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Study of modal properties and crashworthiness performance of crash box numerical model with different joining modelling strategies

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Abstract. It is important to understand the natural frequencies and the mode shapes for automotive structure such as crash box as it will be subjected to the dynamic loading in its real application. In addition, it is also important to study other dynamic behaviour such as crash and buckling as crash box is one of energy absorbing member that is intended for car safety during collision. In this study, modal properties of three different crash box models joint by three different joint modelling strategies and also their crash and buckling behaviour was analysed and investigated. Computational frequency analysis, dynamic crash analysis and nonlinear buckling analysis was performed on all of crash box models. the crash box modelled with node equivalent method to represent the welded joint shows higher stiffness at the joining area and therefore shows higher value of natural frequencies that the model with CBEAM and CBAR elements as their joining elements. In term of crash behaviour, the model with CBEAM element shows higher reaction force compared to the CBEAM. This proves that different type of joint modelling strategies behaves differently.

Keywords: Top hat structure, crash analysis, nonlinear buckling analysis, joint modelling strategies, modal analysis

1. Introduction

A structural natural mode of vibration not only effect on the structure's NVH characteristics but also the knowledge on dynamic characteristics of any structure is very crucial during the design phase. It is more important to understand their dynamic characteristics especially for the structures that will undergo dynamic loading during the actual application. For instance, it is essential to know the natural frequencies and their respective mode shapes for many automotive structures as most of them will be subjected to dynamic loading in real application [1]. This knowledge is very important for making a number of improvements that can be implemented in a design in order for the structure to have better performance.

In making improvements towards various automotive parts and structures, researchers are setting many performances goals and objectives. Mostly, safety is the main criteria that are taking into consideration when making improvements. The study on the dynamic behaviour, the way of deformation of vehicle construction elements during impact and energy transferred during loading for frontal section of vehicle are among popular topic of research among scholars [2]. By gathering the information on the vehicle frontal parts, new implementation were developed and studied such as improving material mechanical properties and geometric characteristics of elements section [3–5].

Crash box, which is one of the frontal parts of a vehicle, is one of the popular topics of study. It is a component that is attached in between the car chassis and front bumper and supposed to deform and absorb energy during crash to provide comfort and safety to the car's passengers [6]. Various types of analysis and development was investigated and implemented on crash box structure in order to maximize its dynamic performance [7,8]. For example, many geometrical optimizations were tested to investigate the capability of many types of geometrical configuration with aim of finding the better performance structure. These studies of many configurations has cause the design of initially simple thin-wall column crash box to be evolved into more complex structure [9]. For example, classic crash box that was normally an extruded square column can now become adapting new profile such as top-hat or hexagonal. In addition, the application of triggers and joining has contributed to different dynamic performance for the crash box structure [10–13]. In fact, joining such as welding can influence the material properties of crash box. The location of joining can cause discontinuities in the stiffness of the box which leads to deformation into different direction. For instance, welding can helps to stiffen the material and makes the non-welded area to collapse easier [14]. In this case, the welding also plays the parts as trigger or collapse mechanism to the crash box and it is very essential to understand how the joining contribute to the dynamic response [14].

In studying the characteristics of structures, finite element method is one of the popular analysis tools to be used to gather as many knowledge and information on the structure. The behaviour of structure, for example a crash box, under dynamic loading can be observed and studied before validating the study with experimental work. For most structure with joining element, mostly, the modelling of joining element is neglected [15]. However, it has been stressed by many researchers that the modelling of joining element is important towards having more accurate analysis [13,16,17].

In this study, the application of several joining modelling strategies in top-hat crash box structure and how the models behave under modal and crushing analysis was investigated. The details on the modelling strategies and the analysis conducted on the crash box are explained in the following section of this paper.

2. Construction of crash box models

In order to perform a prediction analysis on the modal properties of the top-hat crash box structure, finite element analysis by using a software package was used. The finite element model was constructed based on actual top-hat structure as shown in **Figure 1**. The interest to study the top-hat shaped crash box with spot welded joint is due to findings that stated the flange that acts as stiffness which contribute towards the energy absorption capability. In addition, spot weld joint is widely used in automotive and therefore gaining a lot of research interest [18]. The finite element model was constructed and meshed to produce 979 quad-shell elements. The nominal values of material properties assigned on the crash box model are based on aluminium alloy 6061 properties which are as follows; Young's modulus ($\boldsymbol{E}$) is 69 GPa, density ($\boldsymbol{\rho}$) is 2800 kg/m^3 and Poisson's ratio is 0.33. The height and width of the crash box are 60 mm with the flanges are 10 mm on each side, the length is 200 mm and the wall thickness is 1.5 mm.

For replicating the stiff behaviour of the spot-welded joint that were available in the actual top-hat structure several modelling strategies were used. The stiffness of the joint was created by using connecting bar element such as CBAR and CBEAM, and also by constructing node equivalence at the welded location. The CBAR element is a general purpose beam that supported tension and compression, torsion, bending in two perpendicular planes, and shear in two perpendicular planes. The CBAR used two grid points and provided stiffness to all six DOFs of each grid point. With CBAR, its elastic axis, and shear centre all coincided. The displacement components of the grid points were three translations and three rotations. The CBEAM element provided all the capabilities of the CBAR element, plus the following additional capabilities; first, the neutral axil and shear centre did not need to coincide, which were important for unsymmetrical sections, also, the effect of cross-sectional warping on torsional stiffness was included in CBEAM properties (PBEAM) only, and lastly, the effect of taper on transverse shear stiffness (shear relief) was included (PBEAM only) [19]. The CBAR and CBEAM element was using circular profile with diameter of 5mm in order replicate the spot weld nugget size. Very high stiffness value of was assigned in order to replicate the joint stiffness. On the other hand, node equivalencing is a method that combines two nodes from two neighbouring elements into one node. This is to stiffen the connectivity between those two elements which is sometimes used to replicate the stiffness of welded joint in actual structure. In the constructed model, the two nodes at the place of spot weld were equivalence into one single nodes.

The application of CBAR and CBEAM elements as connector elements was explained where different cross section for the element was used (see **Figure 2**) [20,21]. However, in this study, both CBAR and CBEAM elements were created by using same cross section. Location of CBAR and CBEAM elements are shown in **Figure 3**.

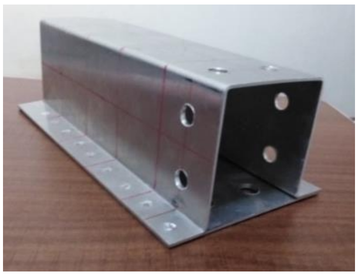

Figure 1. Top-hat crash box structure with spot-weld joint

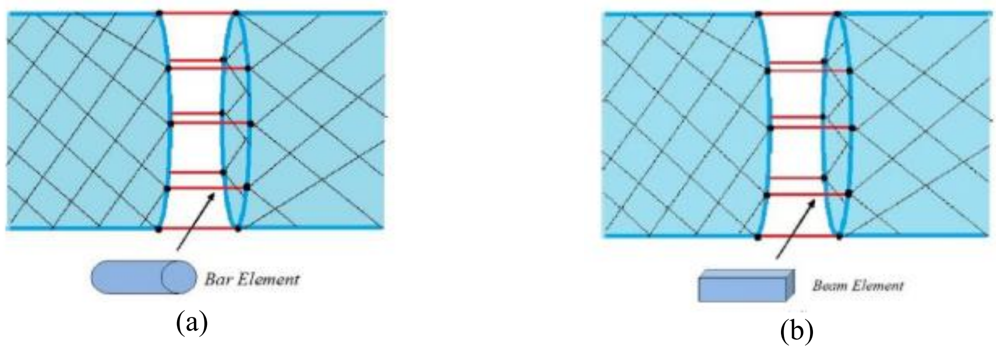

Figure 2. Cross section of (a) CBAR element and (b) CBEAM element [19]

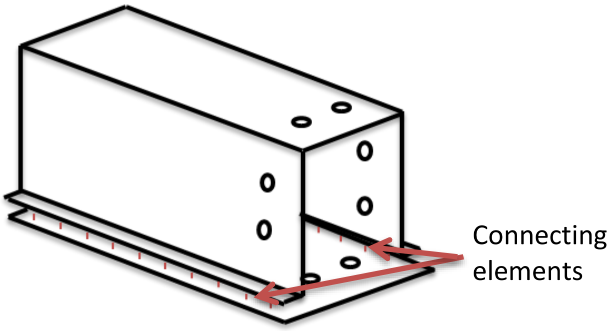

Figure 3. Location of CBAR and CBEAM elements on the crash box model

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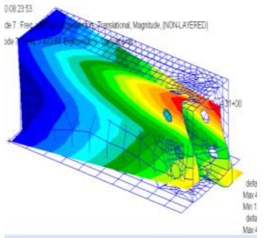
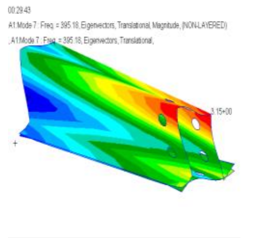
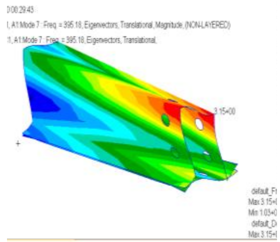
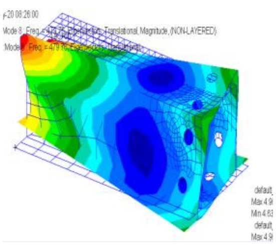
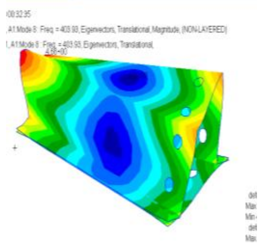
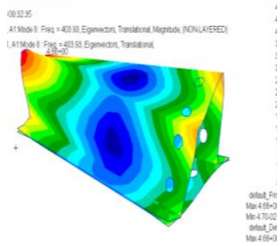
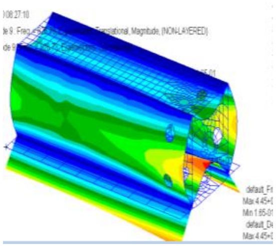
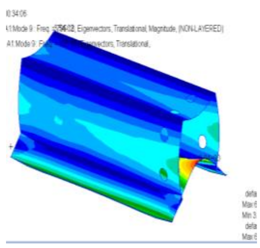
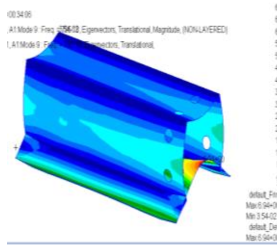
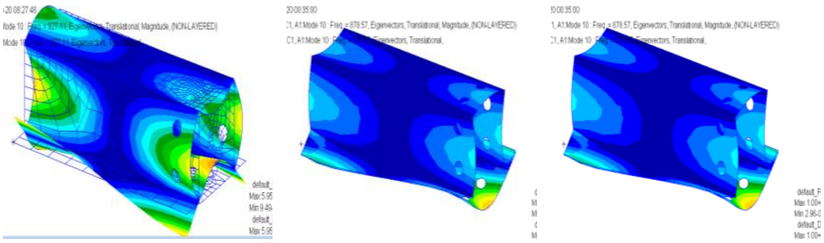
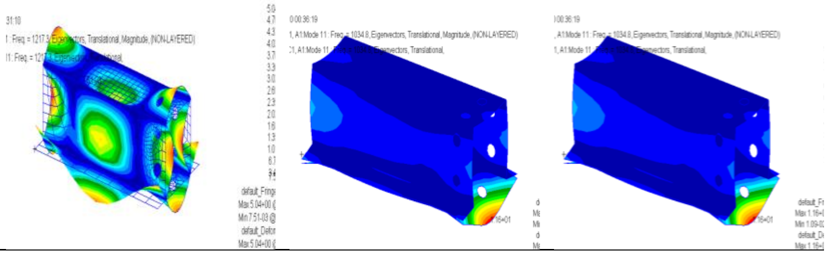
3. Computational modal analysis on crash box model

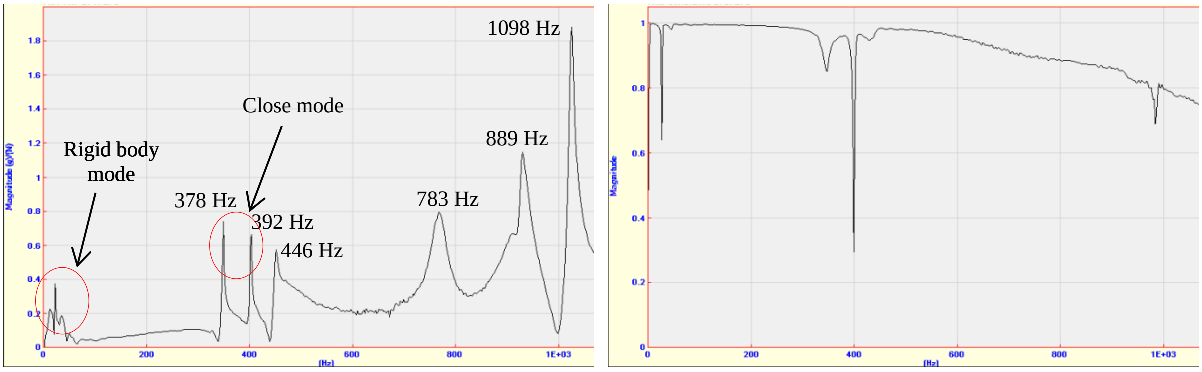
Computational modal analysis or normal mode analysis was performed in order to obtain the modal properties of each crash box model. No load or translational and rotational boundary conditions were applied to any node on the structure which left the model to be analysed under free-free boundary condition. The output of the analysis is as shown in the Table 1. Based on the table, the crash box model with node equivalent joint shows higher stiffness at the joining area and therefore, having higher value of natural frequency compared to crash box models with CBAR and CBEAM element. In addition, the modal properties of crash box models joined by CBAR and CBEAM showed similar characteristics of modal properties. This is due to the similar stiffness and mass properties assigned on both models with resulting on the similar modal properties to be generated.

Experimental modal analysis was conducted in order to validate and measure the discrepancies of respective models. Response from the impact hammer test was shown in Figure 4 where the obtained frequency response functions and their respective coherence signal was analysed. Mode indicator shows that the lower frequency peak is associated with rigid body mode. Correlation with all crash box models shows that crash box model with CBAR and CBEAM joining elements has lower discrepancies (see.Table 2).

Table 1. Modal properties of crash box models

Mode	Natural frequencies (Hz) for crash box model joint by			Mode shapes for crash box model joint by		
	Node equivalence	CBAR	CBEAM	Node equivalence	CBAR	CBEAM
1	472.64	395.18	395.18			
2	479.76	403.93	403.93			
3	826.78	795.18	795.18			

4	927.77	878.57	878.57	
5	1217.3	1034.8	1034.8	



(a) (b)

Figure 4. Signal of (a) frequency response function and (b) coherence of the actual crash box structure

Table 2. Correlation of experimental natural frequencies and finite element models

Mode	Natural frequencies (Hz)						
	Experimental	Node equivalence	Error (%)	CBAR	Error (%)	CBEAM	Error (%)
1	392	472.64	20.57	395.18	0.81	395.18	0.81
2	446	479.76	7.57	403.93	9.43	403.93	9.43
3	783	826.78	5.59	795.18	1.56	795.18	1.56
4	889	927.77	4.36	878.57	1.17	878.57	1.17
5	1098	1217.3	10.87	1034.8	5.76	1034.8	5.76

4. Dynamic crash analysis on crash box model

The same finite element model the crash boxes that were used for modal analysis were used to perform dynamic crash analysis on the respective models. The properties for the models were remained to be same. However, plastic characteristics for the material was added by referring to the data provided by other research on the same material [22-23]. The crash box is considered to be fixed at the bottom and the impactor is considered to be rigid. The impactor was given a velocity of 25 m/s and movement constraint are given for the impactor to move along the z-axis only. Contact was defined between the impactor and the crash box as hard contact and coefficient of friction is defined as 0.3. The simulation set up of the crash analysis is as shown in Figure 5.

The equation of motion for nonlinear dynamic behaviour can be formulated as shown in Equation (1) below [22].

$$M(x)\ddot{Z}_N(t) + C(x)\dot{Z}_N(t) + K_N\big(x, Z_N(t)\big)Z_N(t) = f(t) \tag{1}$$

where M is the mass matrix, C is the damping matrix, K_N is the nonlinear stiffness matrix, $Z_N(t)$ is the displacement vector, $\dot{Z}_N(t)$ is the velocity vector, $\ddot{Z}_N(t)$ is the acceleration vector, and t is time. On the other hand, the $'N'$ represents the response of the nonlinear dynamic analysis and $f(t)$ is the external load vector. The energy conservation during the crash time is expressed as equation (2) as follows [22]:

$$SE = KE + IE - W + VD + FD \tag{2}$$

where SE is the summation of all important energies at any time during the crash analysis, KE is the kinetic energy, IE is the internal energy, W is the external work, VD is the viscous dissipation and FD is friction damping. In addition, the sum of energies is approximately equal to the kinetic energy before the crash. Figure 6 illustrates the energy transfer between the impactor and the crash box models during the dynamic crash analysis. The kinetic energy from the impactor is the highest at the beginning of the crushing, then, as it collapse with the crash box; the kinetic energy was reduced and transformed into internal energy. From the figure, there are no noticeable differences in terms of energy transfer for all three crash box models. The energy change occurs almost at the similar time. The value of external work, viscous damping and friction damping is relatively small and can be summed up as energy lost during the collision. Therefore, the energy transfer curve that is shown in Figure 6 is reasonable with the equation (2).

Figure 7 and Figure 8 shows the force curve and the deformation shapes for each crash box models respectively. All of crash box models are capable of stopping the impactor from continuously crashing the crash box. The impact was stopped after t=0.003 s and the impactor was bounce back from the crash box at t=0.004 s. As the dynamic crash analysis are not showing the full deformation or buckling behaviour of the crash box models, the analysis of nonlinear buckling was performed in order to futher study the buckling deformation of each crash box models.

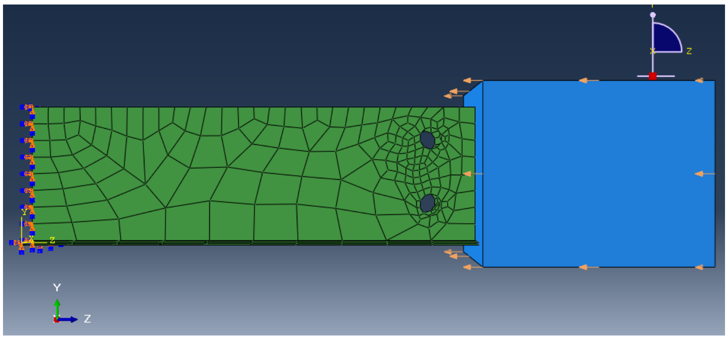


Figure 5. Crash box simulation set up

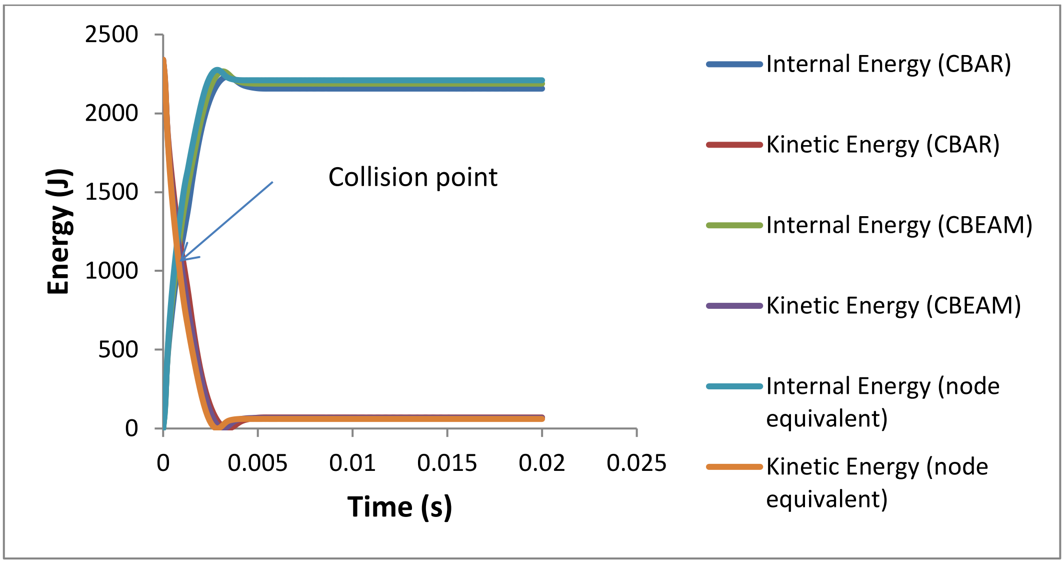


Figure 6. Energy transfer diagram for crash box models of respected joint type in dynamic crash analysis

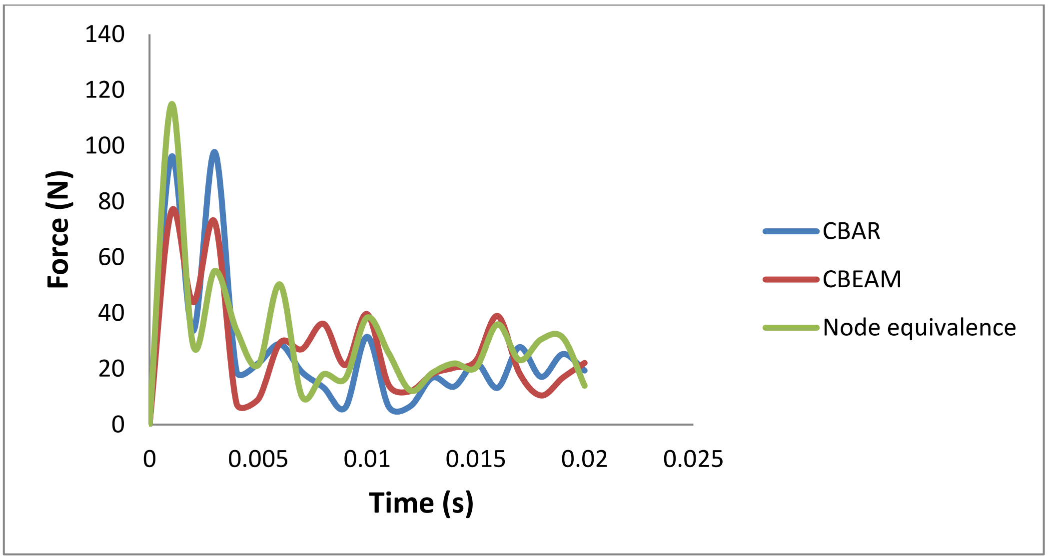


Figure 7. Force diagram for crash box models of respected joint type in dynamic crash analysis

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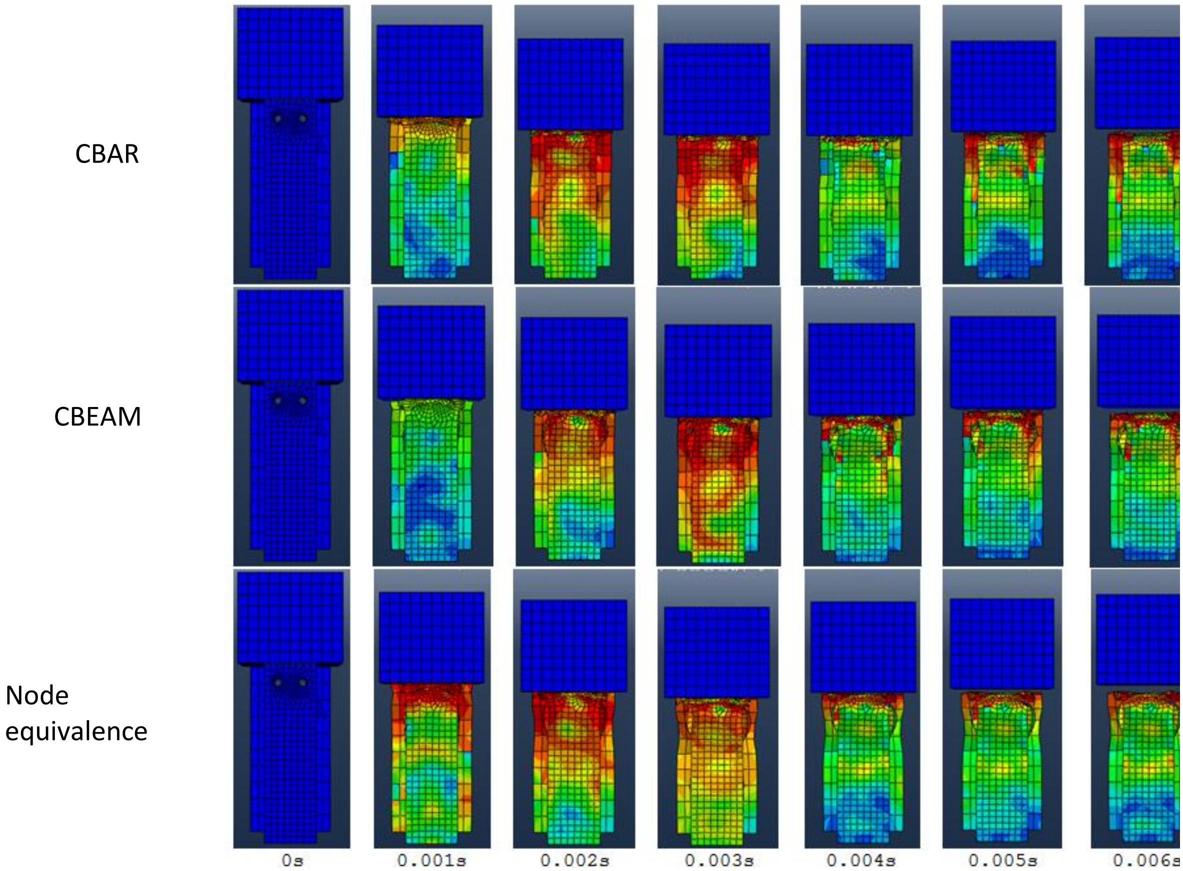

Figure 8. Crash box deformation pattern in dynamic crash analysis

5. Nonlinear buckling analysis on crash box model

Nonlinear buckling analysis was then performed on all crash box models with respective joining type by using same model used in dynamic crash analysis. In this analysis, the crash box models were subjected to mass loading axially in z-axis direction. Instead of rigid impactor with mass and initial velocity, the crash box models were crushed by rigid barrier at a given time and crushing distance. The crash boxes were set up to deform up until half of its original length (100 mm) and the low crushing speed were placed in order to observe the buckling behaviour of the crash box. Contact property remained unchanged with the friction coefficient was set as 0.3.

In nonlinear buckling analysis, among the parameters that are used to evaluate crash box crushing characteristics is the peak crushing force ($\boldsymbol{P_{max}}$). It is the highest force in the load against displacement curve that can indicate the required load to initiate collapse. On the hand, the mean crushing force ($\boldsymbol{P_m}$) is the average of load from zero to total displacement ($\boldsymbol{\delta}$) as shown in equation (**3**) below [18].

$$P_m = \frac{1}{\delta}\int_0^{\delta} P(x)\,dx \qquad (3)$$

Based on the analysis, the value of $\boldsymbol{P_{max}}$ that each crash box model can support before it collapses is shown in Figure 9. Crash box with node equivalence joining has the highest crushing force of 70819 N, which is the point where the column of crash box will start buckling and deform. On the other hand, the crash box with CBEAM joint has the lowest value of crushing force which is 54279 N. The crushing force for crash box with CBAR joint is 67992 N. The deformation modes for each of crash models are as shown in Figure 10. The deformation patterns are shown in the interval of 0.005 s. The deformation ended at 0.02 s where the crashing reach its crushing distance that was set up as its boundary condition. Deformation modes for crash box with CBAR and CBEAM are both started the folding at the middle part while the crash box with node equivalence start folding from the impacted region or the top region. However, the folding behaviour is more stable for the crash box with CBAR elements as compared to the crash box with CBEAM elements.

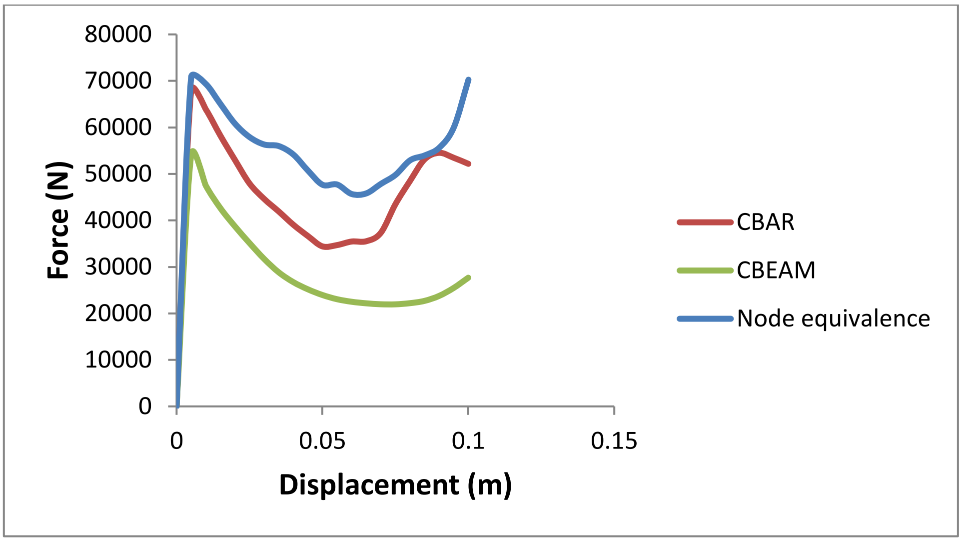

Figure 9. Force diagram for crash box models of respected joint type in nonlinear buckling analysis

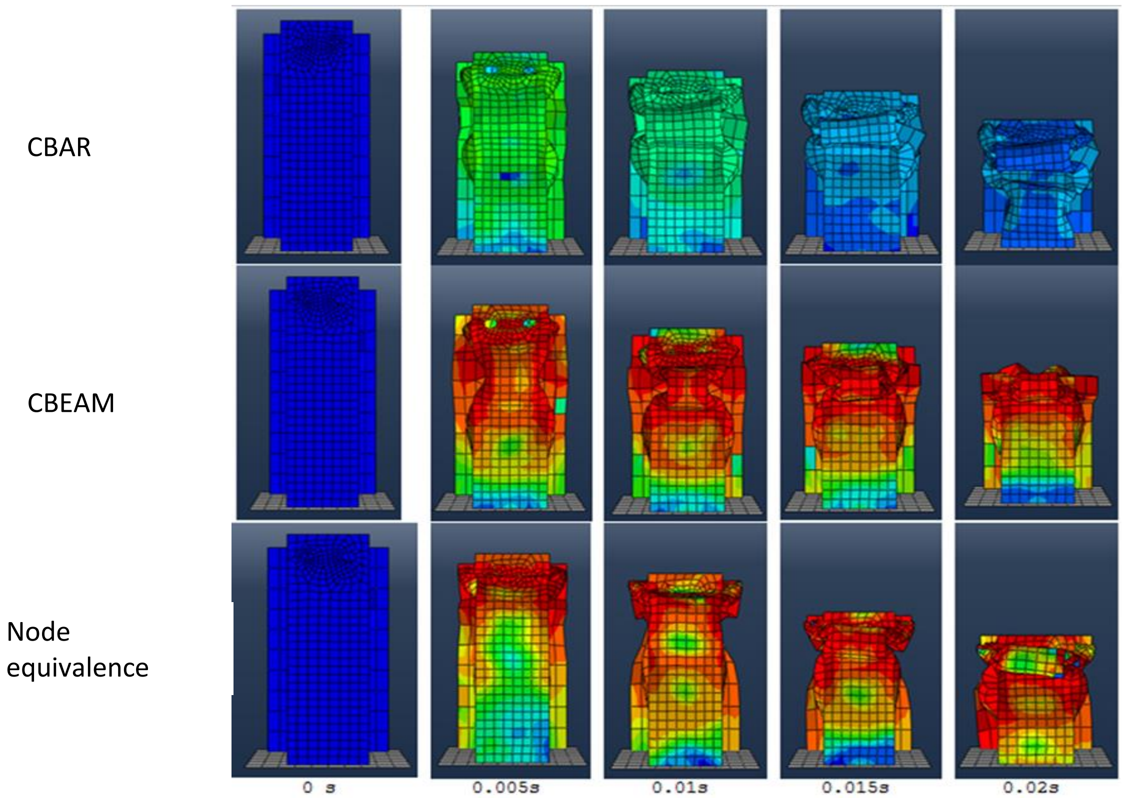

Figure 10. Crash box deformation pattern in nonlinear buckling analysis

6. Conclusion

In the present study, the modal properties and crash behaviour of finite element model of top-hat crash box with trigger and welded joint is investigated. Three different models that were created to model the actual crash box and different joining modelling strategies were used. Based on the output, the crash box modelled with node equivalent method to represent the welded joint shows higher stiffness at the joining area and therefore shows higher value of natural frequencies that the model with CBEAM and CBAR elements as their joining elements. In term of crash behaviour, even if the modal properties of crash box models with CBEAM and CBAR elements shows similar modal behaviour, the model with CBAR element shows higher reaction force compared to the CBEAM. This proves that different type of joint modelling strategies behaves differently. Good correlation with the models that replicate the actual structure behaviour is always needed to ensure the accuracy of computational analysis. Therefore, it is important to have the accurate joining modelling strategy. In future, the application of more joining element such as CWELD, CFAST, CELAS and others in crash and buckling analysis should be investigated.

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