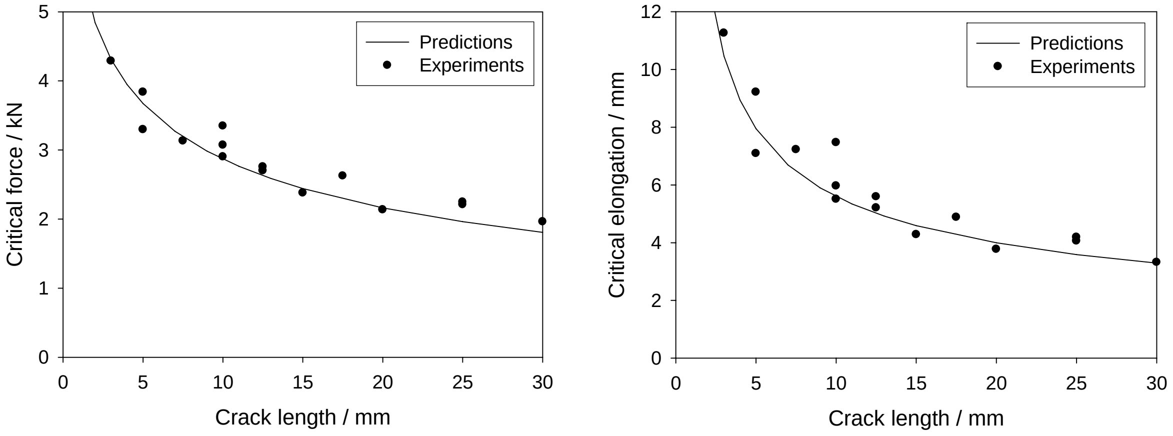

Figure 5. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **Testliner** webs (Length 1880 mm, Width 1000 mm).

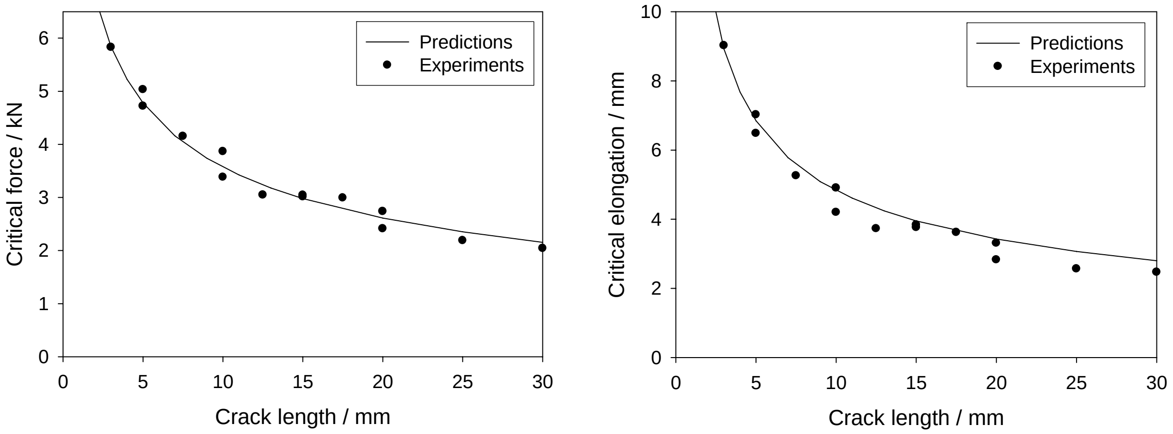

Figure 6. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **Fluting paper** webs (Length 1880 mm, Width 800 mm).

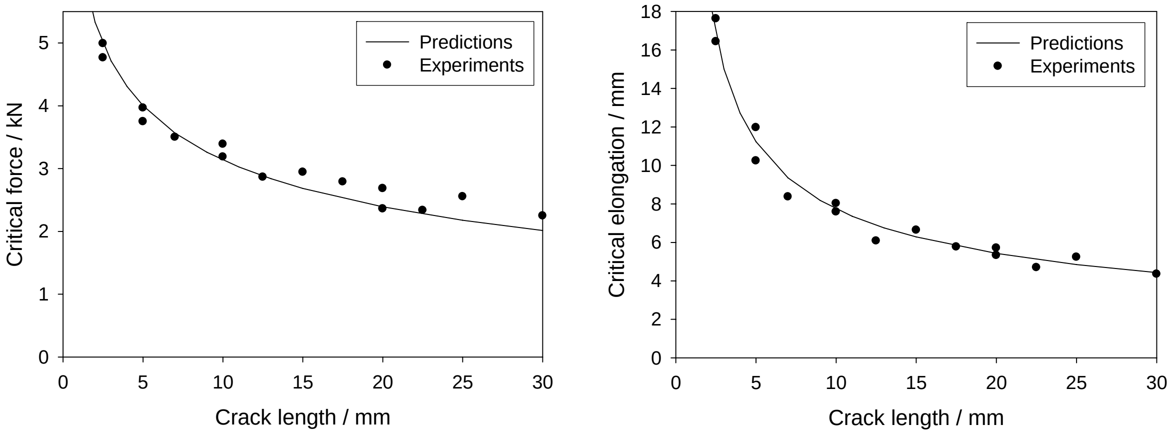

Figure 7. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **Sackpaper** webs (Length 1880 mm, Width 800 mm).

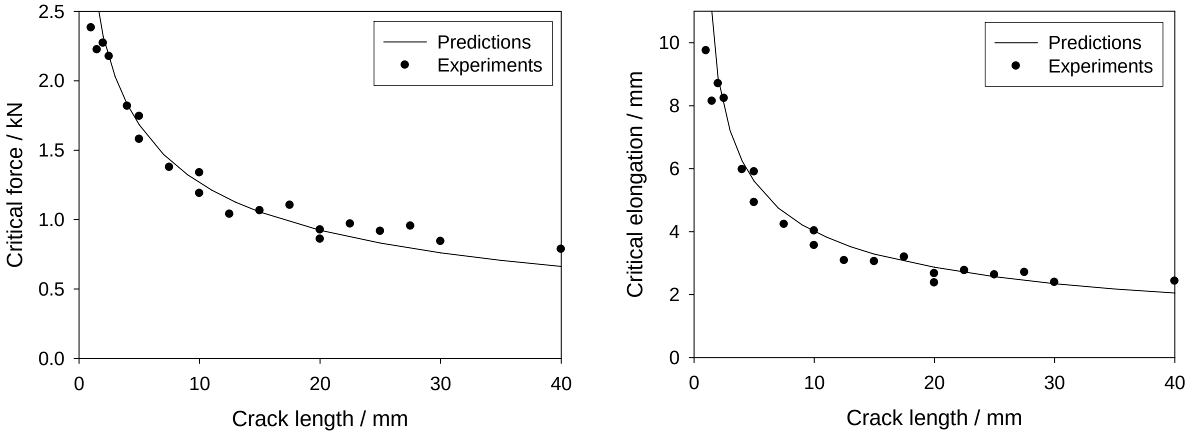

Figure 8. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **News** paper webs (Length 1880 mm, Width 1000 mm).

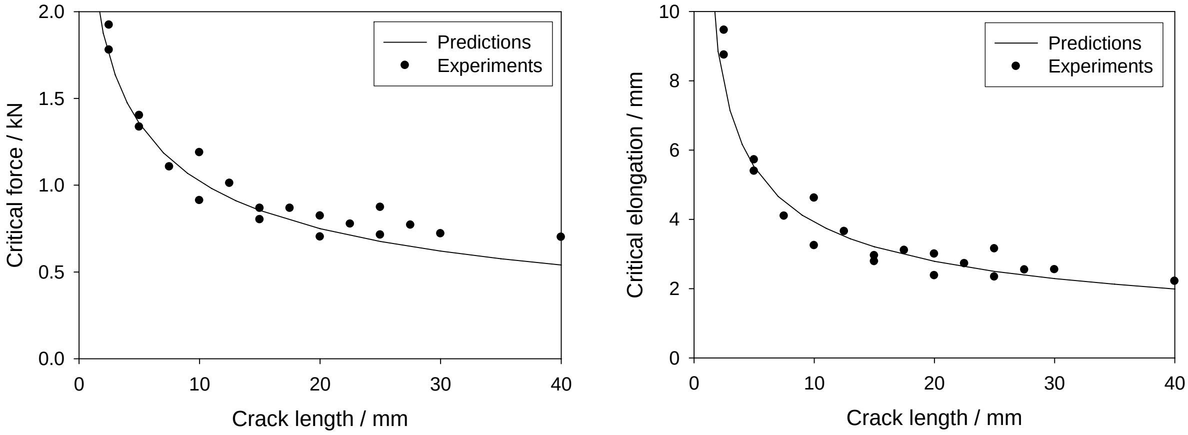

Figure 9. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **SC10** paper webs (Length 1880 mm, Width 1000 mm).

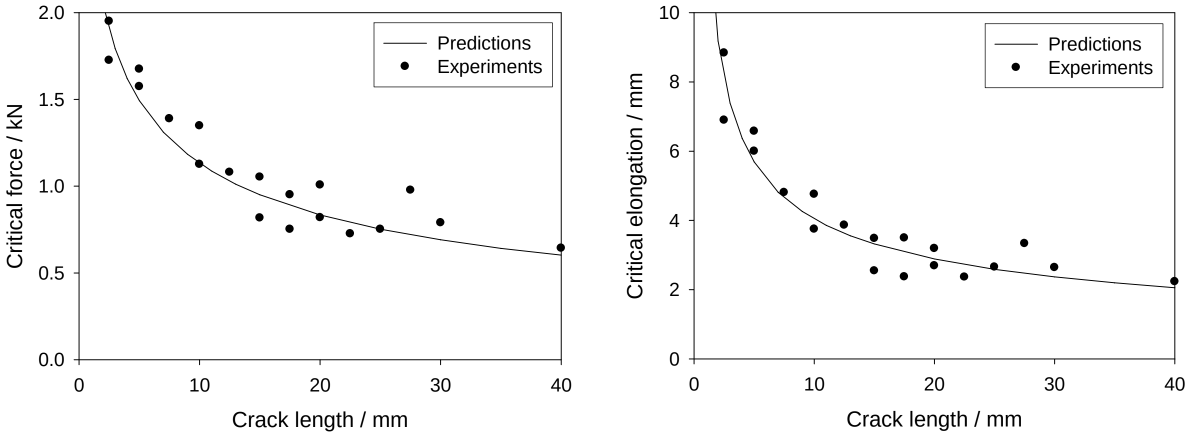

Figure 10. Comparison between experiments and predictions of the ultimate failure of large edge-cracked **SC20** paper webs (Length 1880 mm, Width 1000 mm).

4.3 Comparison of fracture properties of the investigated papers

The fracture properties of the investigated paper materials were compared by predicting the ultimate failure in MD of a paper web that was 1880 mm long and 1000 mm wide, with an edge-crack that was 5 mm long. These predictions are presented in *Figure 11*, where the critical tensile index is defined as the predicted critical force of the web divided by its width and grammage and the critical strain at break is defined as the predicted critical elongation of the web divided by its length.

The results show that the introduction of a defect changed the ranking of strength and stretchability of the paper materials. As an example, the fluting paper had the highest tensile index, but had no longer highest strength when a 5 mm edge-crack was introduced in the web. This result promotes the use of fracture mechanics tools for characterising the performance of paper materials in converting and end-use situations. The large webs, however, did rank in the same way as in the fracture toughness tests (cf. *Table 4*), but predictions of quantitative values for ultimate failure, as presented in *Figure 11*, do require fracture mechanics analysis.

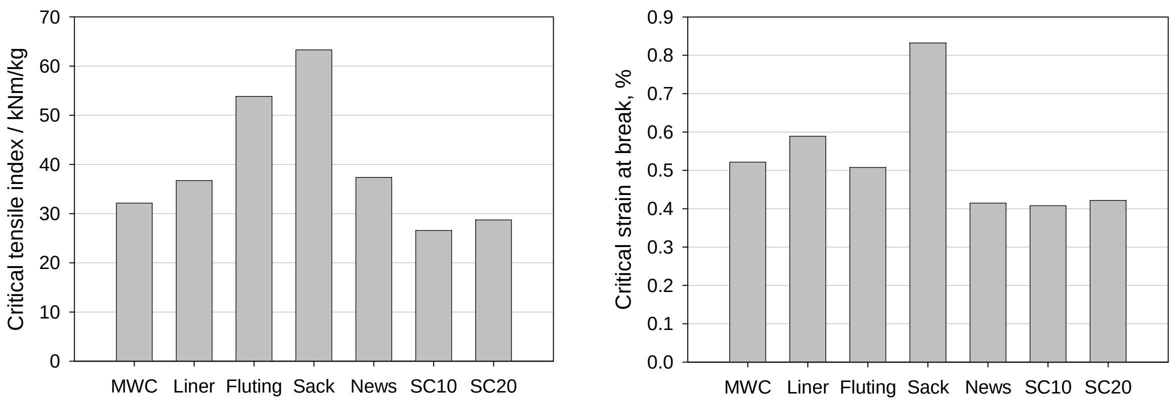

Figure 11. Comparison of fracture properties of the investigated paper materials in terms of specific strength and strain at break at presence of a 5 mm edge crack (Web length 1880 mm, Web width 1000 mm).

Finally, *Figure 12* shows the ratio of the critical tensile index of the notched web to the tensile index of the material and the ratio of the critical strain at break of the notched web to the strain at break of the material, respectively, for the investigated materials. These two parameters show how much of the strength and strain at break, respectively, of the materials that remained when a 5 mm edge crack was introduced in the web. The majority of the materials appeared to have around 56-60 % of their initial web strength left when the 5 mm crack was introduced, while the fluting paper responded with only 43 % of its material strength. The MWC, News and SC-paper webs retained about 38-39 % of their virgin stretchability when the 5 mm crack was introduced, the testliner and sackpaper webs exhibited around 34-35 % of their strain at break, while the fluting paper web exhibited only 26 % of its virgin stretchability.

This comparison of the investigated materials showed that the sackpaper had the highest strength and strain at break at presence of cracks, while the fluting paper was significantly the most crack-sensitive paper grade among the investigated paper materials, when compared to their virgin strength and stretchability.

The increased addition level of reinforcement fibres in the investigated SC-papers resulted in slightly improved fracture properties.

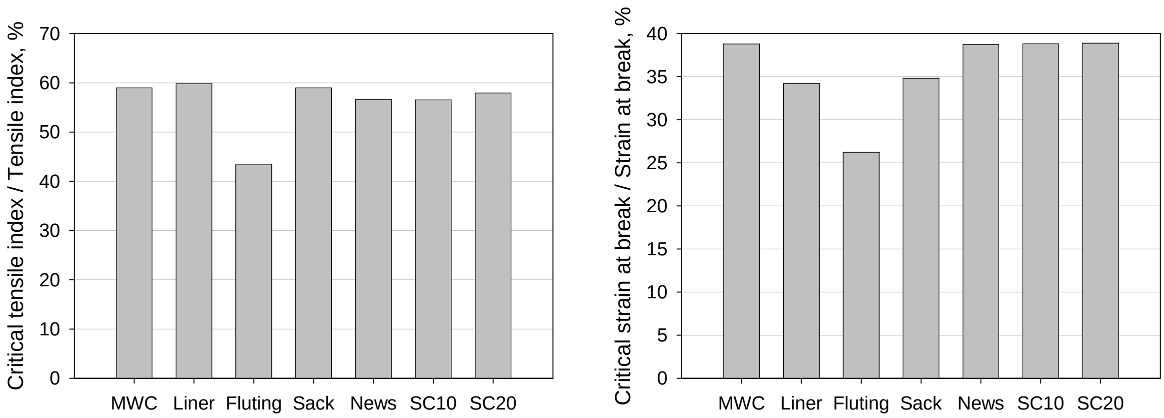

Figure 12. Comparison of fracture properties of the investigated paper materials in terms of the ratio of critical tensile index of the notched web to the tensile index of the material and the ratio of the critical strain at break of the notched web to the strain at break of the material, respectively. (Web length 1880 mm, Web width 1000 mm).

5 Conclusion

The excellent agreement between predictions and measurements of ultimate failure of large edge-cracked paper webs for the different paper materials show that isotropic deformation theory of plasticity is a suitable model for fracture mechanics analysis of paper materials.

The results further showed that the presence of a defect changed the ranking of the strength and stretchability of the investigated paper materials. This result demonstrates that strength parameters determined by standard tensile testing, such as tensile strength and strain at break, may give misleading results when used for ranking of the runnability of paper materials in manufacturing, converting and end-use situations. The results in this work promote the use of isotropic deformation theory of plasticity for material characterisation and fracture mechanics analysis for prediction of the ultimate strength of notched full-size structures in order to evaluate the defect-sensitivity.

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