Modeling Of The Fatigue Cracks in Welded Beam-To-Column Connection of Steel Moment Frame Buildings Submitted to Earthquake

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Abstract. Fatigue cracks in welded connections of steel moment frame buildings submitted to earthquakes are studied. The connections of beams with thick flanges designed to resist to seismic phenomena by plastic dissipation are presented. The structural components, the materials and the crack mechanics are described. To predict the crack initiation, the knowledge of residual internal stresses, generated by the welding process, is required. So these stresses are assessed by a FEM thermo-mechanical analysis. The potential sites of crack locations are detected by using an FEM model of the connection with the continuum damage model of Lemaître and Chaboche. After these FEM analyses, new meshes with specific elements located at the potential crack locations are defined. A cohesive zone law is used to model the crack propagation. This model describes the crack growth by analyzing the energy released by the generation of the new surfaces and damage micro-phenomena behind the crack tip. A constitutive tension-separation law computes this energy. In these cases of low cycle fatigue, the damage and the cyclic loading conditions are taken into account.

Introduction

During the Northridge and the Kobe seism, many welded beam-to-column connections cracked in steel moment frame buildings. In theory, they would have been able to resist to high inelastic strains by plastic dissipation. Consequently, some high scale tests will be performed on this kind of connection. However these tests are expensive so it is necessary to complete them with finite element modeling, which will be validated by performed tests.

The study’s aim is to model the fatigue cracks during cyclic high scale test in welded beam-to-column connection by finite element model. There are three steps as shown in Figure n° 1.

First the welding process generates residual stresses. They influence the fatigue damage because the crack way is normal to the maximal principal stress. They are computed by a thermo-mechanical analysis like Wen, Church and Parker [1].

Then the crack phenomena can be broken in two steps: initiation and propagation. The fatigue damage model of Lemaître and Chaboche analyzes the initiation. It assesses a fatigue damage variable D that follows a stress dependence evolution law in each solid element of the mesh, taking into account the residual stresses. The crack way and the material lifetime can be determined when the damage variable is equal to a critical value.

Finally, the cohesive zone model analyzes the crack propagation. It is an energetic method, which takes into account the generation of two new surfaces, and damage micro-phenomena behind the crack tip. The energy is computed in imputing stresses in the cohesive zone that depends on the separation between the two surfaces. New elements are added in the finite element mesh following the last performed analyses and so a third computation is made. It models all steps of the crack phenomena coupling with fatigue damage.

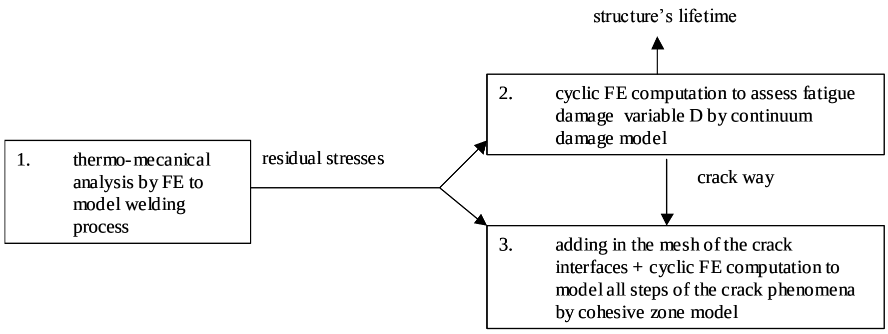

Figure n° 1: flow chart of crack process analysis in welding beam-to-column connection

Description of the Connection

The studied structure is a welded connection between a beam and a column. It is shown in the Figure n° 2. The weldings are between the beam flanges and the column flange. At the end of the web, there are two holes that help to access at the welding places. Moreover a tab is placed below so as to maintain the beam during the welding process. The opening way of the welding is about 45°. The welding is performed by mutlipass and generates residual stresses. Thus the structure is composed of three materials: base metal, welding metal and a heat affected zone since the base metal is transformed by temperature gradient.

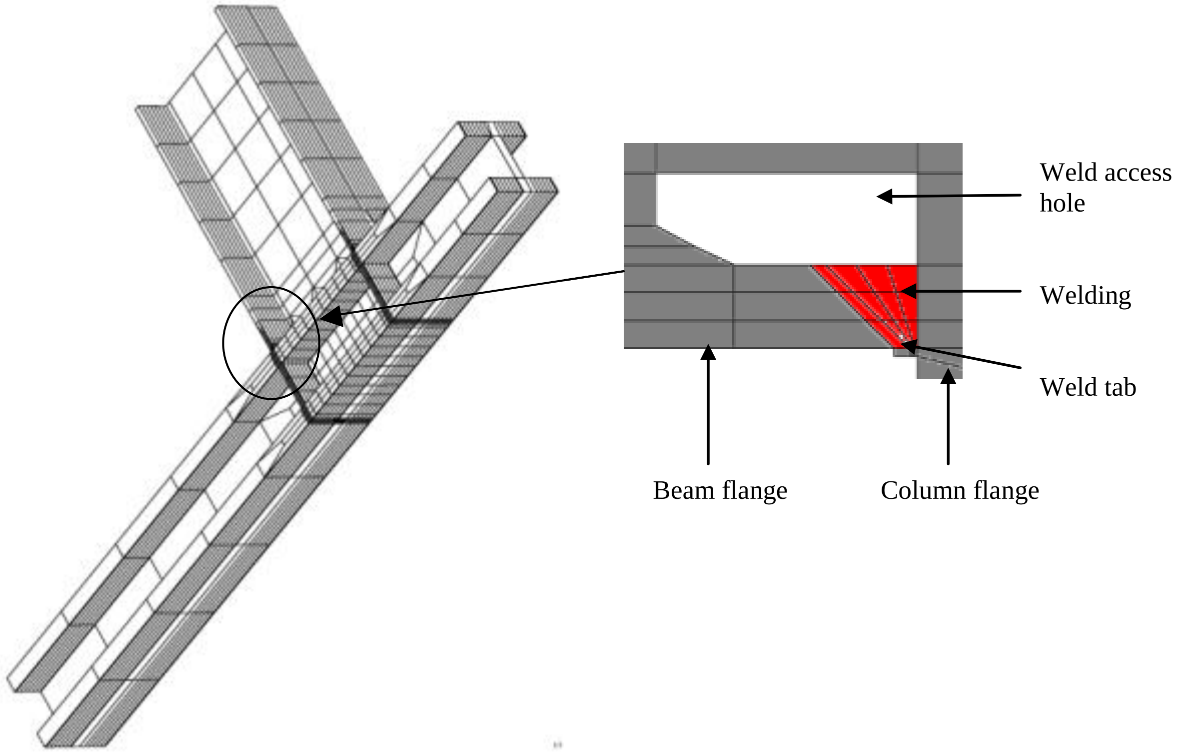

Figure n° 2: mesh of welded beam-to-column connection

Crack phenomena modeling

Initiation modeling. Lemaître and Chaboche [2] provided a method to analyze fatigue damage by introducing a damage variable that is the ratio between damaged section and sound section. This fatigue variable follows an evolution law, which depends on three dimensional stress and material properties. First the fatigue damage three-dimensional stresses limit is determined by a yield surface,

$f_D(\underline{\sigma},D)$, like in plastic theory. The damage evolves only if f_D is positive or null. Sines proposes the yield surface form:

$$f_D = A_{II} - A_{II}^{*} \tag{1}$$

$$A_{II} = \frac{1}{2}\sqrt{\left(S_{ijM} - S_{ijm}\right)\left(S_{ijM} - S_{ijm}\right)} \tag{2}$$

$$A_{II}^{*} = \sigma_{l0}(1-3b\overline{\sigma}_H) \tag{3}$$

$$S_{ij} = \sigma_{ij} - \sum_k \frac{1}{3}\sigma_{kk} \tag{4}$$

$$\overline{\sigma}_H = \frac{1}{3}\underset{t}{Moy}\,Tr\,\underline{\underline{\sigma}} \tag{5}$$

S_{ijM} and S_{ijm} are maximal and minimal deviatoric stress components during one cycle and σ_H is the average of mean stress. σ_{l0} is the damage fatigue stress limit when σ_H is null. Lemaître and Chaboche provided this evolution law:

$$\frac{\partial D}{\partial N} = \begin{cases} 0 \; si \;\; fd < 0 \\ Dc\left[1-\left(1-D\right)^{\beta+1}\right]^{\alpha}\left(\frac{\tilde{A}_{II}}{M}\right) si \;\; f_D \geq 0 \end{cases} \tag{6}$$

$$\tilde{A}_{II} = \frac{A_{II}}{1-D} \tag{7}$$

$$M = M_0\left(1-3b\overline{\sigma}_H\right) \tag{8}$$

$$\alpha = 1 - a\left[\frac{A_{II} - A_{II}^{*}}{\sigma_u - \sigma_{eqM}}\right] \tag{9}$$

The evolution law depends on stress components. σ_{eqM} is the maximal Von Mises' stress during one cycle. M_0, b, a and β are material parameters. Dc is the fatigue damage limit before the cyclic crack initiates and σ_u is the stress limit before monotonic crack initiates.

The number of cycle is low in the case of seism crack in welded beam-to-column so that is possible to compute all cycles by finite element model. The fatigue damage is computed in integration point during each cycle. It is important to note that the stress is not modified by the fatigue damage to be sure that our numerical tool keep robust [9].

Cohesive zone model. A cohesive zone is behind the crack tip where there are micro damage phenomena. The released energy for crack propagation is the required energy to create two new surfaces and to perform micro-damage phenomena. This energy is computed in introducing cohesive stress that depends on crack separation (Figure n° 4). Xu and Needleman [4] propose an exponential law (Figure n° 3):

$$T_t = \left(\frac{\phi_n}{\delta_n}\right)\left(\frac{2\delta_n}{\delta_t}\right)\frac{\Delta u_t}{\delta_t}\left\{q + \left(\frac{\Delta u_n}{\delta_n}\right)\left[\frac{r-q}{r-1}\right]\right\}\exp\left(-\frac{\Delta u_n}{\delta_n}\right)\exp\left(-\frac{\Delta u_t^{\,2}}{\delta^2_{\,t}}\right)$$

$$T_n = -\frac{\phi_n}{\delta_n}\exp\left(-\frac{\Delta u_n}{\delta_n}\right)\left\{\frac{\Delta u_n}{\delta_n}\exp\left(-\frac{\Delta u_t^2}{\delta_t^2}\right) + \left(\frac{1-q}{r-1}\right)\left(1-\exp\left(-\frac{\Delta u_t^2}{\delta_t^2}\right)\right)\left(r - \frac{\Delta u_n}{\delta_n}\right)\right\} \tag{10}$$

$$\Delta\underline{u} = \left|\begin{matrix}\Delta u_n \\ \Delta u_t\end{matrix}\right. \qquad \underline{T}_{CZ} = \left|\begin{matrix}T_n \\ T_t\end{matrix}\right.$$

Material constants: $\phi_t = \sqrt{\frac{e}{2}}\tau_{\max}\delta_t$; $\phi_n = \sigma_{\max} e\,\delta_n$; $r = \frac{\Delta u_n^{*}}{\delta_n}$; $q = \frac{\phi_t}{\phi_n}$; $e = \exp(1)$

T_n and T_t are the components of the cohesive stress. Δu_n and Δu_t are the normal and the shear separation between the crack interfaces. σ_{max} and τ_{max} are the maximal normal and shear stress. δ_n and δ_t are the separation when respectively the normal or the shear stress is maximal. ϕ_n and ϕ_t are the released energy after crack propagation and represented the area behind the cohesive stress-separation curve (Figure n° 3). Δu_n^* is the value of Δu_n after complete shear separation under the condition of normal traction being zero. This parameter is often considered as null [5].

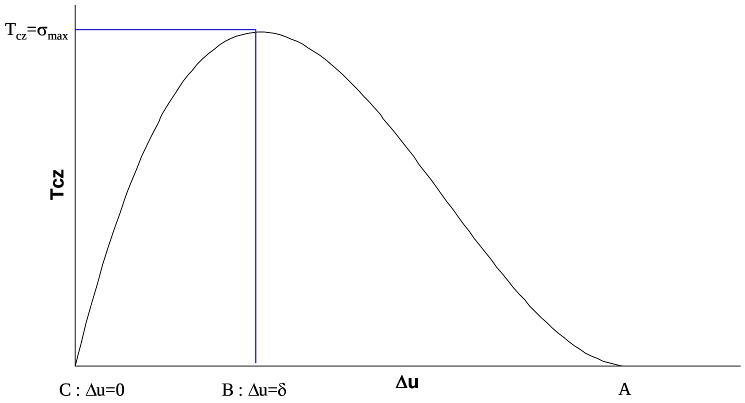

Figure n° 3: cohesive stress-separation curve

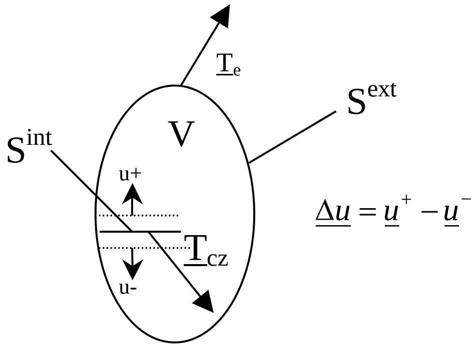

Figure n° 4: volume with a cohesive zone

Coupling with fatigue. However the released energy does not take into account the fatigue damage. Thus the fatigue crack needs less energy to propagate than in monotone condition. To introduce fatigue in this model, the maximal stress is modified like this [5]:

$\sigma_{max}=\sigma_{max,0}(1-D)$ and $\tau_{max}=\tau_{max,0}(1-D)$

$\sigma_{max,0}$ and $\tau_{max,0}$ are the maximal stress components in case of sound material. D is the fatigue damage variable, which follows the presented previously evolution law of continuum fatigue damage (6).

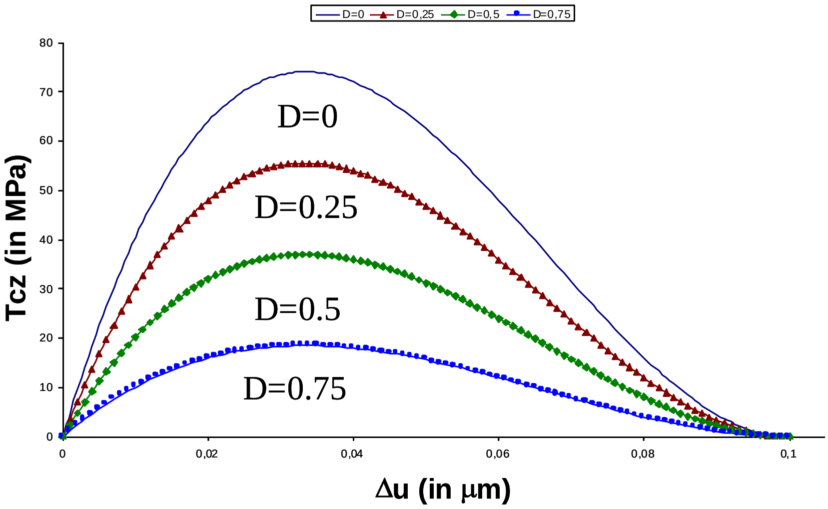

Figure n° 5: influence of fatigue damage on cohesive stress-separation law

Implementation in finite element code

The cohesive zone model is currently implemented in the Lagamine [6] code developed in M&S department of the Liege University. Interface elements, called CZMEL, model the cohesive zone. They are relied on solid mixed element, called BLZ2D [7] and defined by four nodes and one integration point. The finite element model is shown in Figure n° 6. The CZMEL are added in the mesh after the thermo mechanical (step 1) and fatigue (step 2) analysis. For each interface element, there is an associated foundation which informs if there contact or not and provides separation between the facieses of the crack. Consequently the cohesive stress can be computed at the integration point with equation (10). The fatigue damage is assessed in the BLZ2D and extrapolated in the CZMEL.

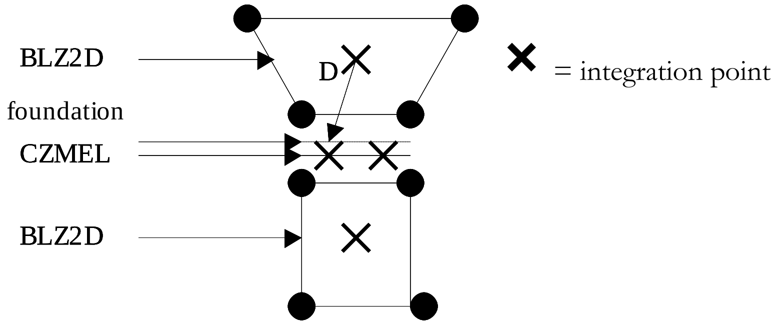

Figure n° 6: cohesive zone model element in Lagamine Code

Academic confirmation of this model

Some modelling of CTOD tests will be performed to confirm the model. A first academic confirmation was performed. An embedded steel sample is loaded by cyclic tension at its end (Figure n° 7). Only one CZMEL is introduced at the base of the sample. The model parameters were determined with the Lemaître and Chaboche 's book. At the end of the computation, a crack appears.

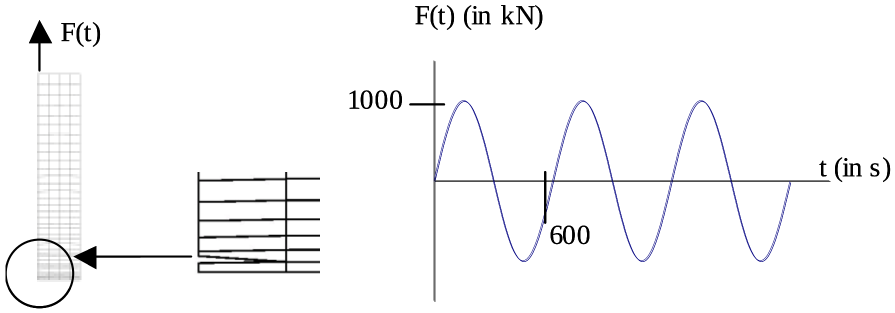

Figure n° 7: computation of a cyclic tension on an embedded steel sample with a cohesive zone model

Discussion

Initiation and propagation crack are modeled by finite element. For the initiation, the continuum fatigue damage model takes into account the three-dimensional effect of stress contrary to classical Manson Coffin model [8]. The stress is not coupling with the damage to avoid robustness loss[9]. For the propagation, the cohesive zone model ensures a right energetic assessment and demands a few parameters and developments unlike local model. Some high scale test will be performed on a welded beam-to column connection. Thus the model will be calibrated and confirmed with computation of this test.

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