ANALYSIS OF VARIOUS CHEVRON NOTCH TYPES AND ITS INFLUENCE ON THE LIGAMENT AREA

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Abstract. *Specimens for the bending tests with the chevron notch are standardized for the evaluation of the fracture toughness of various materials. In this contribution a difference of the ligament area of the specimens with the straight through notch and the chevron notch was investigated.*

Keywords

Chevron notch, fracture mechanics, ligament area, work of fracture.

1. Introduction

The applied testing technique is the chevron-notched beam test (CNB), which is a standardized method to evaluate fracture toughness of ceramics [1][2], also used for brittle metals like bearing steel [3] or aluminium alloys [4]. Experimental bending test set-ups with specimens possessing a chevron notch have been introduced and standardized since the 1960's [5][6]. The advantage of this test set-up is that no sharp pre-crack has to be introduced because a sharp crack is formed during loading at the beginning of the test [7]. Furthermore, no crack length measurement is required, and a stable crack growth can be reached due to the geometry of the notch [8], [9], [10].

The aim of this contribution is to quantify the difference of ligament area for the specimens with the straight through notches and chevron notches.

2. Theoretical Background

In the load-displacement relations, see example in Fig. 1, the area enclosed by the response curve represents the work done by the external load to fracture beam. Suppose that the crack growth is stable, and the work done by external load is spent entirely in crack propagation. Based on the Griffith energy criterion [11], crack growth in an elastic body in the equilibrium state is a natural process of energy transfer between the strain energy of the body and the fracture energy required for creating a new crack surface, so that a state of minimum potential energy is achieved for the system at a given load level. In the present case, the work is consumed in breaking the unnotched part of the beam's cross-section – the ligament in front of the notch.

According the RILEM [12] and Karihaloo [13][14], for three-point bending test (3PB), with initial notch the work of external force (fracture value) W_F, is obtained from the complete load – displacement diagram as follows:

$$W_F = \int F(d)\mathrm{d}d, \tag{1}$$

The value of the specific fracture energy G_F (energy needed to create a crack of unit area) can be expressed as:

$$G_F = \frac{W_F}{A_{lig}}. \tag{2}$$

where W_f is the work of fracture and A_{lig} is the ligament area.

Karihaloo in [13] and in [15] discusses various notch depth on the evaluation of the specific fracture energy G_F. The notch depth has direct influence on the ligament area A_{lig}, hence the knowledge of A_{lig} is crucial in fracture of the brittle materials.

The RILEM test recommendation uses the test specimens with straight through notch (Fig. 2(a)) for the evaluation of the specific fracture energy G_F. Hence it does not provide any recommendation for the specimens with the chevron notch. Fig. 2 shows a various type of notches for three-point bending test, this can be applicable for four-point bending test as well.

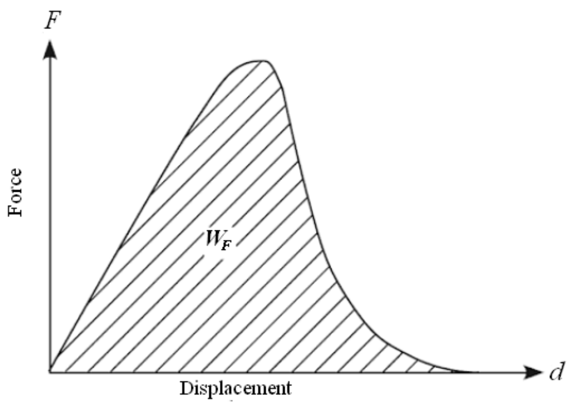


Fig. 1: Determination of work of fracture W_F based on the RILEM method: notched beam under three-point bending and load deformation relations (adopted from [12]).

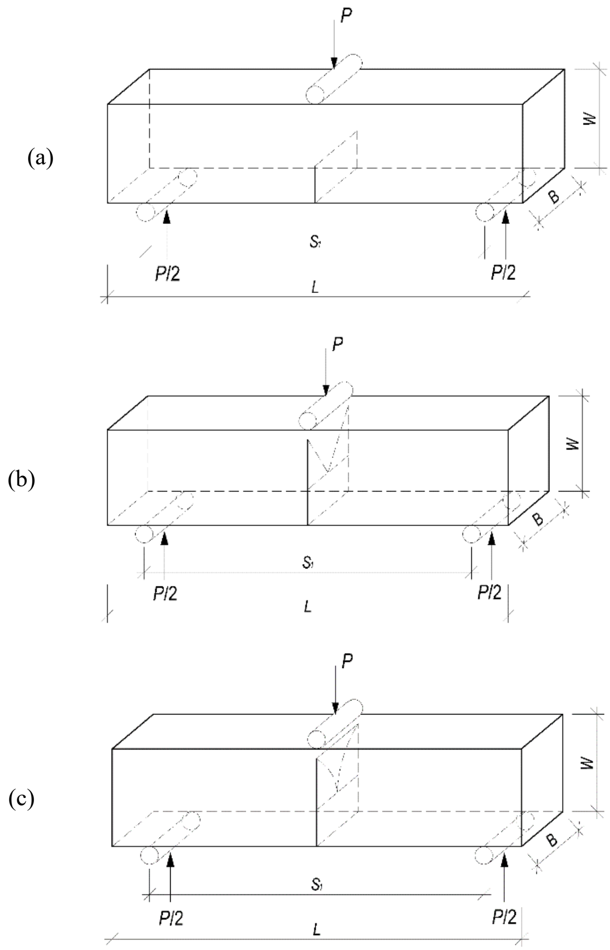
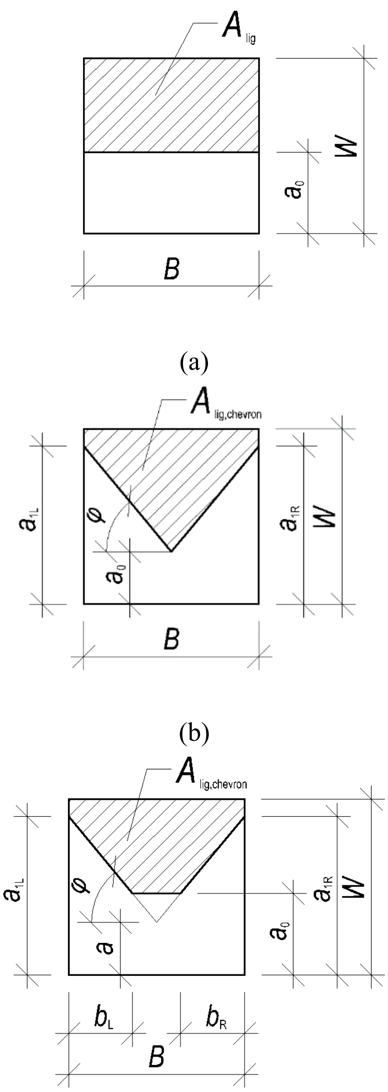


Fig. 2: Comparison of 3PB specimen with straight through notch (a), 3PB specimen with sharp chevron notch (b) and 3PB specimen with round chevron notch (c).

Specimens with the chevron notch has a smaller ligament area $A_{lig,chevron}$ compared to the standard specimens with the straight through notch A_{lig}, therefore more work of fracture/fracture energy is needed for the fracture process. In order to quantify difference of specimen's ligament area a constant value of a_0 (α_0 is then calculated as a a_0/W, where W represents height of the test specimen) with two notch angles φ equal 30° and 45° for the sharp chevron notch and constant value of a_0 with various a_1 (α_1 is then calculated as a_1/W) with various notch angles φ equal 30° and 45° were chosen for the blunt notch ending. This helps to identify the difference of the ligament area. The definition of the cross-section with the straight through, sharp and blunt chevron notches shows Fig. 3.



(c)

Fig. 3: Comparison of ligament area of straight through notch (a), chevron notch with constant angle (b) and chevron notch with constant angle with blunt ending (c).

However, these straight edges of the chevron notch can be in doubt and depends on the skill of the technician who prepares the notch. Based on the practical experience, a chevron notch is sometimes prepared with round edges with radius of the diamond saw [16]. This gives different value of $A_{lig,chevron}$ for the straight edged notches and round edged notches. The illustrative cross-sections of the chevron notches are shown in Fig. 4(a) and Fig. 4(b) for the chevron notch with the round edges with sharp ending and for the chevron notch with the round edges with blunt ending.

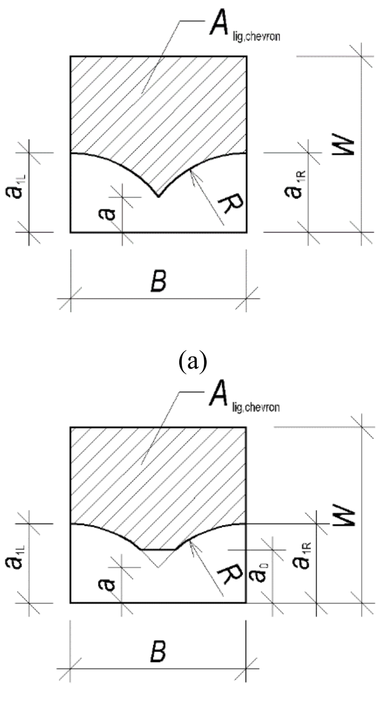


Fig. 4: Comparison of ligament area of the chevron notch with round edges with sharp ending (a) and chevron notch with round edges with blunt ending (b).

The type of the chevron notch influences the fracture toughness KIC. The fracture toughness is evaluated from [3]:

$$K_{IC} = \mathrm{P}_{max} B W^{1/2} Y^{*}_{min}, \qquad (3)$$

where the $P_{\max}$ is the maximum measured force, B is the thickness of the specimen, W is the width of the specimen and th $Y^{*}_{\min}$ is the shape function. The abovementioned types of the chevron notches are considered in the geometry function. The literature [17] and [18] provides various experimental and numerical studies of the influence of the geometry function on the fracture toughness.

3. Results and Discussion

To quantify the difference of the ligament area, a specimen with square cross-section was chosen to for a parametric study. In this study, parameters α and α_1 varied in case of chevron notch specimen and the parameters α_1 and R in case of chevron notch with the round edges. The results presented below are showed in dimensionless parameters $A_{\text{lig,chevron}}/A_{\text{lig}}$.

3.1. Chevron Notch with Sharp Edges

In case of sharp chevron notch, the studied parameter was α_1, which changed from 0.1 to 0.9 (in case of α_0 = 0 the chevron becomes the straight through notch). With different values of parameter α_1, the notch angle φ varies as well. The different notch angle φ can be produced unintentionally in the preparation of the specimens. The results of the influence of the parameter α_1 are presented in Fig. 5, while the development of the φ angle over the various α_1 is shown in Fig. 6. The notch angle φ is equal to zero, when both parameters α and α_1 are equal to 1. This condition confirms the general expectation, for which there is no notch angle present in the ligament area.

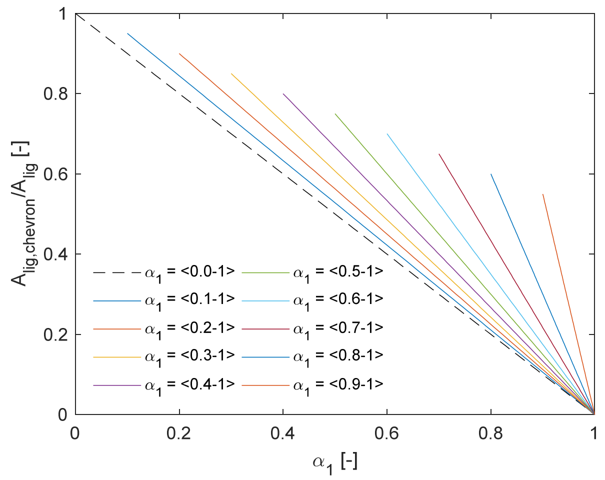


Fig. 5: Influence of the parameter α_1 on the ligament area A_{lig} of the sharp checron notch.

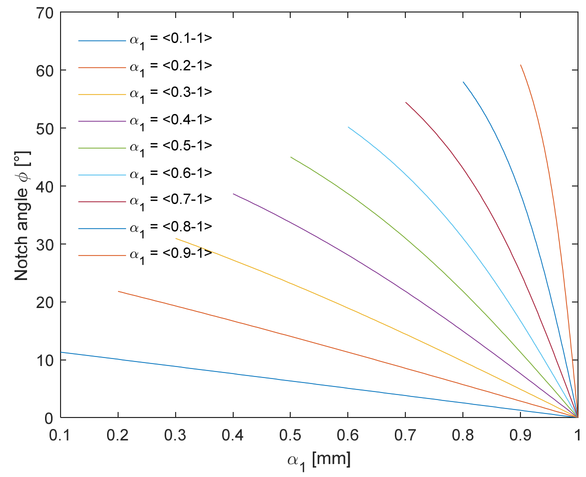


Fig. 6: Influence of paramter α_1 on the notch angle ϕ of the sharp chevron notch.

The development of the ligament area for blunt chevron notch over the parameter α_1 is presented in Fig. 7.

In case of the blunt chevron notch, the notch angle φ is not only influenced by α_1, but also by parameter β (2b/B i.e. the length of the straight edge). This was investigated by a constant value and changing values of parameter α_1, while the parameter α was set to 0 over the various parameter β. The influence of constant value of parameter α_1 on the notch angle φ is shown in Fig. 8, while the influence of the various parameter α_1 on the notch angle φ is presented in Fig. 9.

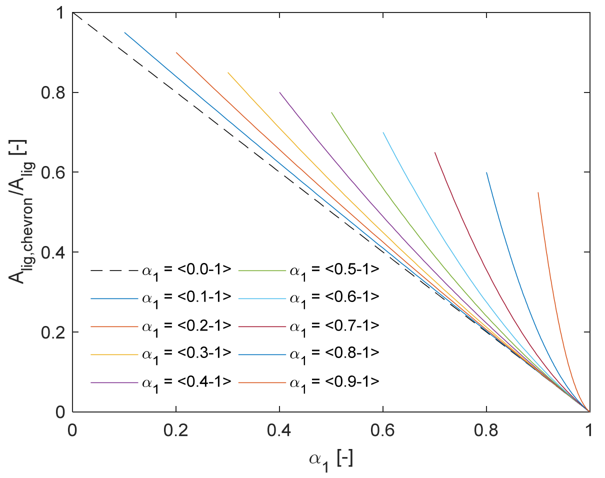


Fig. 7: Influence of the parameter α_1 on the ligament area of the blunt chevron notch.

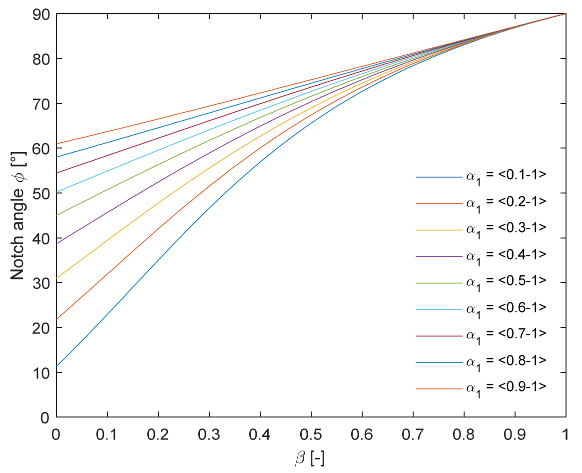


Fig. 9: Influence of the constant parameter α_1 on the notch angle φ for blunt chevron notch for a $\alpha = 0$.

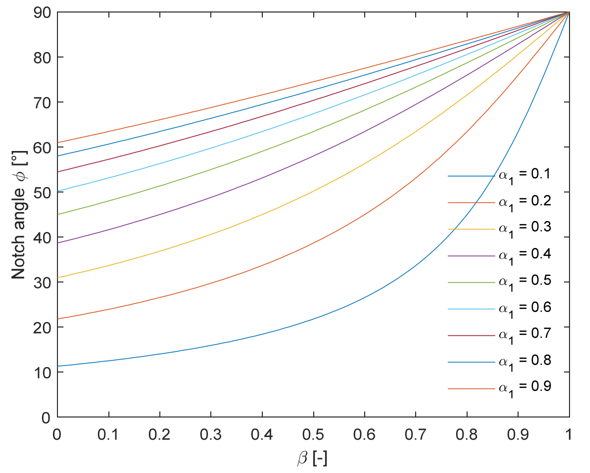


Fig. 8: Influence of the constant parameter α_1 on the notch angle φ for blunt chevron notch for a $\alpha = 0$.

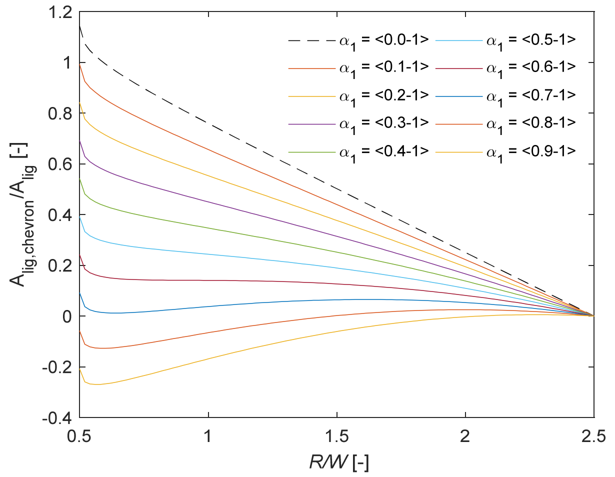


Fig. 10: Influence of the ration R/W on the sharp chevron notch's ligament area with round edges for various α_1 paremters.

From both figures 8 and 9 it can be observed, that the angle φ is equals to 90° when the $\beta = 1$. This is again in agreement with general expectation. However, the development of angle φ is different in both cases. This should be considered in the process of specimen preparation.

3.2. Chevron Notch with Round Edges

In case of chevron notch with round edges, the difference in the size of radius R can influence the ligament area with greater influence than any other geometry parameter. Therefore, this was analyses for both cases of sharp and blunt chevron notch with round edges by changing the parameter α1 from 0 to 0.9. The results are presented in dimensionless ratio of $A_{lig,chevron}/A_{lig}$ over the ratio R/W. The ratio R/W was selected from 0.5 to 2.5 time the width of the specimen. The results for sharp chevron notch with the round edges is shown in Fig. 10 and the results for the blunt case are shown in Fig. 11.

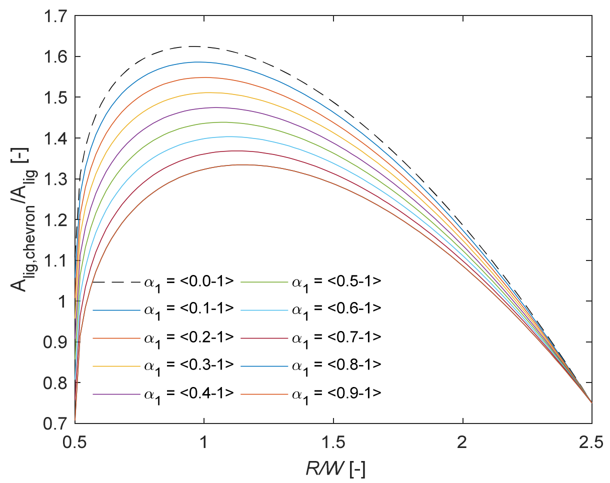


Fig. 11: Influence of the ration R/W on the blunt chevron notch's ligament area with round edges for various α_1 paremters.

The results shown in Fig. 10 have similar trend as results shown for the sharp edge chevron notch i.e. the ligament area decreases with the increasing R/W ratio.

However, the results presented in Fig. 11 are influenced by parameter β, which again varied from 0 to 1. These results should be taken into account the process of specimen preparation or in the experiment measurement, where the coarse aggregate can cause the ligament area reduction. This ligament area reduction has a major influence on the experimental measurement of fracture energy G_F.

3.3. Constant Notch Angle φ

The relative change of the ligament area of the chevron notch specimen was calculated as a $A_{lig,chevron}/A_{lig}$, where A_{lig} was calculated for a constant value of the a_0. The difference of the ligament areas is shown in Fig. 5.

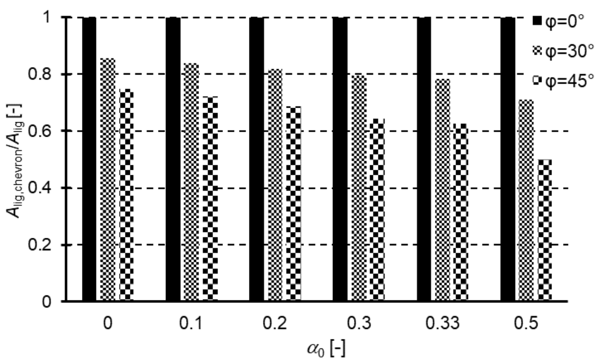


Fig. 12: Comparison of the difference of the ligament area for the sharp chevron notch with straight edges and with a constant α_0 value and angles $\varphi = 0°$ (straight through notch); 30° and 45°.

It is visible in Fig. 12, that with increasing value of α_0 the difference gets higher up to 50% of the ligament area. This means (for material with given fracture energy $G_F = \text{const.}$) that the specimen with the straight through notch consumes more work energy in the fracture process than the specimen with the chevron notch. The value of A_{lig} is for the relative crack length $a_0/W = 0.5$ almost two times smaller in case $\varphi = 45°$.

For the blunt chevron notch with $a_0/W = 0.1$, the decreasing areas are presented in Fig. 13, where the A_{lig} is calculated with constant value of $\alpha_0 = 0.1$.

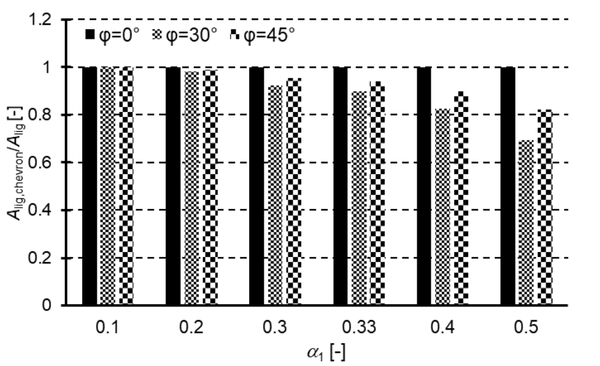


Fig. 13: Comparison of the difference of the ligament area for the blunt chevron notch with straight edges with a constant α_0 value and angles $\varphi = 0°$; 30° and 45°.

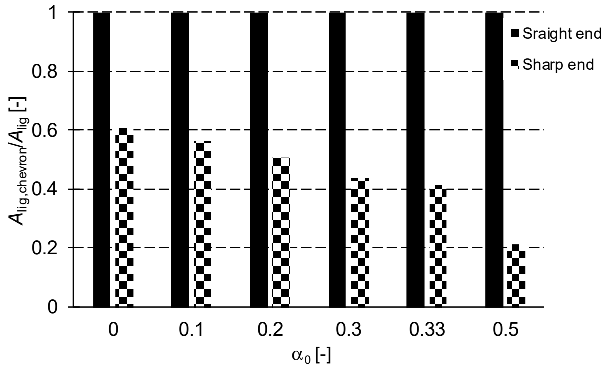


Fig. 14: Comparison of the difference of the ligament area for the chevron notch with a round edges and sharp ending for various α_0.

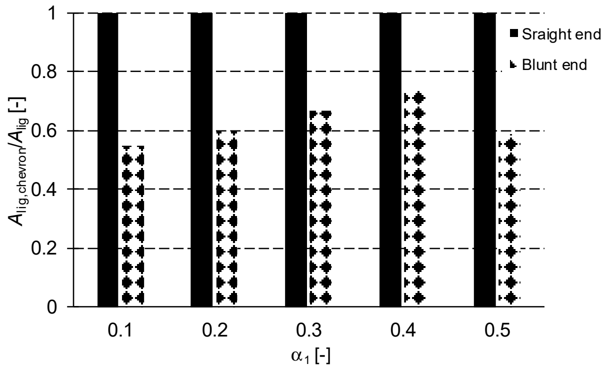


Fig. 15: Comparison of the difference of the ligament area for the chevron notch with a round edges and blunt ending for various α_1 with a constant $\alpha_0 = 0.1$ value.

From Fig. 15 and Fig. 16, it is visible, that the similar observation of the decreasing trend of the ligament area can be drawn for chevron notch with round edges.

4. Example for Specimen with $W = 100$ mm

A dimension of typical specimen with a square cross-section have been employed to investigate the influence of the ligament area. The width W of the specimen was set to 100 mm and radius R of the round edges was set to 50 mm. In order to be able to compare experimental measurement on the chevron specimens with the standardized specimen an equivalent notch length a_{eq} was calculated as W-$A_{lig,chevron}/B$. The equivalent notch length for sharp notch is shown in Fig. 16 and for the blunt notch in Fig. 17.

For the standard 3PB test with initial notch, the researchers use typically two relative lengths of initial straight notch $a_0/W = 0.33$ and 0.5, for the application similar value of area for 3PB with this sharp chevron notch, we could use $a_0/W = 0.185$ for $\varphi = 30°$, $a_0/W = 0.08$ for $\varphi = 45°$, $a_0/W = 0.355$ for $\varphi = 30°$, $a_0/W = 0.25$ for $\varphi = 45°$ respectively.

Same conclusion can be drawn for the case with chevron notch with round edges. Equivalent length of the initial notch a_{eq} for straight through notch of $a/W = 0.3$ and

$a/W = 0.5$ can be evaluated for the sharp end can be as follows $a_0/W = 0.0$ (chevron notch tip exactly at the edge of the cross-section) and $a_0/W = 0.1$. For the case with round edges and blunt end the equivalent initial notch a_{eq} with constant value of $\alpha_0 = a_0/W = 0.1$ and $\alpha_1 = a_1/W = 0.1$ produces a_{eq} to be same as for $a/W = 0.5$ for straight through notches. This effect can be seen in Fig. 18.

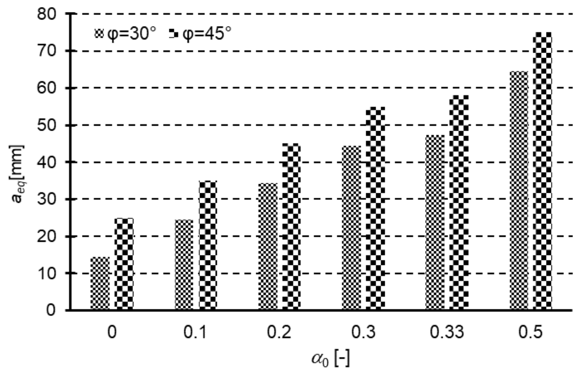


Fig. 16: Comparison of the equivalent notch length a_{eq} for each α_0 for chevron notch with straight edges.

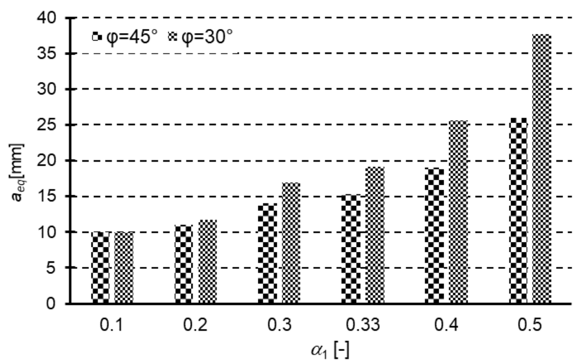


Fig. 17: Comparison of the equivalent notch length a_{eq} for each α_1 for chevron notch with straight edges.

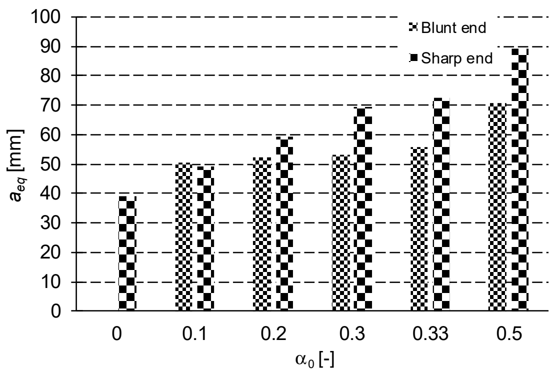


Fig. 18: Comparison of the equivalent notch length a_{eq} for each α_0 for chevron notch with round edges with sharp and blunt ending.

5. Conclusion

In this contribution the influence of chevron notch shape on the total ligament area was studied. From the presented results a following conclusion can be made.

From parametric study in can be concluded, that the ligament area decreases with the increasing α_1 parameter in case of all investigated cases. The influence of the α_1 parameter on the notch angle φ was studied. The results in case of sharp edge chevron notch, shows expected trend, while in the case of blunt chevron notch, the angle φ is influenced by parameter β.

In the case of the chevron notch with the round edges, the ligament is greatly influenced by the radius R and in case of blunt notch by the parameter β.

The results presented for parameter β, should cover the influence of the unintentional mistake in the manipulation of the saw during the specimen preparation.

The result presented for a typical specimen showed again the expected results in case of equivalent notch length a_{eq}.

The ligament area is influences by various geometry parameters, which should be taken in to account during the experimental measurement and in the evaluation of the experimental results. The experimental results can be influenced by other effects like heterogeneities of concrete (pores, aggregate), the human factor during the specimen preparation and the separation of the coarse aggregates during the experimental measurement.

The analytically obtained results were used e.g. for evaluation of data for alkali activated concrete tested by using tree point bending specimen with chevron notch, see [19].

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