Bending Collapse of Closed-hat-section Beams. Part I: Development and Validation of Finite Element Models

Hafizan Hashim
Amir Radzi Ab.Ghani
Wahyu Kuntjoro
Faculty of Mechanical Engineering, Universiti Teknologi MARA, 45050 Shah Alam, Selangor

ABSTRACT

Many articles on bending collapse but not limited to closed-hat-section have been reported mainly from experimental point of view but less in simulation-based approach. This paper presents the procedure for development and validation of a finite element (FE) model of a closed-hat-section beam under quasi-static three-point bending using an explicit non-linear FE technique. Developed FE models were validated through comparison with existing and present experiment results. Firstly, the existing models were rebulit via present modelling technique using information provided in the relevant research report. Simulation results of rebuilt model were compared with existing results for verification and validation. Next, to further validate the present model, actual physical experiment replicating the FE model was set up for comparison of results. Overall, both group of comparison results emphasis force, mean load-displacement relationship, and deformation modes show good agreement. Adequate robustness and stability of the present model were achieved when responses from different material and cross section were well predicted.

Keywords: *Bending, Hat-section, Quasi-static, Finite Element.*

Introduction

In order to remain competitive with new alternative materials, a good understanding on the collapse behavior of closed-hat-section beams is essential particularly for automotive structural applications. This would allow

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enhancement of the development mathematical models to be made, which would take into account the effect of extended flange and closed-plate. Physical experiment provides information and knowledge of collapse behavior with actual condition and truly reliable. However, for optimization of one design, repetitive experiments are considered non-economical for it may require the use of quite a number of test specimens. Here, the role of FEA becomes a tremendous productivity tool, resulting in overall cost and time reduction.

Among the famous articles reporting about theoretical bending collapse of rectangular tubes with analytical approach were made by Kecman [1], Wierzbicki *et al*. [2], and Kim and Reid [3]. Here, only Wierzbicki *et al*. [2] used FE simulation to validate the analytical model. Thereafter, analytical model developed by Wierzbicki *et al*. [2] was criticized by Kim and Reid [3] because it was irreproducible. Cimpoeru and Murray [4] experimentally studied the moment-rotation properties of square tubes under large deflection pure bending and the results acquainted with Kecman [1]. Even though Kecman's theory [1] is not kinematically admissible as one proposed by Kim and Reid [3], it suits well with most of the experiment and simulation works done later. Chen [5] studied experimentally the crushing behavior of empty and foam-filled aluminum closed-hat-section and double hat-section under three-point and deep bending. FE models that replicate actual experiment were well developed and validated. Chen's article [5] provided quite detailed information and has been used by the author to compare the FE results through model rebuilding. A companion study on closed-hat-section was reported by Bambach *et al*. [6] who experimentally studied the influence of perforations at the compression flange on moment-rotation relation when subjected to large pure bending. An empirical procedure was developed to determine the large deformation bending but no numerical approach was reported. Another study on the bending crush performance was reported by Belingardi and Scattina [7]. The aim was to evaluate the adhesion strength of closed-hat-section jointed by structural adhesive and spot weld. Hybrid composite-metal specimens were jointed using adhesive absorbed highest energy, followed by full metal spot-welded and lastly the fully composite hat-section. Results demonstrated the advantages of utilizing adhesive for structural joining to reduce weight. This study however was purely experimental.

A review of literature showed that many articles on bending collapse but not limited to closed-hat-section have been published mainly from experimental point of view but less in simulation approach. This paper presents FE model development using ABAQUS with validation procedures for closed-hat-section beams subjected to three-point bending. The developed explicit non-linear FE model went through two types of validation procedures which are from existing results and present physical experiments. Simulation results are compared with the existing and present testing results which showed a good agreement.

Computer Modelling and Development of FE Model

Specimen / Model geometry and finite element mesh

A closed-hat-section beam is a combination of a hat-section and a closed-plate. For the present experiment, both parts were drilled and bolted together to form a closed-hat-section. This type of connection becomes useful when the overall thickness increases. Beam was modeled using robust conventional shell elements, S4R, which is a four-noded quadrilateral element with six degrees of freedom per node while the indenter and rigid support were modeled using R3D4 rigid element. Similar type of elements were implemented by Amir Radzi *et al*. [8] in modelling a plain square column and rigid impactor. The S4R is suitable for large strain analyses with the ability to enhance hourglass control. To allow nonlinear material behavior, five integration points were employed through the shell thickness. From detailed observation of the preliminary simulation, the deformation mode of full and half model can be treated symmetrically. Therefore, half models were used to reduce the number of degrees of freedom (DOFs) and computational time as shown in Figure 1.

Mesh convergence study

The most fundamental in constructing an accurate FE model is the correct element type and its required smallness. Figure 2 shows maximum indentation force versus element size in the refine mesh or hinge region. The crush load converged as the mesh density increased. Therefore, the element size of 2.0 x 2.0 mm is chosen to model the hinge region, while the rest of parts with a size of 5.0 x 2.0 mm [5]. To avoid an infinite stress, a radius of 2 mm at each flange's corner was introduced and based on the convergence study, the radius size is reasonable as well as number of elements spaced around the corner area.

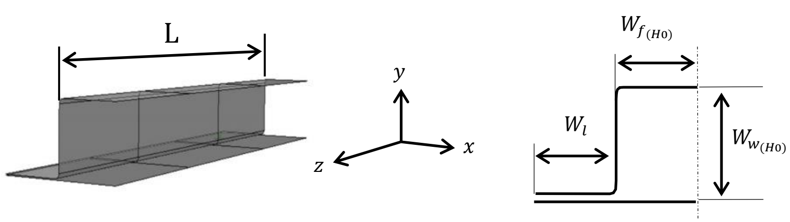


Figure 1: Half model geometry of the closed-hat-section beams

Table 1: Design dimensions of the closed-hat-section beam (Unit: mm)

No. of specimens		**Type**	**Web, $W_{w(H0)}$**	**Flange, $W_{f(H0)}$**	**Lip, W_l**	**Width, W**	**Length, L**	**Thick-ness, t**
3	Conventional	Hat section	30	60	30			1
		Closed plate	-	-	-	120	300	1

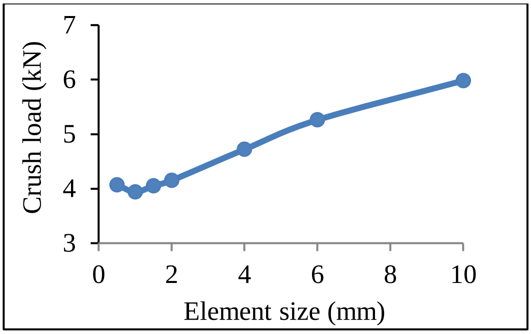


Figure 2: Mesh convergence of S4R element for closed-hat-section beam

Loading, interaction, and boundary condition

The indenter is described as a rigid surface that translates only along the y axis as shown in Figure 3. The beam specimen is supported by a simple supporting system which is fully constrained (i.e. U1=U2=U3=UR1=UR2=UR3=0) to avoid relevant geometric or dimensional change. Here, U1, U2, and U3 are linear displacement while UR1, UR2 and UR3 are rotation about *x*, *y*, and *z* axis respectively. Indenter and rigid supports are tagged by a reference node each to ease control the motion of the body as a whole. Due to mirror symmetry, boundary conditions along free edges of beam are applied symmetrically constraining U1, UR2, and UR3. Other important aspect in modeling would be the size of the step time. This parameter is essential for the convergence of the values as well as the total time of the simulation. For quasi-static nonlinear crushing analysis, the step time is determined from a FREQUENCY linear perturbation analysis step which is provided in ABAQUS/Standard [9]. In this study, the step time was determined at 0.03 s. In an explicit impact analysis, the step time represents the actual impact duration.

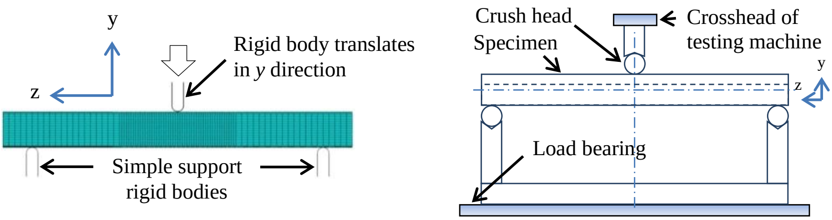


Figure 3: A FE mesh of the full model subject to three-point bending

For a smooth indentation, the motion of the indenter was simulated using the SMOOTH STEP sub-option of the AMPLITUDE option. This option can avoid inaccurate results caused by system noise and at the same time enable user to control the motion of the indenter so it can travel over required time duration as prescribed in the total step time [9]. In modeling contact, the highly automated contact algorithm which includes all surface definition was used for the whole system. The finite sliding "penalty" based contact algorithm with contact pairs and "hard" contact were used to define the self-contact between the beam walls during collapse, and surface-to-surface contact between each rigid surface and the beam. All surface contact in the present finite element models was treated with 0.25 friction coefficient except those contacted with rigid surface which was treated as frictionless.

For an acceptable quasi-static result, the kinetic energy of the deforming part should not exceed a small fraction of its internal energy throughout the majority of the analysis, typically 1-5% [9]. This is because the indenter is massless, so the only kinetic energy is carried by the beam. Figure 4 shows the energy plot of quasi-static simulation of the beam. It clearly shows that the maximum kinetic energy is sufficiently small compared to the internal energy. It also shows both the kinetic and internal energy-time profiles are smooth which indicate that no significant plasticity behavior could affect the solution. To ensure hourglass is minimized, the ratio of artificial strain energy to internal energy was investigated and found to be less than 5%.

Mesh independent spot weld

In this study, mesh-independent spot welds was used to model rigid spot weld which did not fail under any circumstances. The principal advantage of using mesh-independent spot welds instead other connections methods is that the parts that are to be connected can be meshed independently of their assembly, and later the spot welds can be located by specifying a single coordinate point near to the surfaces of the parts; thus, the locations of the spot welds can be independent of the locations of the nodes on both sides of the connection. The size of the region of influence can be modified by changing the radius of influence. In this work, the radius of influence was chosen to be equal to the physical hole radius which is 3 mm.

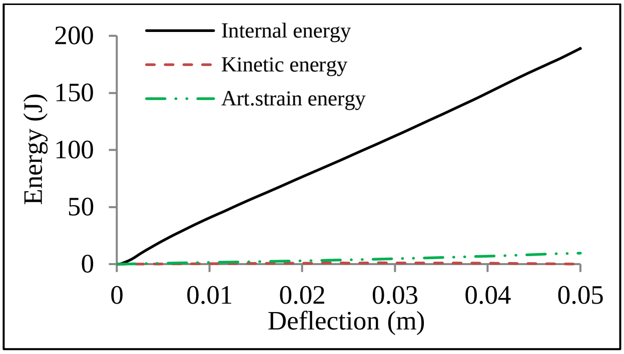


Figure 4: Energy plot of quasi-static simulation of closed-hat-section beam

Material model

The beam was modeled with a piecewise linear elastic-plastic material model with strain hardening. Material coupon tensile test was conducted using the Instron model 3382 Universal Testing Machine (UTM). The material properties for the mild steel are as follows: initial yields stress; $\sigma_y =$ 340 MPa, Young's modulus; E=200 GPa, Poisson ratio; $v = 0.3$, Ultimate Tensile Strength (UTS); $\sigma_u = 391$ MPa, and density; $\rho = 7809\ \mathrm{kg/m^3}$. The engineering stress-strain curve of the material was obtained using a standard tensile test in accordance with AS1391-1991(1991). Figure 5 shows the true stress-strain curve from coupon tensile test. From this curve, the approximated data points which are used in the FE models are tabulated in Table 2. The ancillary strain data was converted into true strain by using,

$$\varepsilon_{true} = \ln(1 + \varepsilon) \tag{1}$$

where, $\varepsilon =$ experimental strain. The true stress data was converted using,

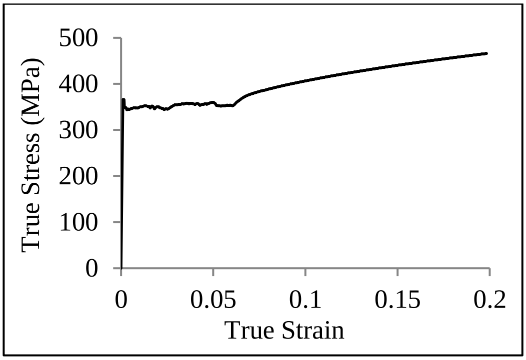


Figure 5: True stress versus plastic strain distribution for mild steel

Table 2: Approximated true stress-plastic strain data points for the FE model

σ_t (N /mm^2)	340.40	354.21	398.41	425.02	446.21	462.10
ε_p	0	0.0613	0.0900	0.1251	0.1600	0.1900

$$\sigma_{true} = \sigma \cdot (1 + \varepsilon) \qquad (2)$$

where, σ = experimental stress.

FEA Validations Against Existing and Present Results

Rebuilding of existing model for validation of the present modelling technique

The International Journal of Solids and Structures is one of the strong sources of relevant literature in the field of structural mechanics. A published article by Chen (2001) [5] contains many relevant works to the present study like the similar cross section and boundary condition which provide worthwhile reading and reference. In the previous study, Chen (2001) [5] used a high strength aluminium alloy of variant AA5754 to produce the closed-hat-section specimens. The true stress-strain curve of the alloy is shown in Figure 6. In the present work, the author managed to remodel the specimen and the experimental setup using present FE modeling approach. This is to verify whether the FE remodel is capable to replicate and predict the experimental behavior of Chen (2001) [5] and thus validate the FE remodel. In addition, the FE remodel was also compared to Chen (2001) [5] FE model that was developed parallel to his experiment work. Figure 7 shows half cross section geometries of conventional and double-hat-section beams used by Chen (2001) [5]. The double-hat-section was also considered for remodelling so as to be more convincing of the present modeling technique. Details about section dimensions are listed in Table 3. The mesh, loading, and boundary conditions all follow Chen (2001) [5] model. Type and element designation were the same used in the present FE model as well as the 25 mm pitch spot welds. For information, Chen (2001) [5] utilized a non-linear explicit code PAM-CRASH throughout his simulation.

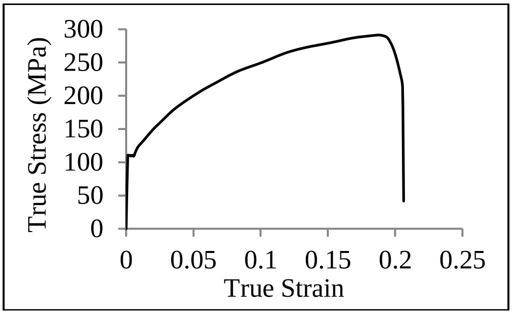


Figure 6: Stress-strain curves of aluminum alloy HS5754 [5]

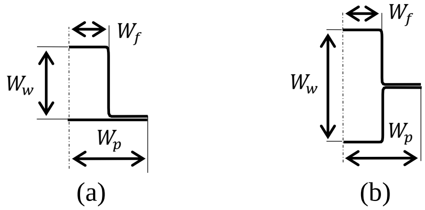


Figure 7: Half geometry of (a) closed and (b) double hat-section [5]

Table 3: Measured section dimensions [5]

Specimen	W_f **(mm**	W_p **(mm**	W_w **(mm)**	***L* (mm)**	**Span (mm)**	***t* (mm)**
Closed-hat-section	25	46	50	675	550	2
Double hat-section	25.5	46	104	675	550	2

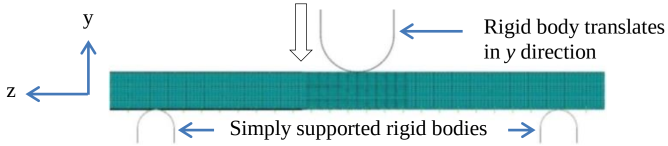


Figure 8: A FE mesh of Chen's remodel under three-point bending [5]

Quasi-static experimental testing for validation of the closed-hat-section beam model

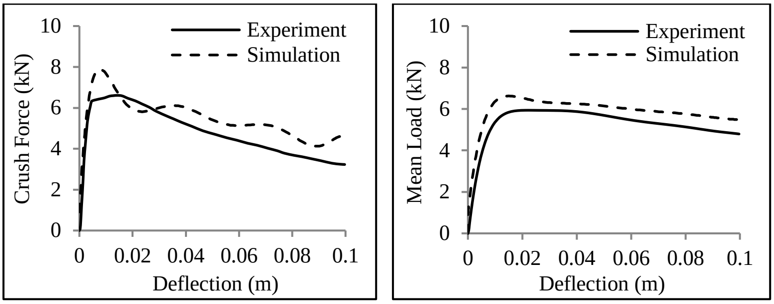
Three-point bending experiment was carried out to validate the present FE model. Beam geometry and dimensions are shown in Figure 1 and Table 1 respectively. Three specimens were fabricated to ensure repeatability and reduce the number of experiments. Quasi-static tests were performed using Instron 3382 Universal Testing Machine (UTM). Specimen is positioned between the indenter and two simple round supports as shown in Figure 3.

Validation Results

Remodelling results of closed-hat-section beams under quasi-static three-point bending

Figure 9 shows comparison of quasi-static load and mean load-deflection curves between present remodel and Chen (2001) [5]. Referring to Figure 9(a), after the indenter crushed the beam center, there were forces that abruptly increased to a peak of just fewer than 8 and 7 kN for both experiment and simulation. Just after the peak, both forces slowly decreased to almost half of their peak load. As shown in Figure 9(b), both mean loads increased to a peak point before they were leveled off throughout the indentation process. The mean load was calculated by dividing the energy absorbed by the crush distance. The energy absorbed was obtained by integrating the crush load with respect to crush distance using functions in MATLAB. On average the difference is within ±6.5%.

Figure 10 shows the comparison result of present FE remodel and Chen (2001) [5] simulation. Both are generally similar in the initial prediction but slightly deviated towards the end. This is possibly due to the effect of curve fitting technique employed on both graphs. The deformation mode predicted by the present FE remodel compared well with experimental results as depicted in Figure 11. Figure 12 shows comparison result of load and mean-load deflection curves between present FE remodel and existing experimental results for double hat-section. Good agreement is seen between FE remodel and experimental results for both curves as well as the collapse mode as shown in Figure 13. As a whole, results from FE remodel demonstrate a reasonable agreement with Chen (2001) [5].



(a) (b)

Figure 9: Comparison of quasi-static (a) load and (b) mean-load deflection curves between present FE remodel and Chen (2001) [5]

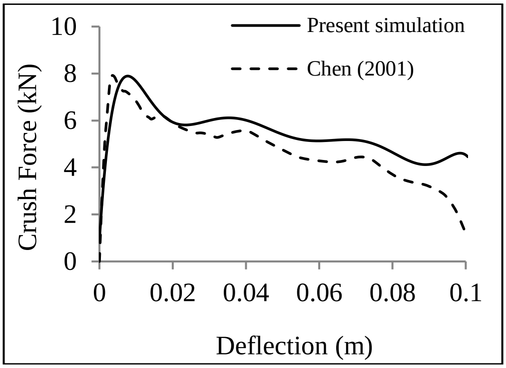
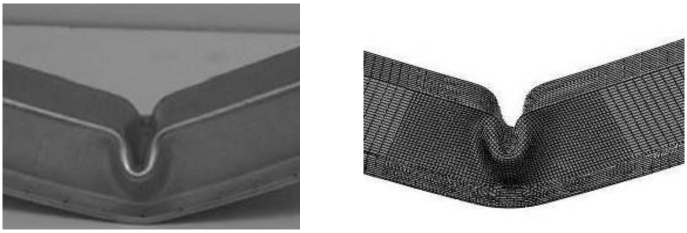
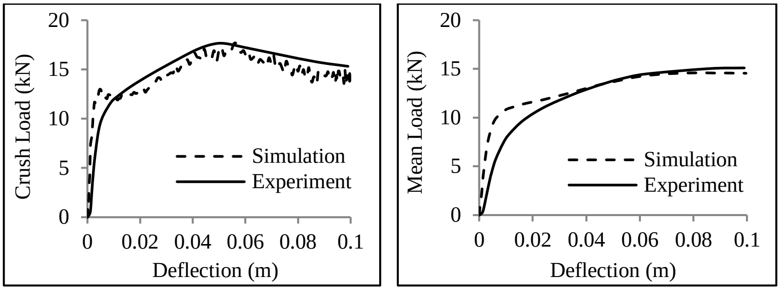


Figure 10: Comparison of present remodel and existing simulation results [5]



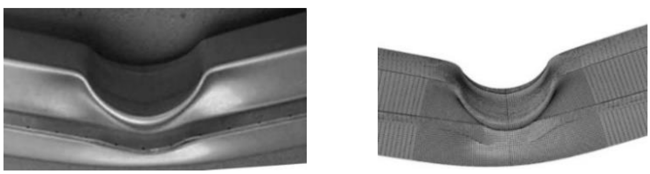
(a) (b)

Figure 11: Comparison of collapse modes of a closed-hat-section beam from (a) existing experiment and (b) present remodel



(a) (b)

Figure 12: Comparison of quasi-static (a) load and (b) mean-load deflection curves between present FE remodel and existing experimental results for double hat-section [5]



(a) (b)

Figure 13: Comparison of collapse mode of a double hat-section from (a) existing experimental result [5] and (b) present FE remodel

Validation results of present FE model against three-point bending experiment

Again, the quasi-static three-point bending results demonstrate a reasonable agreement, this time between present FE model and experimental data. Figure 14 shows the comparison of load-deflection curves between present model and experiment. During inital crush, there were steep rise of forces to a peak of approximately 5 kN for FEA and 4 kN for the experiment result. Just after the peak, both forces gradually decreased before leveling off with little fluctuation throughout the indentation. Figure 15(a) shows comparison of mean load-deflection curves between present FE model and experiment. FE model output and measured output are broadly similar with average difference within 5%. The deformation mode predicted by the FE model also compared well with present experiment result as depicted in Figure 16.

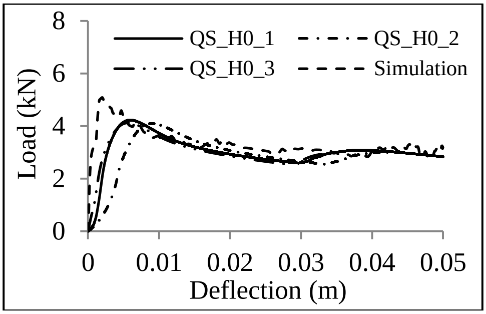
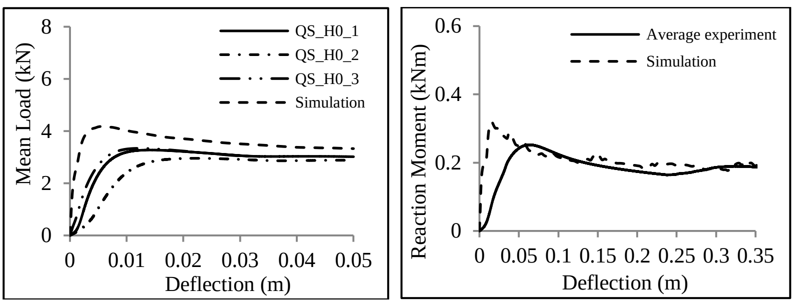
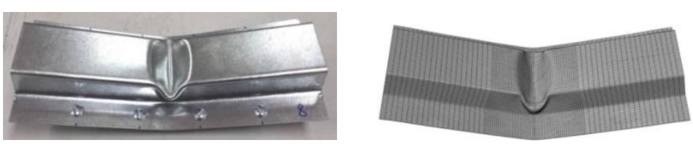


Figure 14: Quasi-static load-deflection for closed-hat-section beams (FEA vs Experiment)



(a) (b)

Figure 15: (a) Mean load-deflection and (b) Moment-rotation curves for closed-hat-section beams (FEA vs Experiment)



(a) (b)

Figure 16: Comparison of collapse mode of closed-hat-section beam between (a) experiment result and (b) present simulation

Conclusion

Development and validation of FE models of closed-hat-section beams subjected to three-point bending were performed. Details procedure have been laid out involving the present model, rebuilt, and experimental model.

Model rebuilding technique was utilized to prove robustness and stability of the FE model in case of different material, cross section, and boundary condition. Results from rebuilt model showed a good agreement with the existing model [5]. Experimental investigation was performed to further verify the validity of the FE model. Measured results and the deformation profile of the beam model compared well to the actual test. Research information is useful in developing procedures for verification and validation under impact scenario.

Acknowledgment

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