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GENERALIZED BLOCK FAILURE

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Abstract: Block tearing is considered in several codes as a pure block tension or a pure block shear failure mechanism. However in many situations the load acts eccentrically and involves the transfer of a substantial moment in combination with the shear force and perhaps a normal force. A literature study shows that no readily available tests with a well-defined substantial eccentricity have been performed. This paper presents theoretical and experimental work leading towards generalized block failure capacity methods. Simple combination of normal force, shear force and moment stress distributions along yield lines around the block leads to simple interaction formulas similar to other interaction formulas in the codes.

1 Introduction

The current codes do not consider the effect of eccentric load in block tearing in an adequate manner. Pure tension block tearing and pure shear block tearing are codified. However the exact position of the acting shear force or the related point of zero moment is not considered. If the connection is loaded eccentrically in shear, then the codes typically introduce a simple reduction factor on the net tension area irrespectively of the magnitude of the eccentricity. This is inappropriate from a static point of view. The typical shear connections will be loaded by a moment of a certain magnitude determined by the connection stiffness and the overall structural behaviour. A designer should base all his structural analysis on consistent models of the structure with specific assumptions of stiffness and points of zero moment; this allows him to assess the design loads also for the connections. In Fig. 1 the block tension and block shear failure mechanisms are illustrated. It can be seen that the position of the shear force is not defined and especially the connection illustrated to the right in the figure has substantial eccentricities.

Theoretical work leading towards generalized capacity methods including the combined influence of normal force, shear force and moment on the block tearing capacity of gusset and fin plate connections will be presented and exemplified in this paper. In fact plasticity based methods including the influence of the moment have previously been described briefly in a few steel design text books and practicing structural engineers normally do perform additional design checks in order to verify the moment transfer capacity; especially when using the traditional gusset plate connections shown to the right in Fig. 1.

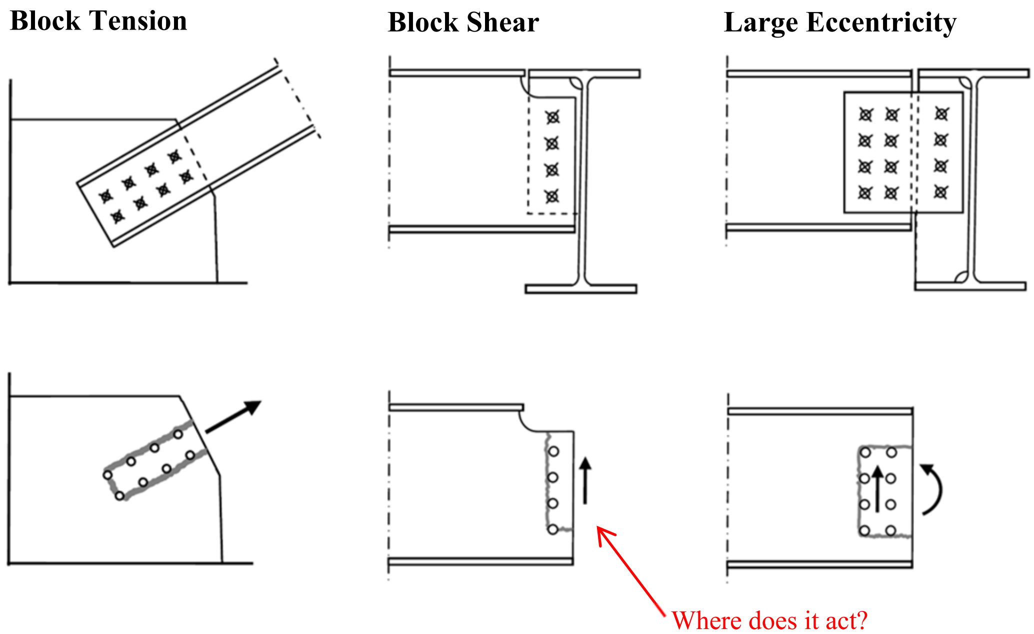

Fig. 1: Gusset and fin plate connections and relevant blocks for block tearing.

The presented work focuses on the development of a few simple block failure capacity formulas and a set of relevant interaction formulas with a format related to those already in use for cross section analysis in the Eurocodes. The practical formulations are most efficiently based on a simple generalization of the current method using very simple stress distributions along the yield lines surrounding the block in combination with a simplified yield condition to be fulfilled along these lines. It is assume that the surrounding plate material is able to sustain these stresses without violating the Von Mises yield criterion. This is to be assured by separate design checks. The blocks considered are C-block and L-block cut-outs. The generalized method is not a rigorous theoretical lower bound method, but an approximate method. The experimental part of this paper only discusses the C-block cut-out. Due to varying strain hardening along the yield lines the final block failure mode may be calculated based on an increased yield stress, which is a function of the material yield stress and the material ultimate stress, e.g. for example the mean value of these. Based on the literature study it seems plausible to use yield lines lying on the outer side of the bolt holes. However normal stress across a yield line cannot be transferred through the bolt holes, but note that compression across a yield line is more complex since the bolt in a bolt hole transfers its force to the outside of the block and the presence of the holes will have much less influence in this case. Since the bolts in an outer bolt line transferring shear also spreads its loads both in to and out of the block it is also a reasonable assumption that shear transferred through the bolt lines may be assumed to act without considering the influence of the holes. All these observations seem to agree with the experimental evidence of the past and the current investigations. Some of the observations will be discussed in connection with the following short review of relevant literature.

2 Literature observations

A paper from early research into block tearing which stands out is the one by Harash & Bjorhovede [1] from 1985. They report primarily on the investigation of tension block tearing and suggested that the connection length governs the magnitude of the effective shear stress to be used. Thus the shear strength varies between the yield shear strength and the ultimate shear strength depending on the length of the connection. The paper reports tests on 28 gusset plate specimens all with concentric tension load and further includes results form 14 other tests. All these 42 tests are used to verify the suggested equation for the ultimate capacity, F_R, which may be given as:

$$F_R = f_u A_{nt} + \frac{f_{eff}}{\sqrt{3}} A_{gv} \tag{1}$$

where A_{nt} and A_{gv} respectively are the net area in tension and the gross area in shear. The effective shear stress is given by

$$f_{eff} = (1 - C_l) f_y + C_l f_u \tag{2}$$

where $C_l = 0.95 - 0.047 \cdot l \geq 0$ with l as the connection length in inches, the material yield strength is given by f_y and the ultimate material strength by f_u. Note that this formula uses the gross shear area with an efficient strength varying between yield and ultimate stress along this line depending on the connection length. However the influence of the connection length may well be due to the elastic deformation along long connections. The paper investigates several positions of the yield lines around the block.

Investigations into coped beams are reported by Franchuk et al [2] in 2003. Different parameters and their influence on the L-block tear-out shear capacity for coped beams were investigated. The paper supports previous papers that suggest that the tension contribution should be reduced by 50% for eccentric load due to non-uniform stress distribution. The experimental tests showed that the shear failure happens very close to the gross shear area along the outer side of the bolt holes and it seems to document that the position of the block shear failure is to be based on the net area for the tension failure line A_{nt} and the gross area for the shear failure area A_{gv}. It is concluded that end rotation does not have a significant influence on the capacity. However the test setup is not representative for all types of fin or gusset plate beam connections and it is statically not well defined, with a complicated test setup.

Three papers [3], [4] and [5], published in the years 2001-2006 by a coinciding group of authors Kulak, Grondin, Huns and Driver are highly referenced. These authors have used available experimental data in order to compare experimental test results to different standards, equations suggested by other papers and their own suggested equations. The papers have varying focus. Test results are collected and compared to the American, Canadian, European and Japanese Standard and the experimental data are categorized in connection types as gusset plates, angles, coped beams with one bolt line and coped beams with two bolt lines. It is also stated that the connection length does not have any influence on the capacity for coped beams.

The third paper by Driver et al. [5] suggests an equation in which the position of the shear failure line is along the outer edge of the bolt holes, i.e. a gross length, as suggested by Franchuk et al. [2] and further that the shear strength is developing beyond the yield strength but not fully up to the ultimate strength. The paper comments on standards and published papers, which have not been able to agree upon a similar consistent approach towards the determination of the block shear capacity. The paper decomposes the experimental data into 3 separate categories: gusset plates, coped beams and angles. The suggested equation is the same for all of the categories; however the constants depend on the connection type. The suggested equation for the resistance is:

$$F_R = R_t f_u A_{nt} + R_v \left(\frac{f_y + f_u}{2\sqrt{3}} \right) A_{gv} \tag{3}$$

where R_t and R_v are constants determined by the connection category as given in Table 1. As seen the average between ultimate and yield strength is used and considered conservative. The paper also states that the effect of the length of the connection is inconclusive and should therefore not be taken into account. This is probably caused by the difference in transfer of shear stresses to the shear yield line, where the shear stress is associated with elastic elongation in the case of tension gusset plate connections.

Table 1: Constants for equation (3) from Driver et al [5]

Connection type	R_t	R_v
Gusset plates	1	1
Angles and tees	0.9	0.9
Coped beams: one bolt line	0.9	1
Coped beams: two bolt lines	0.3	1

To sum up the crucial conclusion of the literature observations is that no papers have been dealing with complex loading including substantial eccentricities and general block failure. It seems very inappropriate just to introduce a reduction factor of 0.3, 0.5 or 0.9 on the tension area in the L-shaped block failure modes in order to accommodate eccentric loading with its magnitude remaining unquantified.

3 Proposed generalized block tearing method

In the following a simple generalization of block tearing analysis is proposed in order to account for a combination of section forces acting on a block to be torn out. Let us generalize block tearing by assuming simple stress traction distributions of normal stress, σ, and shear stress, τ, along the boundaries of the block corresponding to normal force, shear force and moment acting on the block at yielding around the whole block. Let us furthermore assume that the stress tractions on the block have to fulfil the formal yield condition

$$\sigma^2 + 3\tau^2 \leq f_m{}^2 \tag{4}$$

where f_m is a formal yield stress of $f_m=(f_y+f_u)/2$ corresponding to the mean value of the yield stress and the ultimate stress. The straining of the yield lines varies along each line and strain hardening will commence before the yield mechanism has fully formed, therefore a formal yield stress f_m is used. The assumed formal yield condition is not theoretically complete since it does not include the tangential stress component along the yield line. This is accepted. Note that this is also an issue for the current normal force and shear force block shear formulas.

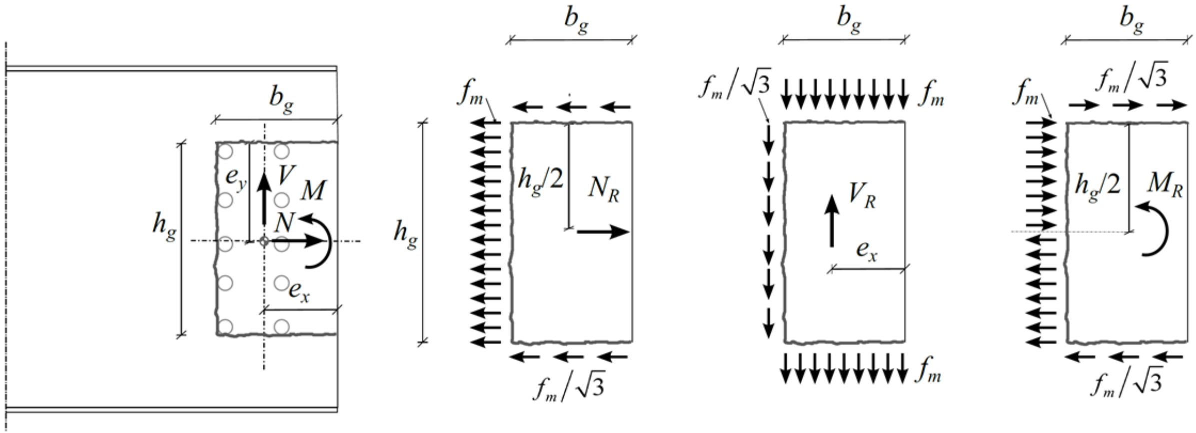

Fig. 2: Normal and shear stress distributions for block tearing forces and moment in a C-cut-out.

Three relatively simple block failure situations for a C-cut-out and for a L-cut-out are shown respectively in Fig. 2 and Fig. 3, in each case corresponding to the normal force N_R, the shear force V_R and the moment M_R block tearing capacities. Based on experimental observations and the fact that the bolt forces in the outer bolt lines also have to be included and may act both into and out of the block, it is assumed that the holes are just inside the block and the outer gross dimensions are given by h_g and b_g. The thickness of the plate is denoted by *t.* The related net lengths h_n and b_n are found by deducting the diameter of all the holes along each length. Furthermore it is assumed that the normal stresses are acting on a reduced section which is given by the gross lengths and a reduced thickness corresponding to the net area ratio, i.e. $t_h = t\,h_n/h_g$ and $t_b = t\,b_n/b_g$ along the respective lines. This assumption leads to a relatively simple way of determining the capacities and including the effect of the holes with respect to the normal stress distribution.

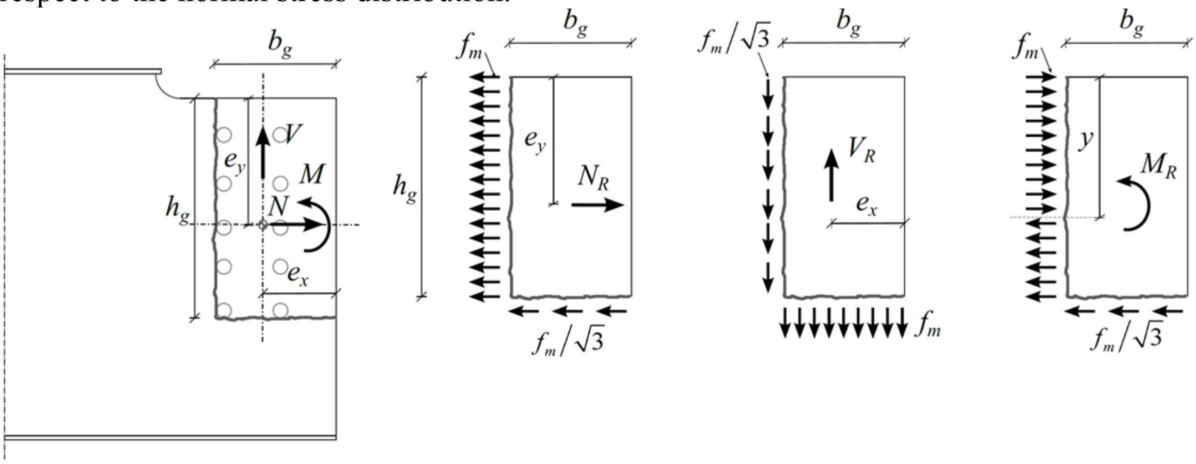

Fig. 3: Normal and shear stress distributions for block tearing forces and moment in a L-cut-out.

The point of action of the forces acting on the block is found by requiring moment equilibrium of the acting section force and the related stress distribution around the block. The position of the point is shown in Fig. 2 and Fig. 3 as the two distances e_x and e_y . These distances can be found as:

$$\left.\begin{aligned} e_x &= \frac{b_g\left(b_n + h_g/\sqrt{3}\right)}{2b_n + h_g/\sqrt{3}} \\ e_y &= h_g/2 \end{aligned}\right\}\text{ for a C-cut-out,}\qquad \left.\begin{aligned} e_x &= \frac{b_g\left(b_n + 2h_g/\sqrt{3}\right)}{2b_n + 2h_g/\sqrt{3}} \\ e_y &= \frac{h_g\left(h_n + 2b_g/\sqrt{3}\right)}{2h_n + 2b_g/\sqrt{3}} \end{aligned}\right\}\text{ for a L-cut-out} \tag{5}$$

The three basic block tearing capacities can be found by the following simple formulae:

$$\left.\begin{aligned} N_R &= tf_m\left(2\frac{b_g}{\sqrt{3}} + h_n\right) \\ V_R &= tf_m\left(2b_n + \frac{h_g}{\sqrt{3}}\right) \\ M_R &= th_g f_m\left(\frac{b_g}{\sqrt{3}} + \frac{h_n}{4}\right) \end{aligned}\right\}\text{ for a C-cut-out,}\quad \left.\begin{aligned} N_R &= tf_m\left(\frac{b_g}{\sqrt{3}} + h_n\right) \\ V_R &= tf_m\left(b_n + \frac{h_g}{\sqrt{3}}\right) \\ M_R &= tf_m h_g\left(\frac{b_g}{2\sqrt{3}} - \frac{b_g^{\,2}}{12h_n} + \frac{h_n}{4}\right) \end{aligned}\right\}\text{ for a L-cut-out} \tag{6}$$

By scaling the three basic stress distributions in Fig. 2 or Fig. 3 by N/N_R , V/V_R and M/M_R respectively and checking the formal yield condition in equation (4) along all yield lines shows us that only the following interaction formula needs to be fulfilled:

$$\left(\frac{N}{N_R}+\frac{M}{M_R}\right)^2+\left(\frac{V}{V_R}\right)^2\leq 1 \tag{7}$$

Other basic stress distributions may be found that fulfill the formal yield condition to a greater extent during interaction, however this typically results in multiple interaction formulas.

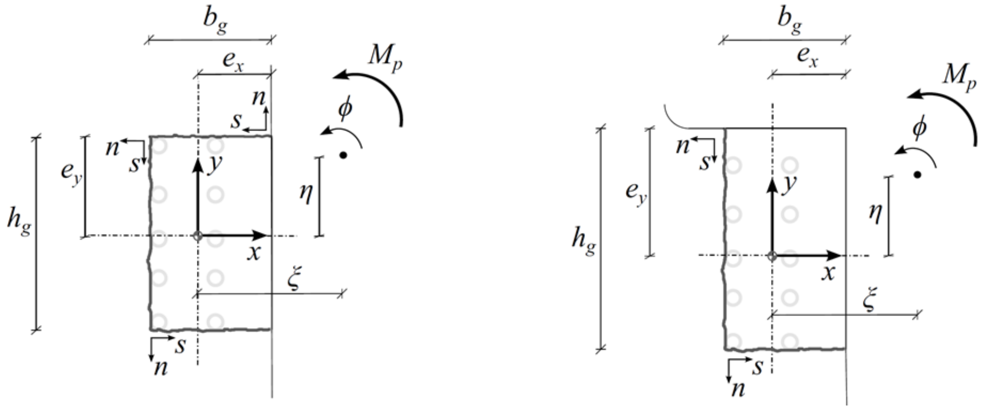

Fig. 5: Geometry, coordinate systems and point of rotation for upper bound estimation.

4 Upper bound yield line method

Assuming that the plate material behaves as a rigid plastic material and that yielding is governed by the Von Mises plane stress yield surface with the use of the normality equation, it can be shown that the rate of energy dissipation in a point of a yield line (narrow band with linear variation of the strains) is given by

$$\dot{w}_{pl}=\frac{2}{\sqrt{3}}f_m t\sqrt{\dot{u}_n{}^2+\tfrac{1}{4}\dot{u}_s{}^2} \tag{8}$$

In which $\dot{u}_n$ is the rate of relative normal displacement and $\dot{u}_s$ is the rate of relative tangential displacement at the given point of the yield line. The block plate and the surrounding plate are assumed to be rigid and have a given relative displacement. Along a straight yield line between the rigid parts with small relative rotations it may be assumed that the relative normal displacements u_n vary linearly and the relative tangential displacements u_s are constant. Introducing a local (*n, s*)-coordinate system, see Fig. 5, along each straight yield line of length l with a rate of relative normal displacement $\dot{u}_{n0}$ at the origin of the yield line and an inclination rate $\dot{\phi}$; the rate of energy dissipation of one straight yield line is given by:

$$\dot{W}_{pl}=\frac{2}{\sqrt{3}}f_m t\int_0^l\sqrt{(\dot{u}_{n0}+\dot{\phi}s)^2+\tfrac{1}{4}\dot{u}_s{}^2}\,ds \tag{9}$$

An (*x, y*)-coordinate system is introduced in the block with origin given by the edge distances (e_x, e_y). If these are chosen as given in equation (5) of the previous section the connection forces will have the same reference point and results may be compared. The relative displacements will be described through the use of a point of relative rotation (ξ, η) and a relative rate of rotation $\dot{\phi}$ as illustrated in Fig. 5. The work performed will of course be influenced by the presence of bolt holes and the bearing forces transferred by each bolt. In this upper bound approach we will represent the reduction in the dissipated energy or work performed approximately by using an effective thickness, so that the thickness will be represented by the relative area reduction, due to bolt holes, i.e. either $t_h=t\,h_n/h_g$ and $t_b=t\,b_n/b_g$ along the respective yield lines. In fact this means that the energy dissipation related to the tangential displacement terms at the bolt holes is neglected compared to the generalized method described in the previous section. The energy dissipation rate of the yield lines of a C-cut-out can be found as:

$$\dot{W}_{C,\text{int}} = \frac{2}{\sqrt{3}} f_m t \left(\frac{b_n}{b_g} \int_0^{b_g} \sqrt{(-\xi + e_x - s)^2 + \tfrac{1}{4}(e_y - \eta)^2}\, ds + \frac{h_n}{h_g} \int_0^{h_g} \sqrt{(e_y - \eta - s)^2 + \tfrac{1}{4}(b_g - e_x + \xi)^2}\, ds + \frac{b_n}{b_g} \int_0^{b_g} \sqrt{(\xi + b_g - e_x - s)^2 + \tfrac{1}{4}(\eta + h_g - e_y)^2}\, ds \right) |\dot{\phi}| \quad (10)$$

The energy dissipation rate of the yield lines of the L-cut-out can be found as:

$$\dot{W}_{L,\text{int}} = \frac{2}{\sqrt{3}} f_m t \left(\frac{h_n}{h_g} \int_0^{h_g} \sqrt{(e_y - \eta - s)^2 + \tfrac{1}{4}(b_g - e_x + \xi)^2}\, ds + \frac{b_n}{b_g} \int_0^{b_g} \sqrt{(\xi + b_g - e_x - s)^2 + \tfrac{1}{4}(\eta + h_g - e_y)^2}\, ds \right) |\dot{\phi}| \quad (11)$$

The external energy dissipation rate $\dot{W}_{ext}$ depends on all three connection forces, *N*, *V* and *M* and is given as the rate of work of the moment, $M_p(\xi,\eta) = M - N\eta + V\xi$, acting at the point ($\xi$, η) through the relative rate of rotation. The external energy dissipation rate is given as:

$$\dot{W}_{ext} = M_p \dot{\phi} = \left(M + N\eta - V\xi\right)\dot{\phi} \quad > 0 \quad (12)$$

Setting the rate of external energy dissipation equal to the rate of internal energy dissipation allows us to find the point of relative rotation (ξ,η) by minimizing the magnitude α of any given combination of connection forces *N, V* and *M*. Thus we find the scaling factor α of the given connection forces at which the block yielding capacity is reached by solving the minimization problem:

$$\text{Minimize } \alpha(\xi,\eta) = \frac{W_{\text{int}}(\xi,\eta)}{W_{ext}(\xi,\eta)} \quad (13)$$

For a given geometry this allows us to determine upper bounds for pure normal force, pure shear force and pure moment and furthermore also the yield surface for interaction for any combination of connection forces. Thus we may assess whether the generalized yield surface is plausible for this geometry. Simple analytical upper bound solutions based on effective thickness can be calculated for pure normal force and pure shear force as:

$$\left.\begin{aligned} N_{R*} &= \frac{2}{\sqrt{3}} t f_m \left(b_n + h_n\right) \\ V_{R*} &= \frac{1}{\sqrt{3}} t f_m \left(4b_n + h_n\right) \end{aligned}\right\} \text{ for a C-cut-out,} \qquad \left.\begin{aligned} N_{R*} &= \frac{1}{\sqrt{3}} t f_m \left(b_n + 2h_n\right) \\ V_{R*} &= \frac{1}{\sqrt{3}} t f_m \left(2b_n + h_n\right) \end{aligned}\right\} \text{ for a L-cut-out} \quad (14)$$

For the C-cut-out the capacity values of both these values and the generalized method can be compared in Table 2 for the tested geometry. It can be seen that both the normal and shear force upper bound capacities are lower than the capacities determined by the generalized method. This is coursed to the assumption concerning the reduction of shear force.

5 Experimental investigations and comparison for a C-cut-out

An experimental test setup has been designed and block failure experiments on bolted connections have been performed and reported in the B.Eng. project and thesis by Nissen [6]. The tested connections have been designed in order to assure that block failure was the decisive mode of failure. Twelve tests were performed on three different loading configurations with the same bolt group of 4x3 M12 bolts (10.9) in 14mm holes. The test setup is illustrated to the left in Fig. 6 and to the right a photograph of block tearing found in the experiment is shown. The geometric, material and capacity parameters are given in Table 2 for the tested connections.

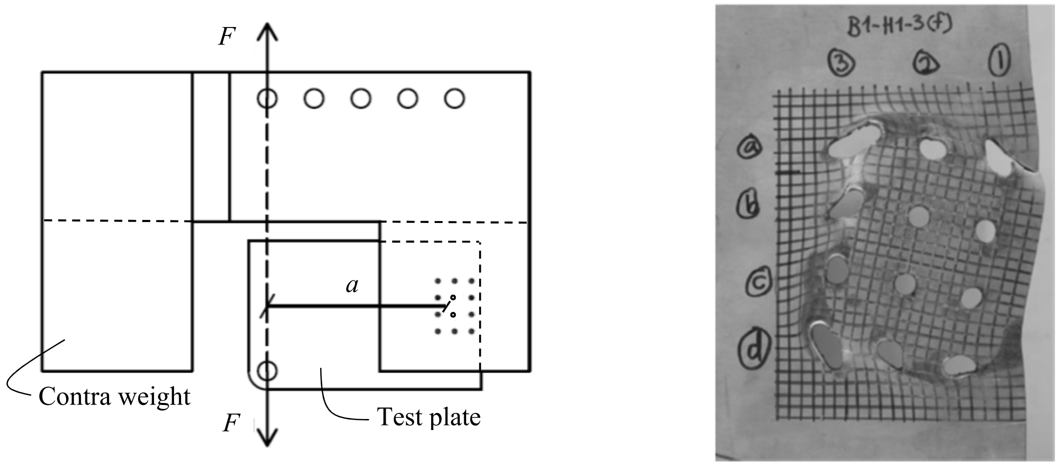

Fig. 6: Experimental test setup and photograph of block failure found in experiment.

Table 2: Geometric, material and theoretical capacity parameters for tested C-cut-outs.

h_g [mm]	h_n [mm]	b_g [mm]	b_n [mm]	e_x [mm] (5)	e_y [mm] (5)	f_y [MPa]	f_u [MPa]	f_m [MPa] See (4)	N_R [kN] (6)	V_R [kN] (6)	M_R [kNm] (6)	N_{R*} [kN] (14)	V_{R*} [kN] (14)	M_{R*} [kNm] (13)
138	84	122	82	81	69	272	375	324	727	782	40.8	616	762	43.6

*"upper bound"

In this paper only results corresponding to the test setup shown to the left in Fig. 6 will be treated. In these tests the experimental loading corresponds to zero normal force N=0, a shear force of $V=F$ applied with a fairly large eccentricity a in relation to the shear distribution centre resulting in a connection moment of $M=aF$. Using the proposed interaction formula (7) for generalized block tearing the capacity with respect to F becomes:

$$F_R = \left[\left(\frac{a}{M_R} \right)^2 + \left(\frac{1}{V_R} \right)^2 \right]^{-0.5} \tag{15}$$

The capacity with respect to the upper bound method is found using equation (13) equation.

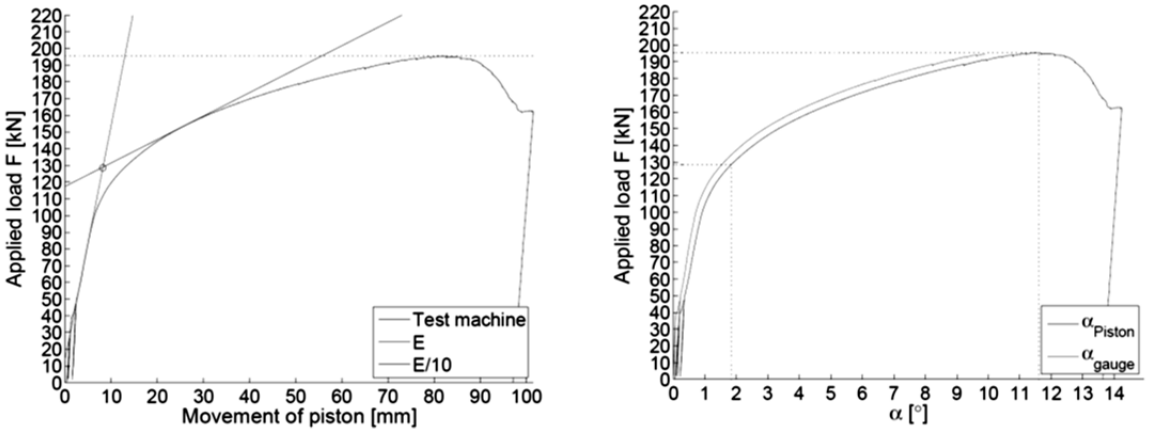

Fig. 7: Applied load verses piston movement to the left and verses the angle of rotation to the right.

The experimental mechanism yield load $F_{exp,y}$ is determined as the intersection point of the observed linear initial inclination (stiffness) and a tangent line with 10% of this inclination just touching the upper part of the curve (corresponding to 10% hardening), see Moore et al [7]. The ultimate capacity is just the maximum achieved load $F_{exp,u}$. The applied test load verses the piston movement and the applied load verses the approximate angle of rotation are shown in Fig. 7 for test B1-H1-3(f). The capacities found using the proposed generalized block tearing method, the upper bound plasticity method and the experimental results of the nine similar tests are shown in Table 3. These results all correspond to a relatively large eccentricity and thereby a large connection moment, which dominates the solution completely.

Table 3: Capacities found by generalized block tearing, upper bound and experimental methods.

Test	a	F_R	F_{R*}	$F_{exp,y}$	$F_{exp,u}$	$F_R/F_{exp,y}$
	[mm]	[kN]	[kN]	[kN]	[kN]	[-]
B1-H1-1(f)	393	103	107	136	-	0.76
B1-H1-2(f)	393	103	107	129	194	0.80
B1-H1-3(f)	393	103	107	129	196	0.80
B1-H1-4	393	103	107	126	192	0.82
B1-H1-5	393	103	107	124	197	0.83
B1-H1-6	393	103	107	125	193	0.82
B4-H1-1	267	150	154	184	284	0.82
B4-H1-2	267	150	154	184	281	0.82
B4-H1-3	267	150	154	192	281	0.78

*upper bound

The first three tests marked with (f) have been performed with 75% pre-stressed bolts. In all other tests the bolts have been tightened corresponding to snug-tight (~50%). The test B1-H1-3(f) was also reported in an initial reporting of these experiments at Eurosteel 2014 in [8].

6 Upper bound interaction surface for the tested C-cut-out

Using equations (10), (12) and (13) for determination of upper bounds for the block tearing capacity (based on the given assumptions) it is possible to create scatter plots illustrating the interaction between the connection forces, i.e. normal force, shear force and moment acting at the point (e_x, e_y) defined by the assumptions of the generalized block tearing method. To do this we introduce dimensionless parameters $n = N/N_{R*}$, $v = V/V_{R*}$ and $m = M/M_{R*}$ and find the capacity for an adequate span of scattered "directions" or force ratios (n, v, m). For interaction couples the interaction planes are shown in Fig. 8 and the whole upper bound yield surface is illustrated in Fig. 9.

7 Conclusion

Block tearing has been generalized to include section force interaction by a few simplifying assumptions. A theoretical plasticity based upper bound method has been used to verify the magnitude of the capacities and the interaction formula. Furthermore a small experimental investigation has been reported for a C-cut-out. The L-cut-out it still needs further verification. The overall geometry should be investigated by parametric variation to see if other stress distributions become relevant for both C- and L-block failure.

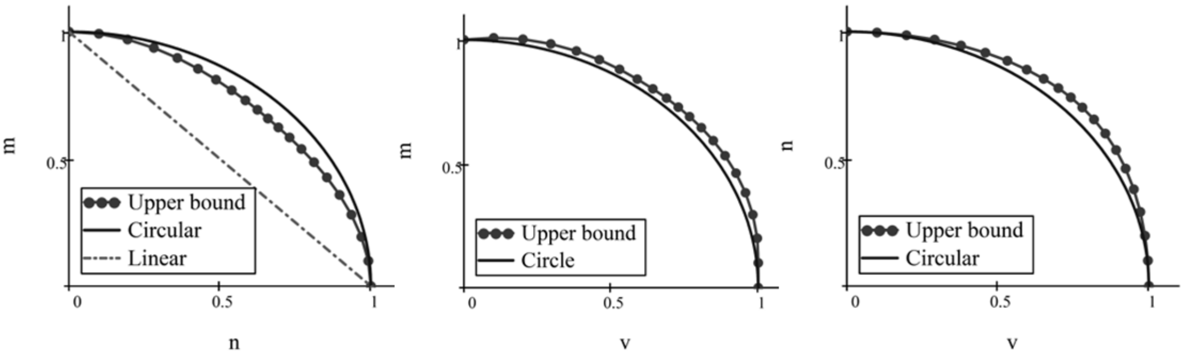

Fig. 8: Upper bound yield surface illustrated for the (n,*m*), (*v,m*) and (*v,n*) interactions planes.

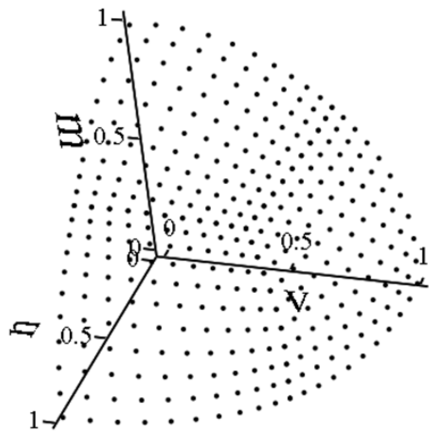

Fig. 9: Upper bound yield surface illustrated for the tested C-cut-out geometry.

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