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Modes of Collapse of Compress–Expand Member under Axial Loading

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***Abstract*—**In this paper, a study on the modes of collapse of compress- expand members are presented. Compress- expand member is a compact, multiple-combined cylinders, to be proposed as energy absorbers. Previous studies on the compress- expand member have clarified its energy absorption efficiency, proposed an approximate equation to describe its deformation characteristics and also highlighted the improvement that it has brought. However, for the member to be practical, the actual range of geometrical dimension that it can maintain its applicability must be investigated. In this study, using a virtualized materials that comply the bilinear hardening law, Finite element Method (FEM) analysis on the collapse modes of compress- expand member have been conducted. Deformation maps that plotted the member's collapse modes with regards to the member's geometric and material parameters were then presented in order to determine the dimensional range of each collapse modes.

***Keywords*—**Axial collapse, compress-expand member, tubular member, finite element method, modes of collapse, thin-walled cylindrical tube.

I. Introduction

ENERGY absorbers, such as a crash box, are one type of vehicle safety device, often placed in the front and rear structures of a car to protect passengers from suffering the impact from frontal collision and to reduce car deformation. They have attracted significant interest in automotive industries because of the increasing awareness regarding automotive safety and crashworthiness.

Energy absorbers are systems that convert kinetic energy into another form of energy. One example is the conversion to plastic deformation energy, where kinetic energy is dissipated in the plastic deformation of metallic energy absorbers [1]. Tubular members are the most common shape to be used for energy absorbers because of their frequent occurrence as structural elements. Until recently, studies have been extensively conducted on the tubular members that rely on the plastic deformation of a progressive fold formation process for the absorption of energy (e.g., cylindrical tubes, square tubes, cylindrical tubes with corrugated surfaces, and hexagonal thin-walled tubes with partition plates) [1]–[17].

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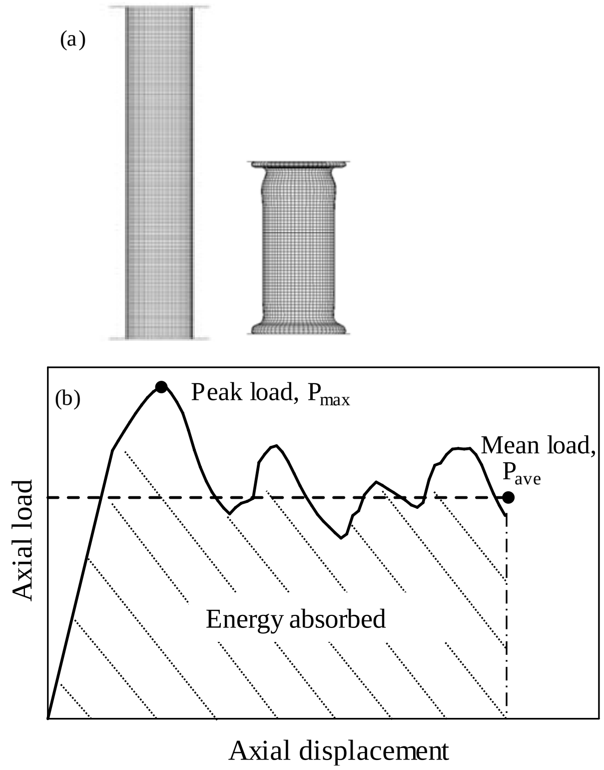

Fig. 1 Axial crush response for cylindrical tube: (a) pre-crushed and post-crushed cylindrical tube model; (b) load-displacement curve from axial crush of cylindrical tube

For instance, Fig. 1 shows the crush characteristics of cylindrical tubes when subjected to axial loading. Here, energy in cylindrical tubes is absorbed by the strain from continuous bending and expanding deformation of the plastic hinge of wrinkles that form during the axial crushing process [2]. When expressed as a load-displacement curve, the process brings a high first-peak load and large load fluctuations. The amount of absorbed energy is directly given from the area under the load-displacement curve. Investigation of crush characteristics on tubular members is very important to determine the feasibility of the members as energy absorbers.

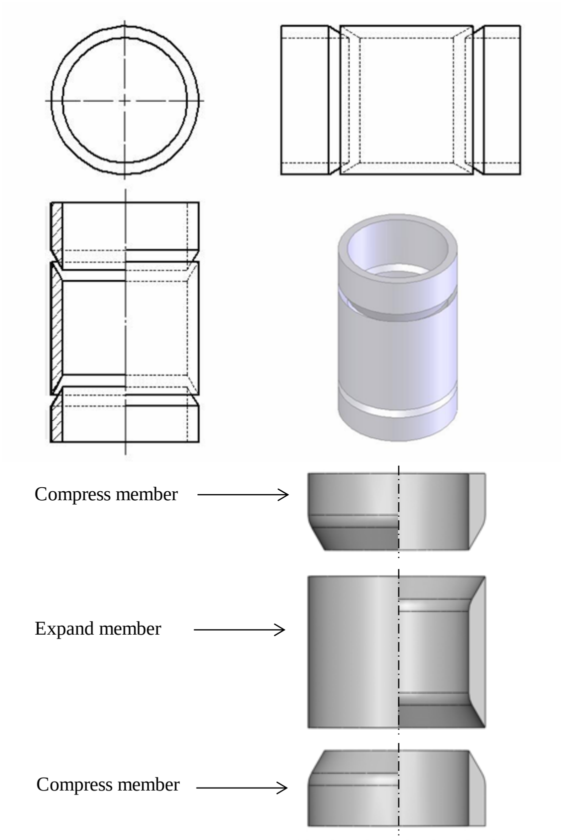

Fig. 2 Compress–expand member geometry

Conversely, investigation on the collapse modes of tubular members when subjected to axial loading is also very important to specify the possible dimensional limit that allows the members to absorb energy efficiently and to specify the preferred deformation shape, which has a large effect on the energy absorption capacity. In a study conducted by Andrews, England, and Ghani [3], seven types of collapse modes of cylindrical tubes were identified (e.g., *Concertina* — axisymmetric and sequential folding starting at one end of the tube; *Diamond* — non-axisymmetric but sequential folding accompanying a change in the cross-sectional shape of the tube; *Euler*—bending of the tube as a strut; etc.). Whereas, Chen and Masuda [4] classified four types of collapse modes: *Concertina, Diamond, Euler,* and *Mix* (mixing of Concertina and Diamond modes). Both studies classify the collapse modes according to the geometric shape of the deformed cylindrical tubes. In another study conducted by Abramowicz and Jones [5], the collapse modes were classified into *Bending* (global buckling of the tubes) and *Progressive folding* (sequential folding starting at one end of the tube) according to the state of deformation in the axial direction.

Most of tubular members with a progressive fold formation as an energy absorption mechanism have problems with instability, large load fluctuations, and poor energy absorption efficiency. In the case of cylindrical tubes, most of them have difficulty withstanding large loads in a small diameter, as reducing the radius would lead to bending failure, whereas increasing the thickness would make local buckling more difficult. For cylindrical tubes with corrugated surfaces, research has found that the collapse modes would be either progressive fold formations that induce load fluctuation (P-mode) or no load fluctuation (S-mode) [6]. In this case, axial crush response with no load fluctuation is desirable since it produces high-energy absorption efficiency, but the limited allowable size is its biggest obstacle. Next, a study on the crushing behavior of hexagonal thin-walled tubes with partition plates [7] found that load fluctuation had decreased but the peak load-to-mean-load gap still affected the energy absorption efficiency.

With the recent trend of industries moving toward more economic and environmentally friendly vehicles, the need for smaller and lighter cars has increased enormously. These trigger a safety issue, particularly for frontal collisions, since the injury risk to a car's occupant increases in smaller and lighter cars [8]. For energy absorbers to be practically deployed in such vehicles, they must be sufficiently small and light, but with a high-energy absorption capability.

To address this issue, new types of tubular members that are light, small and yet capable of absorbing large amount of energy have been continuously proposed. One of them is a tubular member consisting of several combined components as shown in Fig. 2, referred to as the compress- expand member [9], [10]. Instead of plastic deformation of the progressive fold formation process as an energy absorption mechanism; this device will depend on the compression and expansion deformation of combined components to absorb energy. That increase the member's stability, which allow them to have better energy absorption efficiency while remain comparatively small compared to the conventional tubular members.

A. Collapse Modes of Compress–Expand Member

Previous studies on the compress- expand member have proven that the compress- expand member brings significant improvement, in terms of energy absorption capabilities and maintaining stability when compared with the cylindrical tubes [9], [10]. However, similar to most tubular members, under various geometrical and material conditions, the deformations of the compress- expand member when subjected to axial loading can differ from each other completely. These deformations were categorized into several distinctive patterns which commonly referred to as the collapse modes. Collapse modes have impact in energy absorption capability of tubular members. They also have a direct relation with the geometrical dimension and material properties used in designing the member. Therefore, it is important to clarify this relation in a comprehensible manner.

In this study, we investigated the collapse modes of the compress–expand member and made a comparison with the collapse modes of cylindrical tubes. The collapse modes were based on the state of deformation in the axial direction. For the cylindrical tube, as shown in Fig. 3, this study only focused on three modes of collapse: the *stable mode* (sequential folding), *unstable mode* (global buckling), and *transition mode* (global buckling after a number of folds have formed). Fig. 4 shows the corresponded load- displacement curves for each collapse modes. Load response with fluctuation as a result of continuous formation of folds can be seen for load- displacement curve of *stable mode*. The same pattern can be seen for the load- displacement curve of the *transition mode* but with the load decrease at the end due to global buckling. For *unstable mode*, the load response decreases rapidly right after the global buckling occurred.

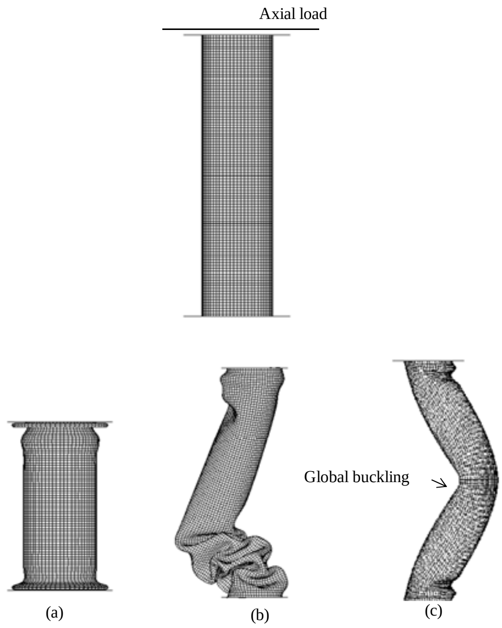

Fig. 3 Collapse modes of cylindrical tubes: (a) stable mode; (b) transition mode; (c) unstable mode.

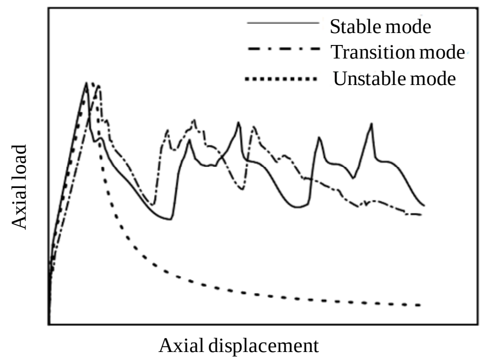

Fig. 4 Load-displacement curves for each of the collapse modes: (cylindrical tubes)

For the compress–expand member, when subjected to axial loading, three collapse modes have been identified:-

a) Axial collapse parallel to the axial axis where compress members penetrate into the expand member with no folds formed.
b) Axial collapse parallel to the axial axis where compress members penetrate into the expand member with folds formed at the end of the penetration.
c) Expand member bends during penetration of compress members.

Similarly, like the collapse modes of the cylindrical tubes, the collapse modes for the compress- expand member were each classified into:- a) *stable mode*, b) *stable mode with folds*, and c) *unstable mode*. Fig. 5 shows each collapse modes for compress- expand member that have been classified.

Next, the corresponded load- displacement curves for each collapse modes of the compress- expand member are shown in Fig. 6. For *stable mode*, monotonous increase of load was seen as a result of gradual compression of compress member and expansion of expand member during compress member penetration. When both compress members at the upper and bottom side start to contact, a rapid load increase appears in the load- displacement curve. Similar pattern can also be seen on the load- displacement curve for *stable mode with folds*. However, as folds appear at the end of the penetration, load response start to fluctuate intensely. For the *unstable mode*, as a result of global buckling, load response decreases rapidly even though after a smooth load increase was obtained.

Each of collapse modes that were classified for both cylindrical tubes and compress- expand member have shown different load- displacement characteristics. It is also clear that the global buckling brings failure to both the compress–expand member and the cylindrical tubes in terms of their ability to absorb energy. Based on the load-displacement curves for all collapse modes as shown in Fig. 4 and 6, load response decreased drastically after global buckling occurred. It is therefore important to have guidelines and indicators, which designers can then use to predict the most suitable design criteria for energy absorbers to reduce the risk of global buckling failure.

In this study the axial collapse modes of compress–expand members were investigated using Finite Element Method (FEM) analysis. The collapse modes were studied with respect to geometry and material factors. The results obtained from the numerical analyses were then used to plot the collapse modes distribution map of the proposed member. This distribution map can be used to predict the geometry limit of when the collapse modes of the compress–expand member start to turn into an *unstable mode*. Finally, a comparison with the results obtained for cylindrical tubes were conducted to highlight the improvement made by the proposed member.

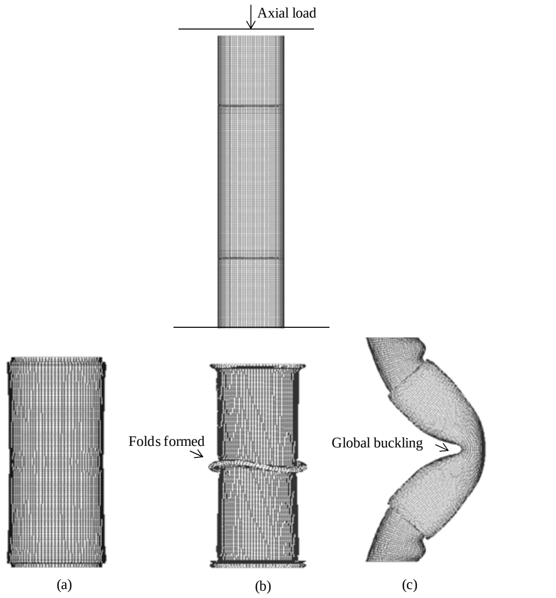

Fig. 5 Collapse modes of compress–expand members: (a) stable mode; (b) stable mode with folds; (c) unstable mode

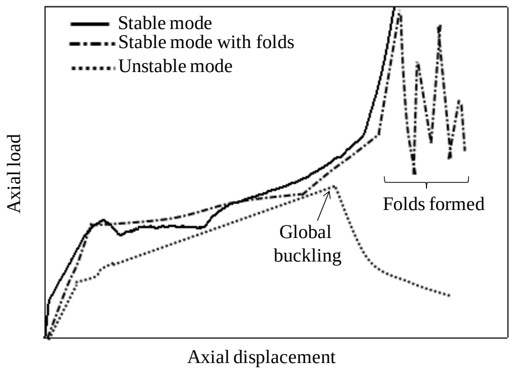

Fig. 6 Load-displacement curves for each of the collapse modes: (compress–expand member)

II. Analysis and Results

This study investigated the effect of geometrical factors (dimension) and the material factors (work hardening coefficient ratio, E_h/E) towards the collapse modes of the compress- expand member. Comparison with the collapse modes of cylindrical tubes were also conducted. TABLE I and II shows the geometrical and material parameters used in this analysis. Each geometrical dimensions (length, L, thickness, t and radius, R) were chosen appropriately to construct the length, *L* to radius, *R*, aspect ratio, *L/R* value, and the radius, *R*, to thickness, *t*, aspect ratio, *R/t* value to be 5, 10, 15, 20, 25, 30, 35 and 40 respectively. Then, collapse modes for each *L/R* and *R/t* were plotted to create a deformation map. However due to time constraint, several results that are corresponded to certain *L/R* and *R/t* value will not be shown.

TABLE I
Geometrical Dimension of Compress−expand Member for E_H/E=1/20

Thickness, t [mm]	Length, L [mm]	Radius, R [mm]
1	25, 50 , 75, 100, 175, 125, 150, 200, 225, 250, 300, 375, 400, 450, 500, 525, 600, 625, 700, 750, 800, 875, 900, 1050	5, 10, 15, 20, 25, 30

Geometrical Dimension of Compress−expand Member for E_H/E=1/100

Thickness, t [mm]	Length, L [mm]	Radius, R [mm]
1	25, 37.5, 50, 62.5, 75, 87.5, 100, 112.5, 125, 150, 175, 187.5, 200, 225, 250, 262.5, 300, 312.5, 350, 375, 400, 437.5, 450, 500, 600, 612.5, 625, 700, 750, 800, 875, 900, 1050	5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 35, 40
2	50, 75, 100, 125, 150, 175, 200, 225, 250, 300, 350, 375, 400, 450, 500, 525, 600, 625, 700, 750, 800, 875, 900, 1000, 1050, 1200, 1225, 1250, 1400, 1500, 1600, 1750, 2100	10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80

A. Analysis Method

This study used MSC. Marc Mentat, a non-linear finite element analysis solution to simulate the static axial collapse of the compress–expand member. An isoparametric, quadrilateral, arbitrary 4-node axisymmetric solid element was used to create the virtual model. Then, to capture and simulate a precise deformation of the compress–expand member, the model was meshed in an axial and radial axis small enough to be an approximately true square-shaped element. For material properties, the model was defined with the properties of steel and assumed an isotropic body that obeyed the Von Mises yield

TABLE II
GEOMETRICAL DIMENSION OF CYLINDRICAL TUBES FOR E_H/E=1/20

Thickness, t [mm]	Length, L [mm]	Radius, R [mm]
1	25, 50 , 75, 100, 175, 125, 150, 200, 225, 250, 300, 375, 400, 450, 500, 525, 600, 700, 750, 800, 875, 1050	5, 10, 15, 20, 25, 30, 35, 40

GEOMETRICAL DIMENSION OF CYLINDRICAL TUBES FOR E_H/E=1/100

Thickness, t [mm]	Length, L [mm]	Radius, R [mm]
1	25, 37.5, 50, 62.5, 75, 87.5, 100, 112.5, 125, 150, 175, 187.5, 200, 225, 250, 262.5, 300, 350, 375, 400, 450, 500, 525, 600, 700, 750, 800, 875, 1050	5, 7.5, 10, 12.5, 15, 17.5, 20, 25, 30, 35, 40
2	50, 75, 100, 125, 150, 175, 200, 225, 250, 300, 350, 375, 400, 450, 500, 525, 600, 700, 800,	10, 15, 20, 25, 30, 35, 40

criterion. Bilinear hardening law, as shown by equation (1), was used to represent its stress–strain relationship, post-yield condition, and strain hardening properties. The stress state was assumed as uniaxial in nature. For boundary conditions, as illustrated in Fig. 7, the compress–expand model was applied with an axial load at the upper end through a rigid wall modeled with surface elements, whereas at the lower end all the degrees of freedom were fixed to another rigid wall. The rigid wall at the upper end was moved downward under displacement control with no friction applied. However, a glue function was used to keep the upper end of the compress–expand model fully restrained immediately after the contact with the rigid wall.

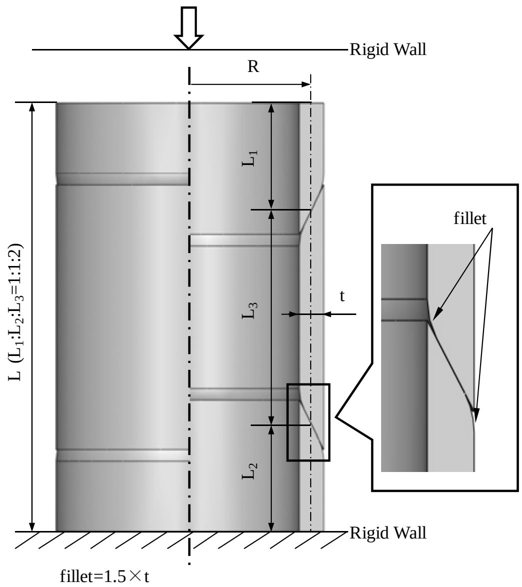

Fig. 7 Analysis model of the compress–expand member

In the analysis, the updated Lagrange method was used to formulate the geometric non-linear behavior. The Newton-Rahpson method was used to solve the non-linear equations.

$$\sigma = E\varepsilon\ , \quad (\varepsilon < \frac{\sigma_y}{E})$$
$$\sigma = \sigma_y + E_h(\varepsilon - \frac{\sigma_y}{E}), \quad (\varepsilon \geq \frac{\sigma_y}{E}) \qquad (1)$$

where: -
σ: stress,
E: Young's modulus,
ε: strain,
E_h: work hardening coefficient,
σ_y: yield stress,
(In this analysis the following values were used:- E=206 GPa, σ_y=206 MPa, E_h/E (work hardening coefficient ratio)=1/20 and 1/100)

B. Analysis Results: Collapse Modes of Compress–expand Member

From the FEM analyses conducted, the results obtained were only focused on the model deformation diagram for collapse modes. The collapse modes of each model were plotted into a deformation map; where vertical axis represents the length (*L*) to radius (*R*) aspect ratio (*L/R*) and horizontal axis represents the radius (*R*) to thickness (*t*) aspect ratio (*R/t*). The plotted deformation maps were shown in Fig. 8 and 9.

From Fig. 8, for work hardening coefficient ratio, E_h/E=1/20, the compress–expand member deformed in *stable mode* for all *R/t* values at *L/R* below 20. As the *L/R* value increased to 20 and above, the border between *stable mode* (including the *stable* *mode with folds*) and *unstable mode* rose gradually with the increase of *R/t* value.

Next, for E_h/E=1/100 (Fig. 9), the border gradient increased slightly compared to that obtained from E_h/E=1/20. This means that reducing the material stiffness can also improve the collapse modes of the compress- expand member. However, the change from the *unstable mode* into *stable mode* only occurred at the vicinity of the boundary between *stable* and *unstable mode*.

Here, from both deformation maps, the collapse modes of the compress–expand member will have higher probability to deform in *unstable mode* when the length to radius aspect ratio, *L/R* value is increased. On the other hand, if the radius to thickness aspect ratio, *R/*t is increased, the probability for *stable mode* deformation to take place will increase. Therefore, if length is the parameter to be increased, the stability of the compress- expand member can be improved by raising the radius or reducing the thickness accordingly.

The deformation maps of the compress–expand member plotted in this study are very important in the design process of the member and could be the key reference in the future. For example, as an indicator for choosing the suitable dimension for optimum performance of the member, if the compress–expand member emerges to be used commercially.

C. Analysis Results: Collapse Modes of Cylindrical Tube

Fig. 10 and 11 show the deformation map of cylindrical tubes. Both figures show that cylindrical tubes had a very limited dimension to deform in a *stable mode*, although reducing the work hardening coefficient brings improvement to a certain limit.

In Fig. 10, for work hardening coefficient E_h/E=1/20, a distinctive border between stable mode and unstable mode was obtained at approximately *L/R*=10~15 range. When the work hardening coefficient, E_h/E was reduced to 1/100, range for *stable mode* to take place increased at *R/t* near 30.

D. Analysis Results: Comparison of Collapse Modes between Compress-expand Member and Cylindrical Tube

In this study, the proposed compress–expand member absorbs energy from the compression and expansion deformation of its combined components [9]. Compared to the cylindrical tubes that absorb energy through the progressive fold formation, the proposed member has more stability. To prove this, a comparison was made between the deformation maps for compress–expand members and cylindrical tubes. Fig. 12 and 13 shows the deformation map for the compress–expand member overlaps with the map of the cylindrical tubes. The figures show that the proposed compress–expand member covers a wider area of dimension especially the *L/R* range in which to allow the *stable mode* to take place compared to the cylindrical tubes.

Therefore, with a wider dimensional limit, the compress–expand member proposed in this study will be the more convenient choice for designing energy absorbers, rather than the cylindrical tubes.

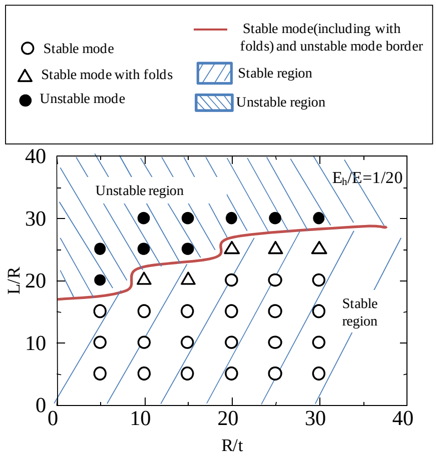

Fig. 8 Deformation map for compress–expand members with work hardening coefficient ratio, E_h/E=1/20

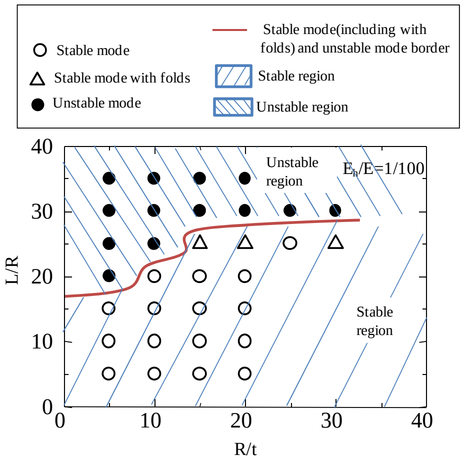

Fig. 9 Deformation map for compress–expand members with work hardening coefficient ratio, E_h/E=1/100

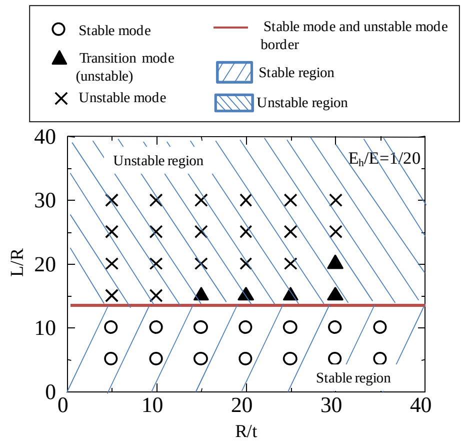

Fig. 10 Deformation map for cylindrical tubes with work hardening coefficient ratio, E_h/E=1/20

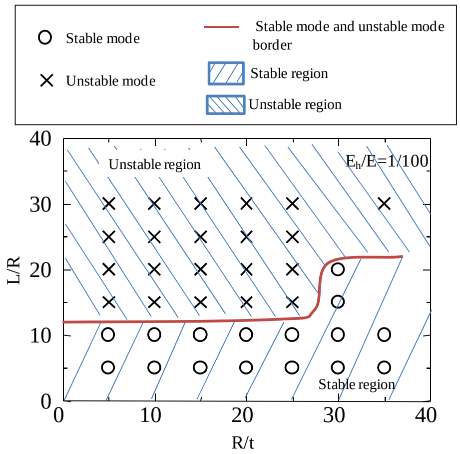

Fig. 11 Deformation map for cylindrical tubes with work hardening coefficient ratio, $E_h/E=1/100$

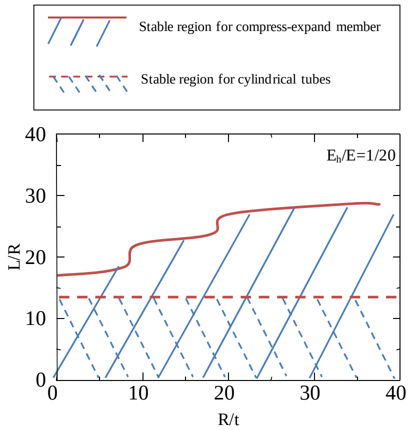

Fig. 12 Deformation map for the compress–expand member overlaps with the deformation map for the cylindrical tubes (work hardening coefficient ratio, $E_h/E=1/20$)

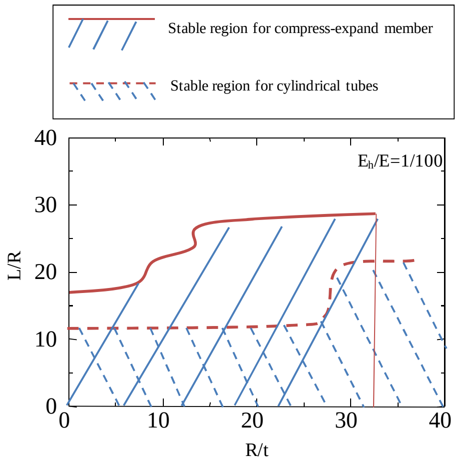

Fig. 13 Deformation map for the compress–expand member overlaps with the deformation map for the cylindrical tubes (work hardening coefficient ratio, $E_h/E=1/100$)

III. Conclusions

This study has given a clear view on the collapse modes of the compress–expand member, which have an important influence on the designing aspects of the member in the future. In addition, comparison made with the cylindrical tubes, serves as visible proof that the proposed member brought several improvements.

From the numerical analyses and experiments conducted, the following conclusions can be drawn:

1) The collapse modes of compress- expand member can be categorized into three modes which are:-
    a) *Stable mode*: axial collapse parallel to the axial axis where compress members penetrate into the expand member with no folds formed.
    b) *Stable mode with folds*: axial collapse parallel to the axial axis where compress members penetrate into the expand member with folds formed at the end of the penetration.
    c) *Unstable mode*: expand member bends during penetration of compress members
2) The collapse modes of the compress–expand member will gradually change to *unstable mode* if the length to radius aspect ratio, *L/R* is increased and radius to thickness aspect ratio, *R/t* is decreased.
3) Reducing the work hardening coefficient ratio of the compress- expand member makes the compress-expand member collapse modes change from the unstable mode into the stable mode more easily. This also means that less stiffer materials increase the probability for the compress-expand member to deform in *stable mode*.
4) Compress- expand members have a higher *L/R* range to deform in *stable mode* compared to the cylindrical tubes. Therefore, the degree of freedom to be chosen in designing the compress- expand members are larger than in designing the cylindrical tubes.

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