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A new mixed mode fracture specimen (2MCG): numerical and experimental results

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Abstract. An original Mixed Mode Crack Growth specimen (2MCG) providing fracture stability during crack propagation is presented. This geometry is a complex compromise between CTS (Compact Tension Shear) and DCB (Double Cantilever Beam) fracture specimens. Using a CCD camera and a testing machine equipped with data acquisition system, an image analysis protocol allows to plot instantaneous crack propagation is performed and the Force-displacement curves are recorded. With these data, the forces-cracks lengths curves are plotted. As results, the experimental (obtained by the compliance method) and numerical (given by M integral in finite element) energy release rate are compared.

1. Introduction

In fracture mechanics, the one difficulty meet by the scientist community is to perform experimental tools providing of fracture characteristics as the crack length, the compliance variation or the energy release rate. These difficulties are reinforced on the one hand, by the complex solicitations, inducing crack growth process in mixed modes, and on the other hand, by the heterogeneous character, orthotropic properties or the viscoelastic behavior of wood material.

This work deals with an identification technique of fractures parameters with a new wood specimen using an image correlation method. The new geometry named Mixed Mode Crack Growth (2MCG) developed by Moutou Pitti [1,2,3] is a combination between DCB [4] and CTS [5] specimens. Its design is also due to the observation of a stability range of numerical energy release rate computed with M-integral [6] parameter by finite element process for different mixed mode ratios.

Firstly, in order to separate fractures modes in orthotropic media, the M-integral is recalled. In the second part, the design of the 2MCG specimen is presented. The thirds part shows the experimental device and the force-displacement curves in opening mode and mixed mode respectively. The device is composed with a LVDT sensor, a zwick testing machine with it acquisition system and a CCD camera recording images during the crack growth process. In this fact, the load-displacements curves are exploited in order to calculate the crack length and the corresponding critical energy release rate G_c using the compliance method. At the end, numerical and experimental data of G_c are confronted.

2. Integral parameter

In order to separate fracture mode during instantaneous crack growth process in timber structure, Moutou Pitti et al. [3,7] have proposed an adaption of the M-integral initially developed by Chen [8] and using Noether's theorem [9]. However, this integral is defined on a curvilinear contour. For plane configurations, the finite element method necessitates, for modeling reasons, a surface in term of integration domain. The transformation of the initial curvilinear integration domain into a surface is performed using the θ -method proposed by Destuynder [10]. The following expression is obtained:

$$M\theta = \frac{1}{2} \cdot \int_{\Omega} (\sigma_{ij}^{(u)} \cdot v_{i,j} - \sigma_{ij,k}^{(v)} \cdot u_i) \cdot \theta_{k,j} d\Omega \quad [1]$$

$\bar{\theta}$ is a vector field continuously derivable and defined around the crack tip [3]. $\sigma_{ij}^{(u)}$ and $\sigma_{ij}^{(v)}$ indicate the real and virtual stresses, respectively. In the same way, u and v are real and virtual displacements. In this context, the mixed-mode separation is obtained by performing two distinct calculations of real stress intensity factors ${}^u K_I$ and ${}^u K_{II}$ [3,6,7] for particular values of virtual stress intensity factors ${}^v K_I$ and ${}^v K_{II}$, such as:

$$\begin{aligned} {}^u K_I &= \frac{8}{C_1} \cdot [M\theta({}^v K_I = 1; {}^v K_{II} = 0)] \quad \text{and} \\ {}^u K_{II} &= \frac{8}{C_2} \cdot [M\theta({}^v K_I = 0; {}^v K_{II} = 1)] \end{aligned} \quad [2]$$

The energy release rate in opening and shear modes (G_1 and G_2 respectively) are given by:

$$G = G_1 + G_2 \quad \text{with} \quad G_1 = C_1 \cdot \frac{({}^u K_I)^2}{8} \quad \text{and} \quad G_2 = C_2 \cdot \frac{({}^u K_{II})^2}{8} \quad [3]$$

Where C_1 and C_2 are the elastics compliances in each fracture mode [6,7].

3. Mixed mode crack growth specimen

The new 2MCG specimen [1,2,3], Fig. 1, is a combination between the stable Double Cantilever Beam (DCB) specimen developed by Dubois [4] for opening modes, and the unstable Constant Tension Shear (CTS) specimen initially developed by Richard [11] for mixed modes in isotropic material, and adapted to wooden material by Valentin [5]. This design optimization is obtained using a finite element discretization. The wooden specimen is completed by two PVC Arcans providing symmetric loadings. Numeric results present a crack growth

stability range for elastic energy release rate versus crack length in mixed mode 45° (F_{I+II}). This fact enables us to obtain simultaneously, during creep crack experiments, viscoelastic characteristics and fracture parameters in the same geometry. The different proofs of this stability in all mixed mode configurations are shown by Moutou Pitti et al. [2,3].

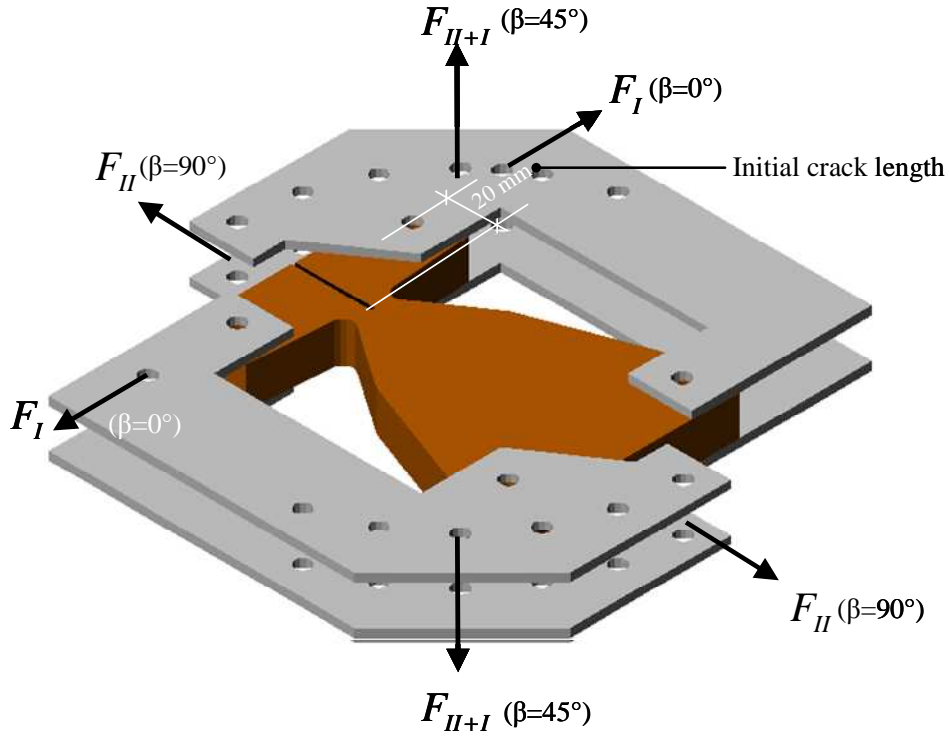


Fig. 1. Mixed Mode Crack Growth specimen (2MCG)

4. Numerical and experimental results

4.1 Force-displacements curves

The curves force-displacement are posted in Fig. 2 and Fig. 3 in opening mode ($\beta = 0^\circ$) and mixed mode ($\beta = 45^\circ$), respectively. The displacement is measured between the two points of force application with a LVDT sensor. These figures show us three distinct parts: a linear zone due to an elastic behavior according to a stationary crack. A second zone characterized by the different pop-in traducing the critical load F_C which causes a specific crack growth. The increasing pop-in proves the crack stability domain. At the end, we observe the crack growth instability inducing the final collapse of the specimen characterized by the failure force $F_R = 840 \text{ N}$ in mode I, and $F_R = 2975 \text{ N}$ in mixed mode, respectively.

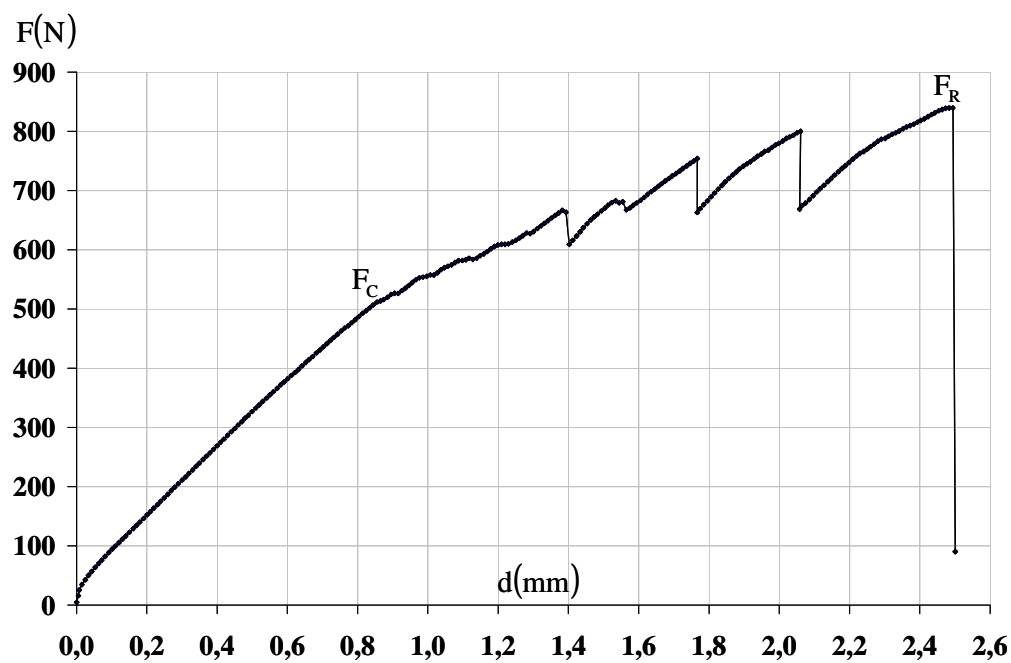


Fig. 2. Force-displacement curve in Mode I ($\beta = 0^\circ$)

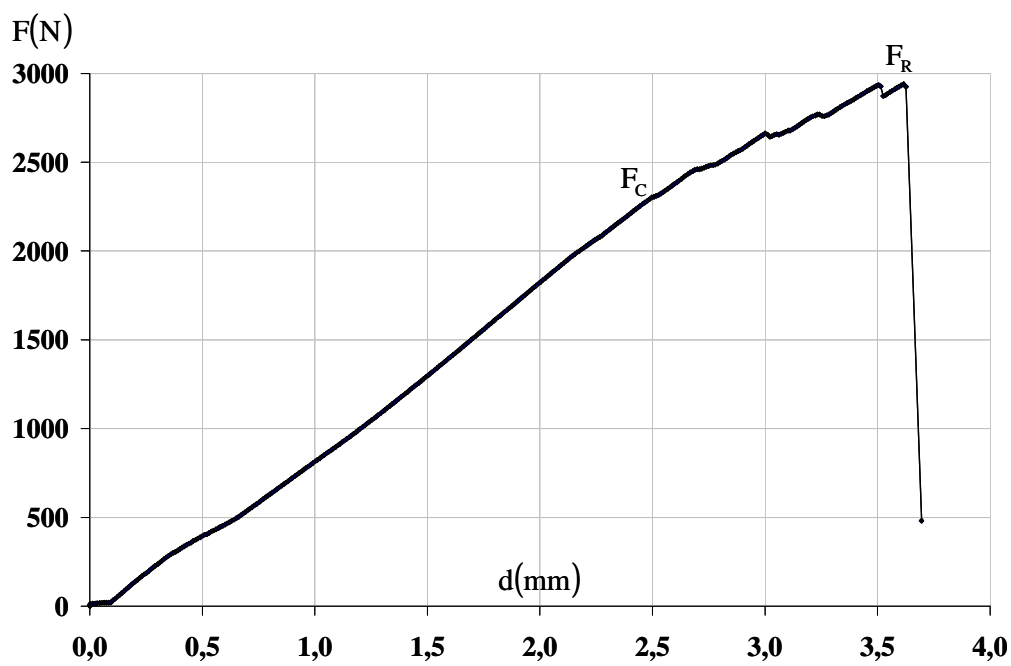


Fig. 3. Force vs. displacement in Mixed mode ($\beta = 45^\circ$)

4.2 Load-crack length curves

Fig. 4 and Fig. 5 present the evolutions of load versus crack length in opening mode ($\beta = 0^\circ$) and mixed mode ($\beta = 45^\circ$) respectively.

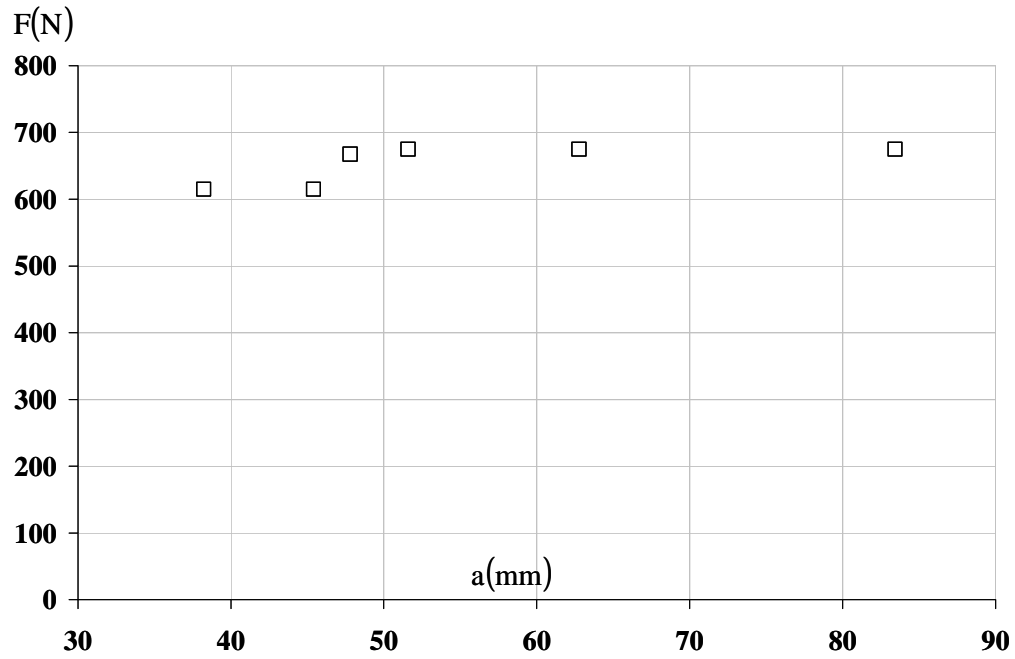


Fig. 4. Force vs. crack length in Mode I ($\beta = 0^\circ$)

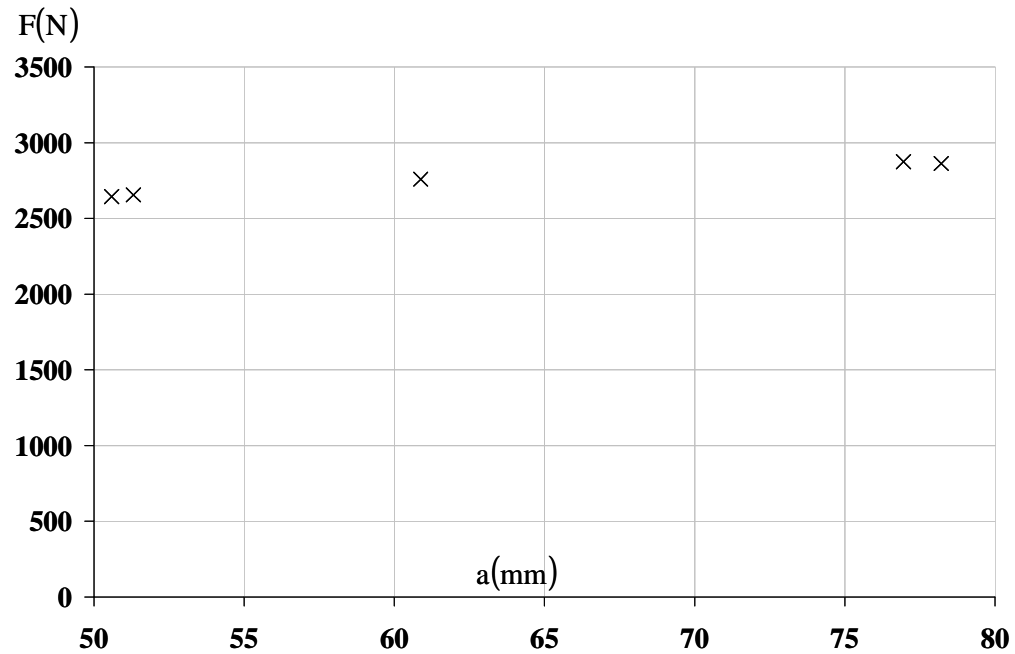


Fig. 5. Force vs. crack length in Mixed mode ($\beta = 45^\circ$)

The different points of these graphs are obtained with perfect synchronization between the critical loads F_C (given by the acquisition system) and the corresponding crack a (given by CCD camera). It's observed that the crack load F_R in mixed mode is four time superior than that in opening mode. Due to the importance of the pop-in, the crack growth range is more important in opening mode.

4.2 Energy release rate

In following results, the elastics modulus of wooden are: $E_x = 14100 \text{ MPa}$, $E_y = 400 \text{ MPa}$ and $G_{xy} = 300 \text{ MPa}$. Fig. 6 and 7 show us the different evolution of numerical and experimental values of critical energy release rate G_C in opening mode ($\beta = 0^\circ$) and mixed mode ($\beta = 45^\circ$) respectively. Numerical data of G_C are given by equation (3). Experimental results are obtained according to compliance method in imposed displacement configuration, as follow :

$$G_C = \frac{F_C^2}{2 \cdot b} \cdot \left(\frac{\partial C}{\partial a} \right)_d \quad [4]$$

F_C is a critical load inducing a crack length a . The specimen thickness b is 25mm. C is the compliance. The final observations traduce a very good similarity between numerical and experimental results.

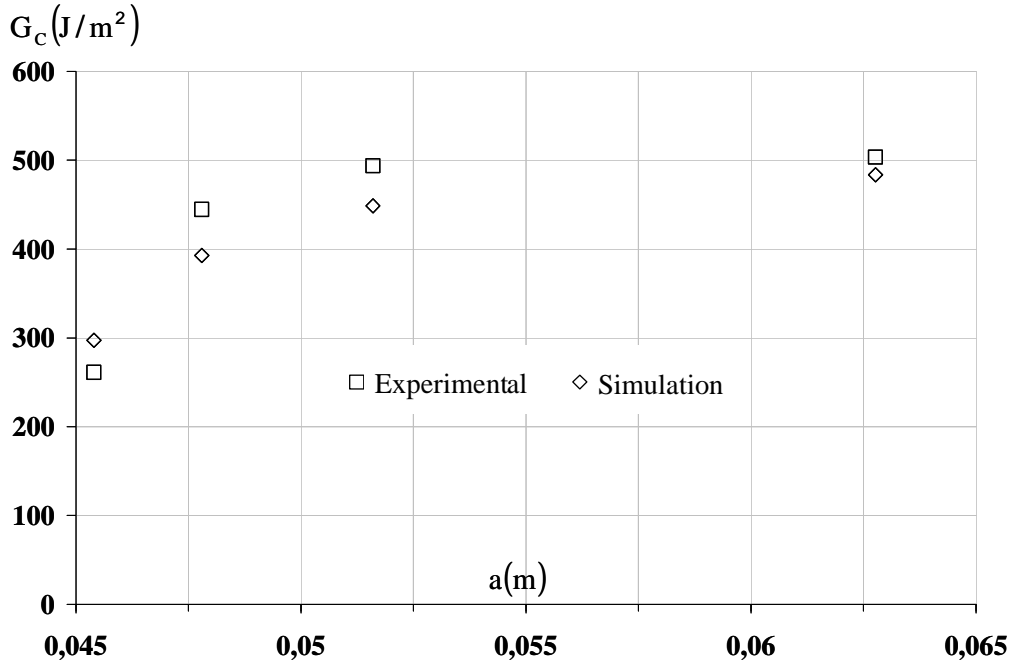


Fig. 6. Energy release rate vs. crack length in Mode I ($\beta = 0^\circ$)

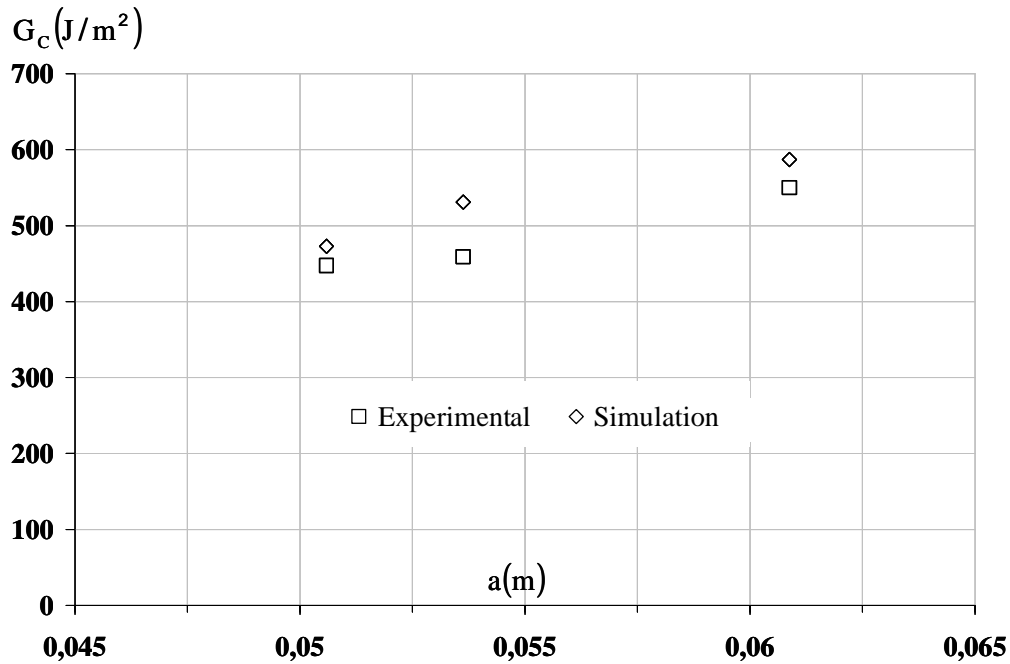


Fig. 7. Energy release rate vs. crack length in Mixed mode ($\beta = 45^\circ$)

5. Conclusions

A new Mixed Mode Crack Growth (2MCG) specimen providing the energy release stability during crack growth process has been proposed. Its design is due to the judicious combination between DCB and CTS specimen. According to the image correlation methods and the press with acquisition system data, the crack length and the critical load have been obtained after a perfect synchronization. As results, the experimental and numerical energy release rates are well compared in opening mode and in mixed mode 45° . Now, using 2MCG specimen, different test must be performed in order to obtain the part of mode I and mode II in the all mixed mode ratio. Now, this work must be completed by performing crack growth tests employing creep loadings. Results will be able to compare with numerical tools as M-integral generalized for creep crack growth process.

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