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REVIEW ARTICLE

A Review on Post – Buckling Behaviors of Composites: Crippling Phenomenon

Kompozitlerin Son Burkulma Davranışı Üzerine Bir İnceleme: Burkulma Sonrası Dayanım Olgusu

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Abstract

Buckling phenomenon is a common failure mode for composite materials under the effect of compressive loading which is mainly investigated in two stages as pre – buckling and post – buckling. At the pre – buckling phase, the deformations take place temporarily in elastic range. However, load carrying capacity of a member can be increased by regarding the post – buckling process. Therefore, it is important to determine the final and maximum load carrying ability of the structure. Since, at the end of the post – buckling, the body cannot carry load and crippling failure takes place. In this review article, crippling behavior of the composite structures is investigated. After describing the crippling phenomenon, this study mainly investigates both experimental and theoretical points of views. In this scope, affecting parameters such as stacking sequence, geometrical properties and boundary conditions are determined. Then, the improved theoretical approaches are stated. The compatibilities of the test results are assessed with theoretical studies.

Keywords: Post – buckling, crippling, composite, one – edge – free (OEF), no – edge – free (NEF)

Özet

Burkulma, basma yüklemesinin etkisi altındaki kompozit malzemeler için yaygın bir hasar biçimidir. Burkulma olgusu temel olarak ön burkulma ve son burkulma olmak üzere iki aşamada incelenir. Ön burkulma aşamasında, bozulmalar geçicidir ve elastik bölgede gerçekleşir. Ancak son burkulma aşaması dikkate alınarak bir yapının yük taşıma kapasitesi arttırılabilir. Bu nedenle yapının nihai ve maksimum yük taşıyabilme kapasitesinin belirlenmesi önemlidir. Çünkü son burkulma aşamasının nihayetinde ilgili parça, daha fazla yük taşıyamadığından hasar meydana gelir. Bu inceleme makalesinde de kompozit yapıların son burkulma dayanımları incelenmiştir. Son burkulma dayanımı tanımlandıktan sonra bu çalışma, temelde deneysel ve teorik olarak yapılan çalışmaları ele almaktadır. Bu kapsamda dizilim sırası, geometrik özellikler ve sınır koşulları gibi etken parametreler belirlenmiştir. Daha sonra geliştirilen teorik yaklaşımlar anlatılmıştır. Test sonuçlarının uygunluğu teorik çalışmalarla değerlendirilmiştir.

Anahtar Kelimeler: Burkulma sonrası, son burkulma dayanımı, kompozit, bir kenarı serbest, kenarları serbest olmayan

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1. INTRODUCTION

Aviation industry is one of the areas where the employment of composite materials is widespread day by day. In this point of view, it is necessary to determine the usage limits of the composites. Therefore, failures of composites need to be determined by considering the applied loads. Since, the characteristics and distribution of the load are important to prevent the structure from an unexpected out of use. Based on this, it is possible to state that the most critical loading type for the composites is compression.

One of the failures caused by compression loads is buckling which is known as the deformation of the body shape suddenly under the effects of compressive loads. The concept of buckling is explained by Euler and it is pointed that the body keeps its straightness as long as the applied load is less than the structural failure load. In other words, when the axial compressive load reaches and exceeds the structural failure threshold at a member, the body loses its stiffness and stability suddenly. This failure is called as 'buckling'.

Buckling phenomenon is mainly investigated in two stages as pre – buckling and post – buckling. At the pre – buckling stage, the deformation is temporary up to a critical buckling threshold which means that the structure is deflected elastically. Namely, at the pre – buckling process, the equilibrium is conserved, and the body returns its stable condition at any disturbances. However, the members have still load carrying capability after initial buckling. Due to the weight saving precautions of the structures for especially aerospace industry, it is desired to take the advantages of more load carrying potential. So, the applied load is increased, and the critical buckling threshold is exceeded. Then, the plastic deformation starts, and this stage is called as post – buckling. Despite that the post – buckling phase is attractive during designing to deal with less structural weight, the significant aspect is to be able to determine the upper limit of the post – buckling stage accurately due to the prevention of the body from detrimental damages. This maximum load carrying capability in the post – buckling stage is simply known as crippling strength [1-2]. Kassapoglou [1] states that crippling failure can be prioritized instead of column buckling failure during sizing the parts Since, after first crippling, the remaining members of the stiffened panels are still able to resist the loading. On the contrary, if column buckling is observed firstly, there is a risk to face the collapse of the whole body at once [1].

Describing the crippling strength with experimental and analytical approaches is quite straightforward for isotropic materials like metals. However, when composites are taken into consideration, the methods to reach the crippling strength become more complex due to the anisotropic features of the material. In spite of all difficulties, some experimental and theoretical improvements have been made to find the crippling strength for composites [2-10]. In order to understand the crippling mechanism, it would be better to concentrate on the acting parameters such as stacking sequence, geometrical properties of the profiles, loading and displacement constraints. To illustrate, the position and the amount of 45° plies play a key role to enhance the crippling strength [1, 11–12]. Besides, flange width, fillet radius and cross sections of the profiles have a significant contribution on crippling [1, 13–16]. Also, the loading and displacement restrictions affect the post –

buckling behaviors of the structures [17–19]. Mainly, the investigations essentially stand on experimental and theoretical approaches. By considering these kinds of research that have been made so far, this article is prepared about the crippling behaviors of the composite structures under the effects of compressive loadings. Firstly, the crippling phenomenon is described. Then, the effective parameters are presented with the help of experimental works. In this scope, the effective parameters like stacking sequence, geometrical properties, loads, and boundary conditions are introduced by regarding the empirical studies. Moreover, the testing procedure for composite crippling is simply presented. Then, theoretical searches are emphasized in detailed. Finally, the article is concluded with a summary.

2. DESCRIPTION OF CRIPPLING CONCEPT

Buckling is defined as the shape change of a body due to loss of stability under the effects of compression and shear loads. Depending on the loading and boundary conditions, buckling can occur on the entire structure or in a restricted area. In this manner, it is possible to mention two types of buckling as global and local. While lateral deflection is observed in global buckling as shown in Figure 1 a), the deflection is partial and axial form of the member is preserved in local buckling as displayed in Figure 1 b).

a) b)

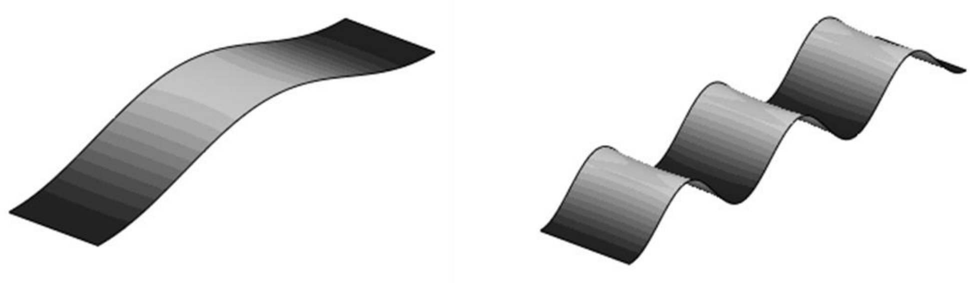

Figure 1. Buckling types a) Global buckling b) Local buckling.

By considering the level of loading, buckling takes place in two stages as pre – buckling and post – buckling. In pre – buckling stage, the body returns its original shape after any disturbances. In other words, there is no plastic deformation in pre – buckling region and the member is still capable of much more loads. As the applied load is increased and excessively far away from the buckling threshold, the process becomes post – buckling in which the deformation is permanent. Even if this situation seems a chance to be able to carry more loads with the help of plasticity, it is significant to determine the upper bound of the load carrying capacity to ensure the employment of the structure in safe. If the applied load exceeds the maximum value in the plastic region, then crippling failure is observed. The diagram in Figure 2 denotes a typical buckling behavior of a member. Accordingly, pre – buckling stage is indicated in linear region. Post – buckling region is started after exceeding the critical buckling load. Hence, plastic deformation is started. The maximum load carrying capacity is reached and then crippling failure begins [20]. It should be noted that crippling strength has a lower value than material strength [1].

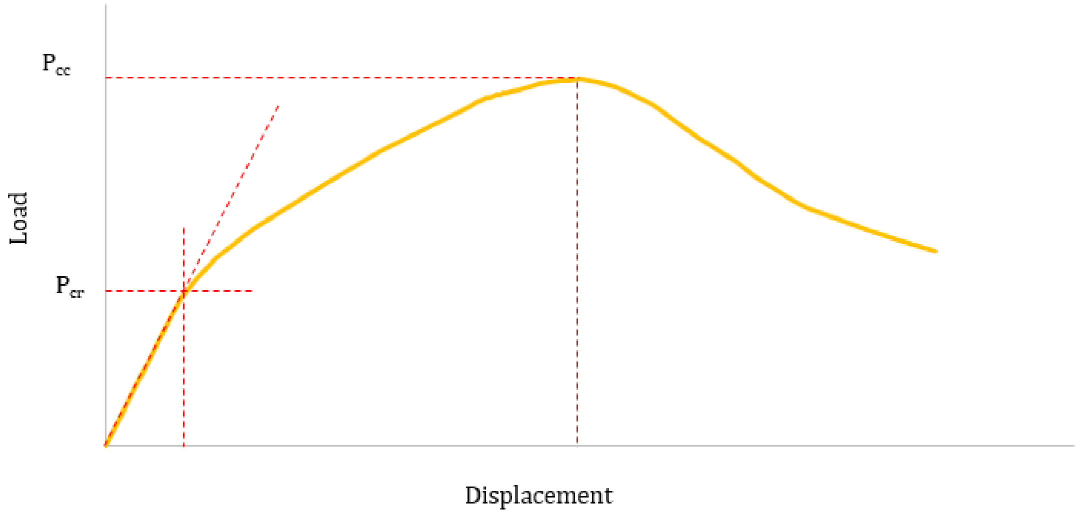

Figure 2. Pre – Buckling & Post – Buckling behavior of a thin structure.

In general, Euler approach is utilized to determine the buckling stress. For this aim, a diagram is depicted as in Figure 3 that helps to find the critical buckling stress level of a structure for the corresponding length. This Euler approach has been improved empirically by Johnson for the failure of short columns. Most of the time, the length of the structure is symbolized with a term called as 'slenderness ratio' which is based on the ratio of the body length to the cross-sectional area. It is possible to identify the buckling types by looking at the slenderness ratio. Consequently, high slenderness ratio means that the failure mode is global buckling. As the slenderness ratio decreases, the main failure mechanism generally becomes due to local buckling. It should be noted that if the slenderness ratio is below a certain value, crippling mechanism excites the governing failure mode. Besides, despite that Johnson – Euler approach is generally utilized for metals, there are much research that use the same approach for composites to specify the critical column length [3, 6, 21–26].

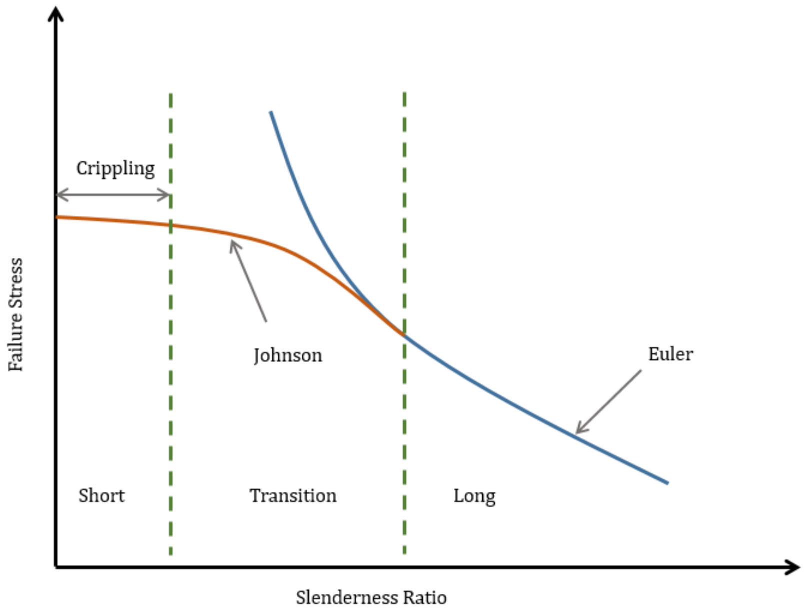

Figure 3. Buckling behavior of a column.

3. EXPERIMENTAL STUDIES

Nowadays, composites are preferred at the industries rather than metals; but the calculations and/or assessments with composites are not simple like metals due to anisotropy. Therefore, empirical methods become inevitable after a while. In this point of view, it is stated that experimental approaches are also frequently employed to assess the local buckling and crippling behaviors of the composite bodies.

At the early phase of the crippling phenomenon, Spier et al. [3–4, 27–30] made many investigations by considering composite materials. These studies were mainly based on empirical practices at which the crippling curves were created in non – dimensional form by following the similar methodology to generate metallic crippling graphs. It was noticed that Johnson – Euler parabola, which was employed for metal buckling, helped to interpret crippling of laminates. Besides, classical buckling theory was utilized to predict crippling strength for laminated plates mathematically. At the beginning, the analytical approaches were inconsistent with test results. Then, the reasons of unconformities were generally considered to be the boundary conditions. As the application of boundary conditions and calculations were improved, it was observed that the test results were converged to theoretical values. However, it was realized that buckling strength were mostly conservative to determine crippling.

In general, the usage of orthotropic laminates is common to catch the isotropy at the composite materials. Noticeably, plies are often laid up in symmetric and balanced form to enhance the material property. Thus, it could be easier to deal with the behaviors of the laminate under the effects of loadings. In literature, there are a lot of searches about the post – buckling of composites which are designed as orthotropic [6–7, 31–37].

Experimental studies provide to understand the mistakes during modeling and specify the effecting parameters of crippling. Therefore, verification the theoretical approach with tests is essential for the future studies. For this purpose, the affecting parameters and crippling test procedures will be handled in this section with details.

3.1. Effective Parameters of Crippling

Obviously, experimental studies show that there are lots of factors affecting the crippling behaviors of the composite structures. Stacking sequence, boundary conditions (e.g., no – edge – free, one – edge – free, etc.) and geometrical properties of the cross sections (e.g., cross sections, fillet radius, etc.) are some of the influential parameters for composite crippling. In this part, these effects are assessed one by one.

3.1.1. The Effects of Layup Properties on Crippling

Composites are created by combining two or more materials for a certain intention like high stiffness, lightness and so on. Moreover, by changing the fiber orientation, stacking sequence and/or constituents, it is possible to enhance the composite qualifications according to the purpose of the usage. By keeping this point of view, the roles of the material in the crippling failure and the methods of the material improvement against post – buckling failure are investigated in this paper.

Typically, modifying the layup is the most appealed way to prevent the laminated structure from crippling. It is possible to achieve this material improvement in two ways as changing the fiber orientation and changing the stacking sequence at each layer. Therefore, the layup properties of composites are significant for post – buckling. So far, many investigations have been made by researchers to determine the crippling stress of composites for different layup configurations.

In order to attain the homogeneity, fibers are generally placed as symmetrical and balanced [12]. During arranging the layup, it is expected to consider the critical failure modes of the structure [7, 9, 38–43]. To illustrate, both experimental and analytical studies have proved that 45° ply is the most powerful fiber orientation for crippling [1, 4, 40, 41, 44]. Besides, it is necessary to locate the 45° plies as far as possible to reduce the failure due to crippling [1, 12–13, 41]. On the other hand, it is known that 0° ply should also be positioned away from the midplane of the laminate to enhance the material strength [1]. Although it seems that there exists a conflict at the place of the fiber orientation, a compatible design is achieved depending on the mission of the structure. During designing the members, if the axial loading causes failure, 0° plies (or 90° for transverse direction) are utilized to increase the strength. Additionally, 45° plies are added to laminate to improve shear loading capability [12].

Taking everything into consideration, it is specified that the crippling strength can be improved by changing composite material’s layup and/or fiber orientation. Despite that 45°plies have significant importance to determine crippling, it is thought that geometrical factors have more influences on crippling than stacking sequence [13, 45].

3.1.2. The Effects of Geometrical Properties on Crippling

Obviously, the geometrical properties of the profiles such as cross – sectional area, flange width, web width, thickness and fillet radius are remarkable factors to determine composite crippling. Geometrically, flange width (b_f), web width (b_w), thickness (t) and fillet radius (r) for various profiles are exemplified as in Figure 4 a). Commonly, these parameters are expressed in rational formats during evaluations. To illustrate, flange width – to – thickness ratio is one of the major elements for formulations that should be cared to approach composite crippling [1]. Likewise, crippling strength is usually represented in proportional form with buckling strength.

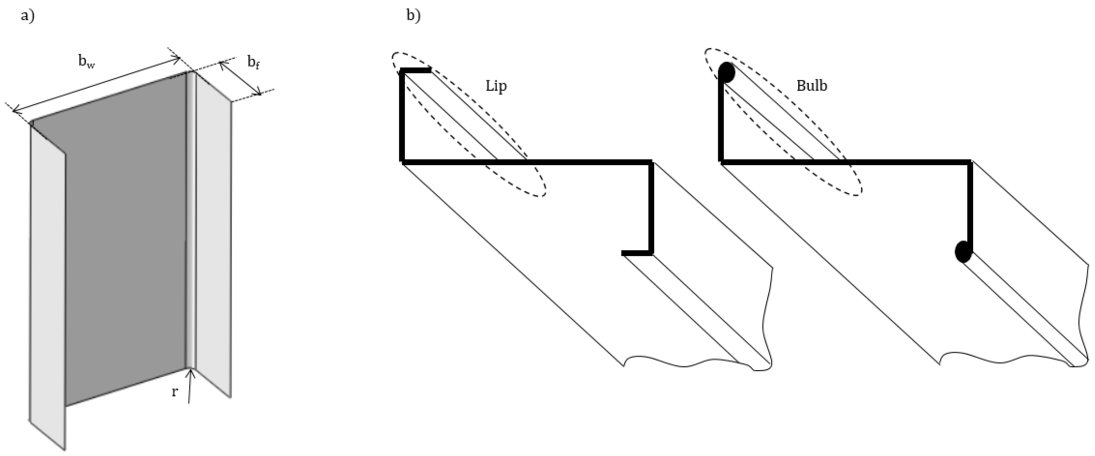

Figure 4. Geometrical parameters of crippling a) Dimensional properties b) Precautions.

Flanges and webs have important roles to specify the buckling behaviors by enhancing the structural stiffness. Notwithstanding, very long flange or web widths might have negative effects on buckling and crippling after a while. Similarly, very short widths may not provide the intended contribution. Therefore, it is required to find optimum flange / web widths to prevent from buckling and crippling [13, 46–49]. Kweon [13] displayed the buckling sensitivity of a stringer for constant web height and various flange widths in Figure 5. Accordingly, the stringer globally buckled due to the small flange width – to – length ratio. However, as flange width ratio was increased, local buckling had become prior instead of global; because flange had behaved like a plate and bending moment of inertia had also increased. Eventually, it was pointed out that the restriction effects of web height for a Z section had decreased with enhancing the flange width too much and local buckling had also decreased subsequently. Moreover, despite that it seems stacking sequence had been one of the most powerful actors on local buckling and crippling, the results of the researches had showed that flange width effect had a more dominant role on post – buckling strength [13].

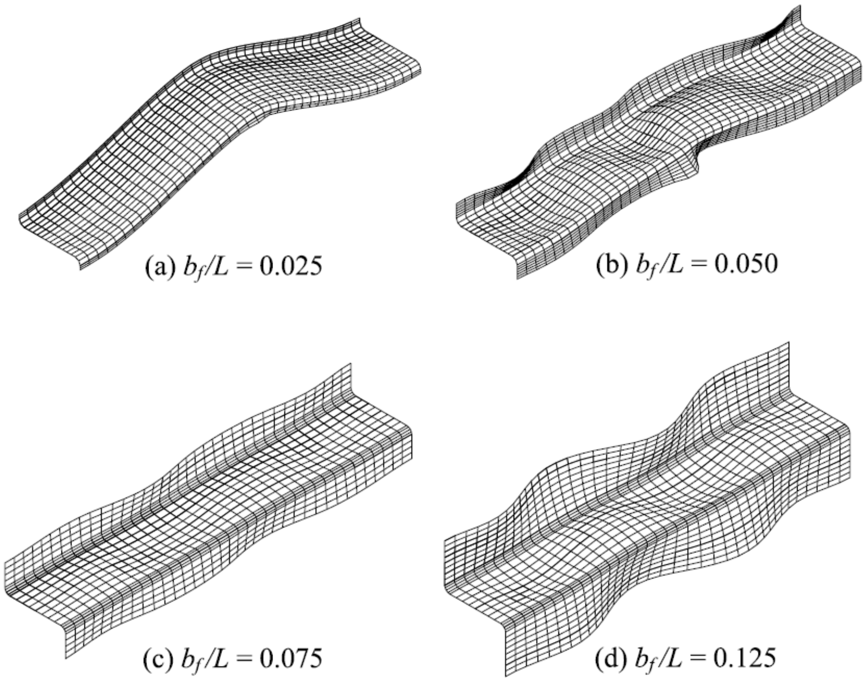

Figure 5. Post – buckling behaviors for various flange widths (b_w / L = 0.175) [13].

As another geometrical precaution, the flange widths might be extended with lips and bulbs as indicated in Figure 4 b) to avoid from the buckling and crippling failures [50–55]. Since, it is obviously known that lips and bulbs put rotational constraints to the free edges. The dimensions of these extensions affect the failure strength, but it should be remarked that the applications of lips and bulbs are widespread for metallic materials. So if the material is composite, it is necessary to verify the effects of lips and bulbs on crippling with both experimental and theoretical investigations.

It is a common application to connect the flanges and webs via a radius as displayed in Figure 6. This kind of region is mostly called as fillet radius which is another valuable geometrical parameter that should be taken into consideration in the buckling and crippling calculations [1, 38, 56–57]. Since structural integrity is broken down at the corner joint and thus, the mechanical responses of the laminated parts under the effects of forces are dissimilar to metallic bodies. Additionally, it is worthy to note that there are gaps at the junction region that are enclosed with filler as shown in Figure 6. Depending on the geometry of the gap and filler property, stress distribution at the fillet radius is not soft due to the inconsistent properties between plies and filler like thermal expansion, stiffness, and Poisson's ratio [58–61]. So, it is tried to reduce the influences of the gaps by reinforcing the fillers with various manufacturing techniques such as braiding [62], weaving [63], laying up [64–65] or any other ways [59, 62, 66–67]. Similarly, it is attempted to modify the filler geometry in order to minimize the peak stresses at the connection region in various ways like changing fillet radius [57, 67–70], splitting the filler region [71–73], and / or other approaches [74–75]. Bonanni et al. [38] signified that the increment at the fillet radius was the reason of increase in buckling and crippling strengths. The reason of this increase was explained with the existence of resin material. Moreover, in that study, it was emphasized that there was no ascend in buckling and crippling stresses for a Z – section due to the absence of filler. Likewise, Gan et al. [56] explained the reason of the local buckling strength increment as the rising in the fillet radius for I beams. Still, more detailed investigations about the fillet radius effect on buckling and crippling for composites are required to establish a correct assessment.

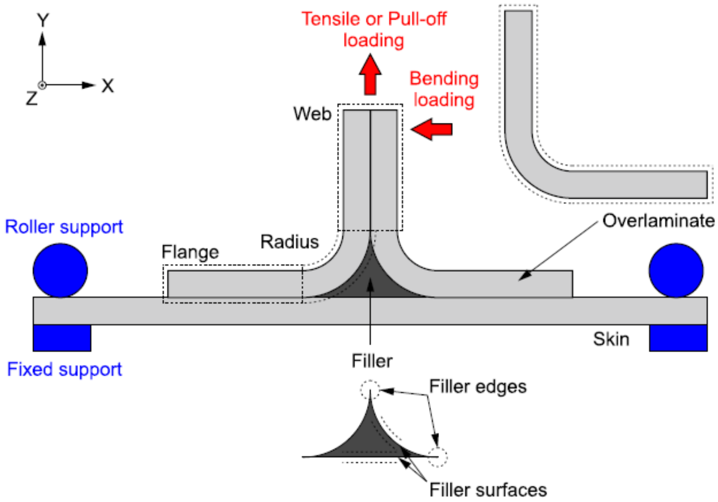

Figure 6. Filler geometry [59].

To sum up, geometrical factors have valuable effects on post – buckling responses of the members. In addition to make a change in flange and web widths, it is also recommended to take into account an improvement in fillet radius for an enhancement in crippling strength. Nevertheless, it should be kept in mind that more investigations are necessary for fillet radius effect on post – buckling strength. Moreover, cross sections have also considerable influence on load carrying capacities of the structures [16]. Therefore, modifying the profile of the section can be assessed as an option during designing the structures.

3.1.3. The Effects of Boundary Conditions on Crippling

Defining the boundary conditions precisely is an essential step to build up a reliable evaluation. In general, boundary conditions are specified in two parts as loading and displacement constraints. Depending on the loads and restrictions, it is possible to mention two types of crippling. One of them is web crippling and the other one is flange crippling which are shown in Figure 7 and Figure 8, respectively.

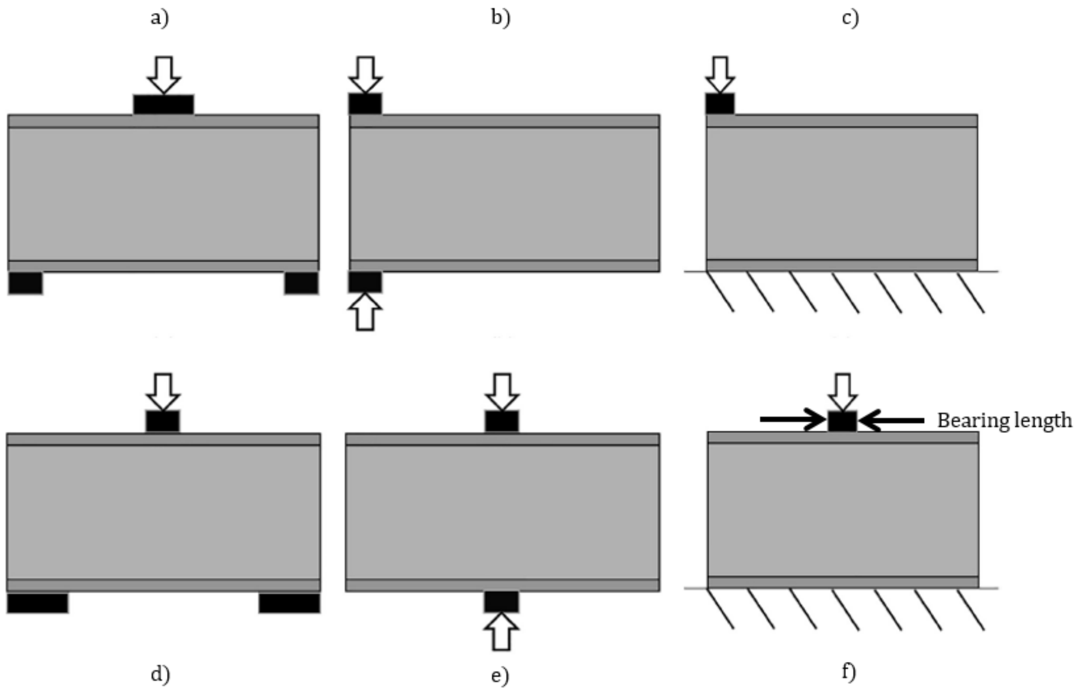

Figure 7. Web crippling boundary conditions a) EOF b) ETF c) EG d) IOF e) ITF f) IG [19].

Web crippling is usually taken into consideration for civil engineering applications. The boundary conditions for this failure mode have been presented in Figure 7 as [19, 76–80] a) end – one – flange (EOF), which is similar to three points bending test with narrower supports, b) end – two – flange (ETF) which is performed with loading of flanges simultaneously, c) end – ground (EG) that is loaded at one end and supported along the opposite side, d) interior – one – flange (IOF) that is similar to EOF with narrower bearing plate length, e) interior – two – flange which is performed the loading at inner sides, f) interior – ground that is similar to EG . Investigations [7, 19, 77–79, 81–85] has demonstrated that loading capacity is higher at interior models rather than end models. Besides, it has been clearly declared that web crippling strength can be increased by enlarging the bearing plate lengths due to the increment at the structural stiffness [7, 19, 76–77, 81–83, 85].

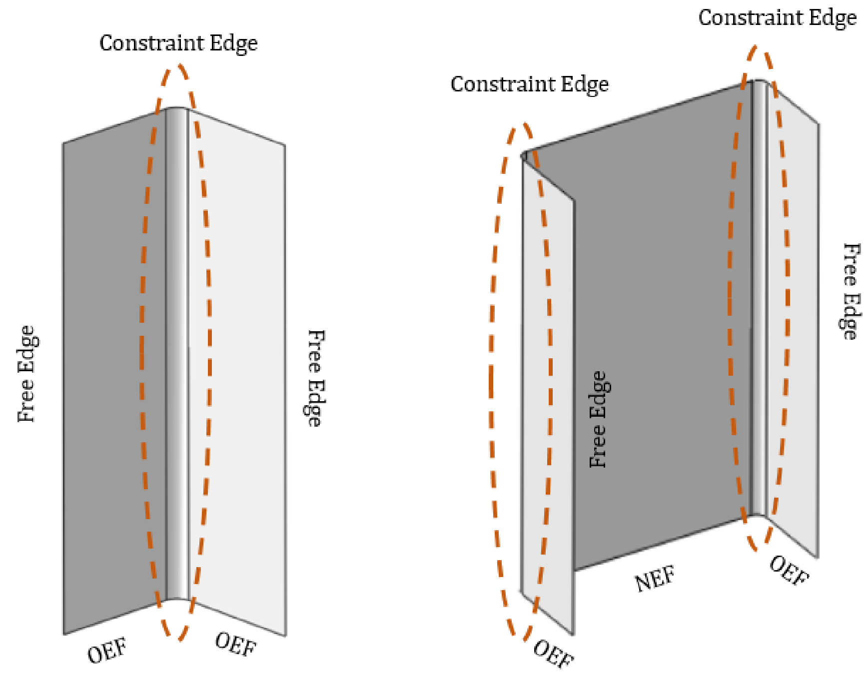

Figure 8. Flange crippling: One – Edge – Free (OEF) & No – Edge – Free (NEF) Sections.

On the other hand, flange crippling phenomenon is mostly examined in aerospace industry. Belonging to the applied load and displacements, it is possible to sort flange crippling in two classes as indicated in Figure 8. If all edges of a cross section are constrained, the section is simply called as 'no – edge – free (NEF)'. Instead, if only one edge of the cross-sectional area is free and the movement of the remaining edges are restricted, then the section is termed as "one – edge – free (OEF)' [1, 29]. Kassapoglou [1] explained that the load handling ability of the NEF section element is higher than the OEF ones. Besides, the maximum failure potential is affected from the characteristics of the load.

3.2. Composite Crippling Tests

Test is an important step for the verification of the approaches which can either be through finite element method and/or analytical calculations [45, 86–87]. After deciding the geometries, boundary conditions and stacking sequences of the test specimens, test setup is prepared. The crippling test is generally examined into two processes as arrangements of the specimen and test setup.

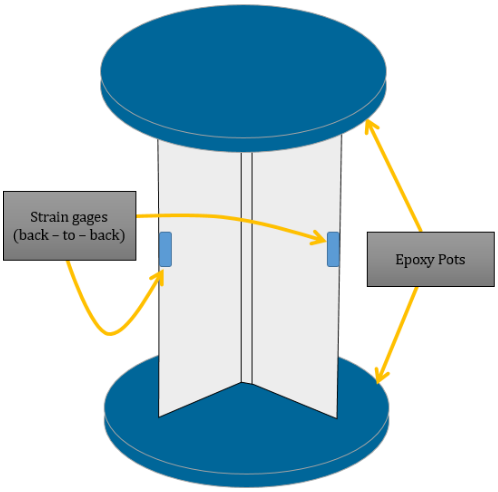

Figure 9. A typical specimen sample for crippling test.

A simple test specimen is denoted as in Figure 9. Properly, the ends of the test specimen are placed into a parallel potting compound with epoxy content that is surrounded by metallic circle. The aim of the potting compound is to provides an identical load distribution and avoid the ends of the specimen from brooming [38]. In this way, the ends cannot rotate or move along the axial direction. Moreover, strain gages are placed back – to – back at the middle of the length as shown in Figure 9. Since it is intended to control whether loadings are the same at the two sides of a flange.

The test procedure is simply explained by Minguet [44]. Accordingly, before starting the test, the specimen is loaded up to 25% of buckling load and the data are recorded by strain gages. After that, the specimen is unloaded and the strain gages data at the flanges are checked for the identical match. If there is a great gap at the data, the specimens are re – aligned to ensure equal loading at the flanges. This process is repeated until reading the same loads in two flanges. Eventually, the loads become equal for the flanges and the loading mechanism is fixed to start the test. This procedure helps to satisfy the accurate load redistribution during post buckling regime. Otherwise, an early failure becomes unavoidable due to the possibility of the off – axis loading.

4. THEORETICAL STUDIES

The post – buckling treatments of the composite structures are theoretically dealt in two parts as analytical and numerical approaches. Numerical studies are generally based on finite element solutions while analytical calculations try to state a solution with formulations. In this section, analytical and numerical investigations are assessed separately.

4.1. Analytical Approaches

As mentioned before, analytical calculation of crippling phenomenon for laminated materials is not straightforward as metals due to the anisotropic behaviors of the composites. Therefore, it is a common approach to simulate isotropy as far as possible by changing the fiber orientations and stacking sequence. Even though it could not be attainable to reach purely isotropic structure like metals, orthotropic layups are generally taken into consideration during designing. So, the computations are generally built on these points of view [2, 5–6, 9].

The elementary gate of the analytical formulations for composite crippling is usually classical laminated plate theory by regarding the geometry and boundary conditions of the members [5–6, 9, 88–92]. Nonetheless, it is possible to notice some inconsistent points between test results and mathematical calculations. The reasons of the discrepancy might be the assumptions about the application of loads and boundary conditions. Besides, high amounts of $\pm 45°$ plies may cause material non – linearity in the composite [93]. If boundary conditions were taken into account in an accurate manner, it would be obvious that the test results and analytical computations could be concurred.

Mostly, crippling curves are plotted in non – dimensional forms. Therefore, one of the axes implies the crippling strength and the other one states the nature of the composites [93]. In detailed, crippling strength is widely converted into the dimensionless format with the aid of material yield strength for metallic parts; meanwhile ultimate compression strength is employed for composites. On the other hand, the nature of the structure is generally transformed into the non – dimensional format by considering the extensional stiffness. Since it is known that bending stiffness is an important parameter for pre – buckling and crippling behaviors, extensional stiffness can be correlated to bending stiffness directly for isotropic materials. However, the relation between extensional and bending stiffness terms are not direct for composites. Besides, it is possible to observe buckling at different load levels for non – identical layup configurations even if the in – plane stiffnesses are equal. Hence, the following terms are introduced for vertical and horizontal axes of the crippling curves for laminated structures, respectively [93]:

$$\frac{F^{cc}}{F^{cu}}\frac{E_x}{\bar{E}} \quad \text{and} \quad \frac{b}{t}\frac{\bar{E}}{E_x}\sqrt{\frac{F^{cu}}{\sqrt{E_x E_y}}} \tag{1}$$

where F_{cc} is the crippling strength, F_{cu} is the ultimate compression strength, E_x is the extensional stiffness in longitudinal direction, E_y is the extensional stiffness in transverse direction, b is the plate width, t is the plate thickness, $\bar{E}$ is the effective modulus and formulated as Equation (2):

$$\bar{E} = \frac{12\,D_{11}}{t^3}\left(1 - \nu_{xy}\nu_{yx}\right) \tag{2}$$

where D_{11} is the bending stiffness term, ν_{xy} is the Poisson's ratio in longitudinal direction and ν_{yx} is the Poisson's ratio in transverse direction.

It should be noted that stiffened structures are composed of some configurations like one – edge – free (OEF) and no – edge – free (NEF) as introduced previously in § 3.1.2. Considering this point of view, composite crippling phenomenon is tried to calculate for individual elements via analytical ways as presented in § 4.1.1 and § 4.1.2 [1]. Then, weighted average summation is utilized to reach the overall crippling of the stiffened panel with the help of Equation (3) [93–95]:

$$F_{overall}^{cc} = \frac{\sum_{i=1}^{N} F_i^{cc} b_i\, t_i}{\sum_{i=1}^{N} b_i\, t_i} \tag{3}$$

It should be added that the thickness is assumed to be uniform at the stiffened panel to apply these approaches [93].

4.1.1. Crippling of OEF Cross Sections

Theoretically, buckling loads for orthotropic composite plates are derived by using the following equation [1, 93]:

$$N_x^{cr}\,(OEF) = \frac{12D_{66}}{b^2} + \frac{\pi^2\, D_{11}}{L^2} \tag{4}$$

It should be noted that Equation (4) is valid for symmetric and balanced laminates with respect to the mid – plane of the composite. Besides, bending stiffness term (D_{66}) has a great effect to determine the initial buckling for long plates. Kassapoglou [1] clearly explains that 45° plies should be placed away from the mid – plane of the lamina as far as possible to make the bending stiffness term (D_{66}) higher. Therefore, the crippling value can be maximized by locating the 45° plies away from the mid – plane. Additionally, it is stated that 0° plies should be placed away from the mid – plane to increase the structure stiffness. Hence, it is important to specify the priority of the structure which property is essential during deciding the ply layup. Then, optimum design is provided [1, 11–12, 40–42, 96].

Equation (4) is mainly employed for initial buckling and this equation has a good agreement with test results for low b/t values as denoted in Figure 10. However, as b/t increases, initial buckling equation becomes quite conservative due to the reflection difficulties at the boundary conditions. So, Equation (5) is stated to cover more data as displayed in Figure 10 ([1], [38], [93]):

$$\frac{\sigma_{crip}}{\sigma_u^c} = \begin{cases} 1, & b < 2.91t \\ \dfrac{2.151}{\left(\frac{b}{t}\right)^{0.717}}, & b \geq 2.91t \end{cases} \tag{5}$$

where σ_{crip} is crippling stress, σ_{cu} is material ultimate stress, b is the width of the member and t is the thickness of the member. For the design safety, Equation (5) has been improved with B – Basis approach ([1], [38], [93]):

$$\frac{\sigma_{crip}}{\sigma_u^c} = \begin{cases} 1, & b < 1.98t \\ \dfrac{1.63}{\left(\frac{b}{t}\right)^{0.717}}, & b \geq 1.98t \end{cases} \tag{6}$$

It must be remarked that at least 25% of the laminate must have 0° plies and at least 25% of the laminate must have 45° plies to calculate the crippling stress via Equation (5) and Equation (6). Otherwise, these equations are not applicable [1, 38, 93].

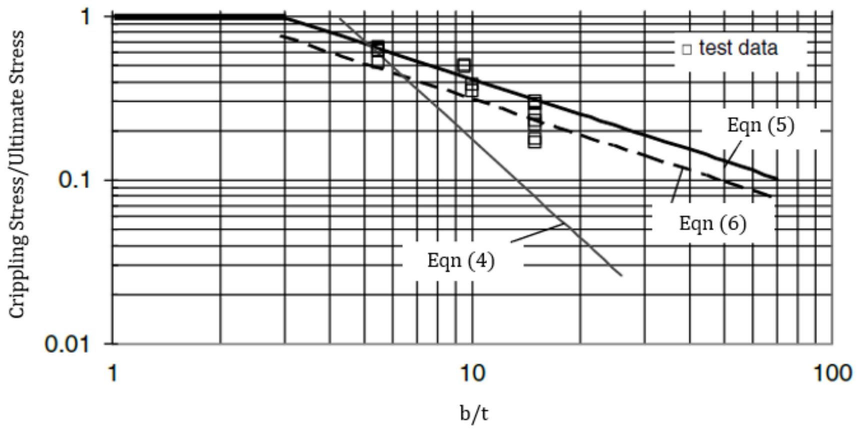

Figure 10. Normalized OEF Crippling Test Data [1, 38, 93].

4.1.2. Crippling of NEF Cross Sections

Buckling loads for NEF orthotropic composite plates are found by employing Equation (7) [1, 93]:

$$N_x^{cr}\ (NEF) = \frac{2\pi^2}{b^2}\left[\sqrt{D_{11}D_{22}} + D_{12} + 2\,D_{66}\right] \tag{7}$$

The laminate is expected to be symmetric and balanced if Equation (7) is used to calculate initial buckling. Similar to OEF plates, bending stiffness term (D_{66}) is increased by locating the 45° plies away from the mid – plane of the lamina. Besides, 0° plies are placed to enhance compression strength [1].

Since Equation (7) is utilized for initial buckling, more realistic approaches can be necessary to reach crippling strength and Equation (8) has been developed as follows [1], [38], [93]:

$$\frac{\sigma_{crip}}{\sigma_u^c} = \begin{cases} 1, & b < 11.07t \\ \dfrac{14.92}{\left(\frac{b}{t}\right)^{1.124}}, & b \geq 11.07t \end{cases} \tag{8}$$

where σ_{crip} is crippling stress, σ_{cu} is material ultimate stress, b is the width of the member and t is the thickness of the member.

When comparing the Equations (7) and (8) as displayed in Figure 11, it is obvious that Equation (7) covers test results better. However, B – Basis approach is used to ensure design safety and Equation (9) has been improved [1, 38, 93]:

$$\frac{\sigma_{crip}}{\sigma_u^c} = \begin{cases} 1, & b < 8.443t \\ \dfrac{11.00}{\left(\frac{b}{t}\right)^{1.124}}, & b \geq 8.443t \end{cases} \tag{9}$$

In a similar manner with OEF composite plates, at least 25% of the laminate must have 0° plies and at least 25% of the laminate must have 45° plies to calculate the crippling stress via Equation (8) and Equation (9). Otherwise, these equations are not applicable [1, 38], [93].

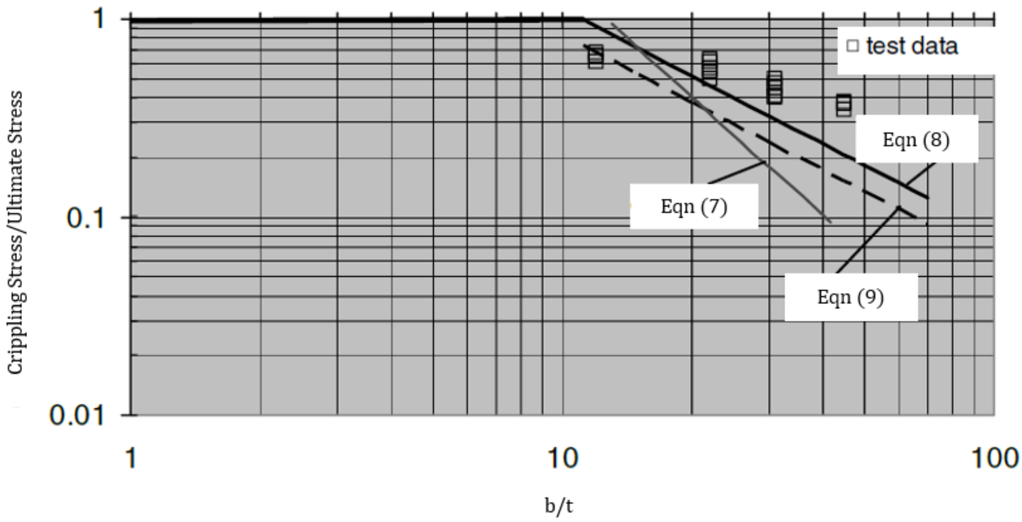

Figure 11. Normalized NEF crippling test data [1], [38], [93].

4.2. Finite Element Approaches

Finite element analysis is widespread day by day with the enhancement of the calculation capacity of the computers. For this aim, some programs like Abaqus, Patran/Nastran and ANSYS are utilized to find the buckling strength of the structures. Whichever program is used in the analysis; the critical aspect of the finite element applications is to establish the model accurately as far as possible. So, there are some prominent factors like mesh size [35, 97–104] constraints [35, 105–108] and geometrical imperfections [107, 109–113] that affect the exactness of the finite element analysis. In addition to these, if the material is created as composite, it is also important to define the material coordinate system accurately during modelling structure, since each lamina has different fiber orientation, and the behaviors of the fibers can change under the effects of loadings. Although the critical points are constructed carefully, after a while it is inevitable to encounter some discrepancies between finite element solutions and test results.

Mesh size is one of the major parameters that influences the sensitivity of the analysis [98, 101–104, 114]. Despite that it is known that increasing the number of elements helps to approach the test results, in applications, it is not always recommended to mesh the bodies with very fine sizes. Instead, most of the time, coarse elements are preferred if it is possible. Since, the enhancement in the element number induces the increment of the computation time. Besides, the greater number of elements is created, the more memory space is necessary in addition to stronger processor to make the calculation. Thus, it is advised to find an optimum mesh size during modeling to compute the pre/post – buckling loads [98, 115]. Furthermore, the mesh size through an element does not need to be uniform. In other words, the regions of which high stress is observed can be meshed denser, while the regions that has low stress flow can include coarse elements. To illustrate, the stress concentration is greater at the fillet regions with respect to the flat parts. So, it would be better to prepare the fillet regions with fine meshes while the remaining parts could be kept coarser as depicted in Figure 12. To illustrate, Kim et al. [101] exemplified that welded zones for a stiffened panel should be divided into small sized elements due to the high stress intensities. Besides, ply drop – off areas are recommended to mesh with fine elements [116]. Moreover, Kim et al. [101] and Li et al. [102] followed three numbers of instructions to reach an optimum mesh density. First one was to mesh the plate with even number of elements through the length of the body. Secondly, the minimum number of elements at the long side of a panel was calculated by multiplying the number of elements at the width with aspect ratio. Lastly, the number of elements was increased as the structures became thinner to provide the accuracy at the results.

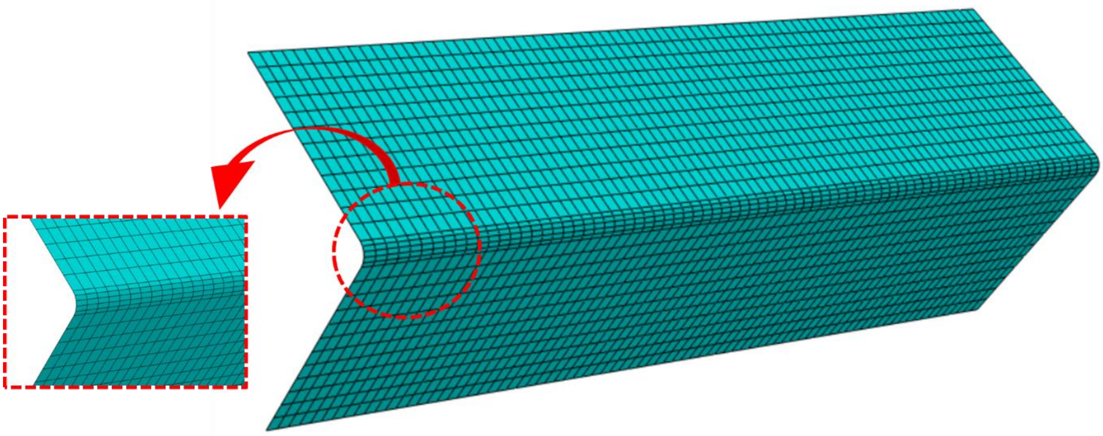

Figure 12. Various mesh sizes at different regions.

Boundary condition is another primary factor that should be defined exactly for the analysis. As stated earlier in § 3.1.3, boundary conditions are handled in two aspects. One of them is displacement restrictions and the other one is load control. Regarding to the provided motion of the structure throughout the test, the body movement is allowed or constrained along the specified direction [35, 105, 108, 117–118]. For instance, as specified by White et al. [33] and Krishna et al.[118], if a test specimen is potted into epoxy as shown in Figure 9, it is necessary to set the finite element model (FEM) with displacement constraints through the depth of the epoxy ring as given in Figure 13. If an epoxy ring was not utilized, it would be enough to prepare the FE model with displacement restrictions at the edge of the specimen. Besides, Figure 13 also indicates the permitted translational motion of the specimen through the length of the body. Depending on the analysis, rotational constraints can be applied at both ends of the structure. Li et al [102]. remarked that rotational displacements are set to be free when simply supported boundary is assumed in the existence of only axial loads. If there is any shear load, rotational restrictions will be necessary [117].

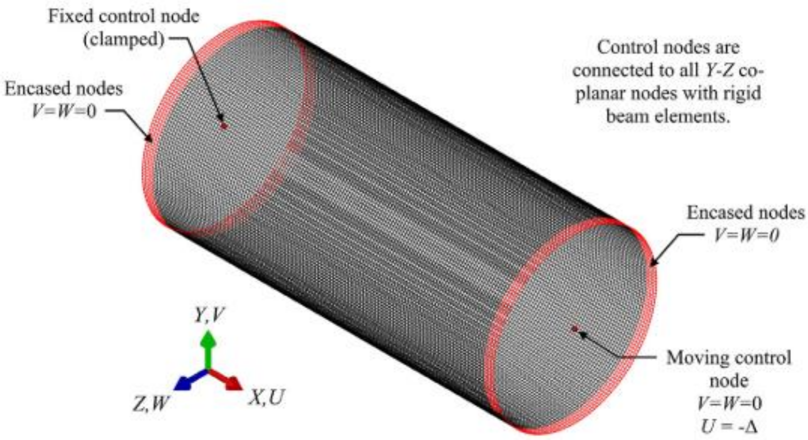

Figure 13. Boundary conditions of a finite element model [33].

Moreover, load application is also another important concern during determining the crippling strength. Wysmulski et al. [119] study the effects of load eccentricity for composite C – sections. For this aim, two different layups are employed in this search. Besides, eccentric loads with respect to the gravitational center of the cross sections are applied to the specimens. Both numerical and experimental results of the study are presented in Table 1 [119]. Accordingly, loading can be divided into three groups: In the first group, loading is axial (i.e., through the gravitational center, shown as axial in Table 1). In the second group, the loading point is offset 10 mm horizontally with respect to axial loading point (i.e., shown as Eccentricity 1 in Table 1). In the third group, the loading point is offset 10 mm vertically with respect to axial loading point (i.e., shown as Eccentricity 2 in Table 1). When the results are compared in Table 1 [119], premature failure is observed on the specimens which have eccentric loadings. In other words, the applied loads cause bending moment due to the eccentricity. In this study, finite element models (FEM) are verified with test results very well as shown in Table 1 [119].

Table 1. FEM vs test results [119].

	Crippling Loads (N)		
Specimens	**Axial**	**Eccentricity 1**	**Eccentricity 2**
Experimental C1	2123	951	1649
FEM C1	2141	954	1665
Experimental C2	2126	887	1576
FEM C2	2145	912	1611

Distortion or geometrical nonlinearity is known as imperfection which is also another affecting concern of the finite element results. In order to catch the compatibility between tests and analysis [109–111], it is necessary to reflect the distortions on the FE models correctly. For this aim, it is pointed that the magnitudes of the geometrical nonlinearity stand on the average values of the statistical measurements [33], [110]. Besides, there are some studies to compute the imperfections analytically [110–111]. Most of the time, imperfections are introduced to models as the 10% - 50% of the thickness to initiate the nonlinear post – buckling analysis [35, 120]. In this scope, Debski et al. [35] stated that low imperfection values may not provide the enough sensitivity to the analysis. Therefore, in general it is advised to take the amount of imperfection as up to 50% of the thickness.

Finite element solution procedure for buckling analysis is generally built in two parts as pre – buckling and post – buckling [35, 37, 43, 87]. Initially, buckling modes are defined with eigenvalue analysis in the pre – buckling. After that, post – buckling analysis is performed for a geometrically nonlinear points of views. In the first step, pre – buckling process is solved linearly using the computer programs, since this phase takes place in the elastic region and the deformation is temporary as mentioned earlier during the pre – buckling. Clearly, it is known that linear buckling analysis is a kind of classical eigenvalue problem, and the eigenvalues are found by regarding the Euler method. The first eigenvalue assists the minimum buckling load which also means the worst buckling condition. Then, the linear buckling mode results is merged into the model to give the structure a perturbation as the beginning of the second step [23, 35, 121]. Thus, post – buckling phase is prepared for nonlinear solution [35, 105–106, 122].

To sum up, it is known that crippling analysis is performed in nonlinear implicit form for numerical calculations. In that way, the impacts of the load on the member can be followed step by step. Besides, it is suggested modeling the initial imperfections to reach the exact test simulation. Also, boundary conditions should be regarded to build the precise numerical solution.

5. CONCLUSION

Buckling is a concern that is generally investigated in two stages as pre – buckling and post – buckling. In the pre – buckling process, the deformation is assumed to be temporary. This temporary damage means that the structure has still load carrying capacity until reaching failure. Therefore, it is desired to benefit the capability of the members more loads during designing because of the weight restrictions. In that case, post – buckling stage is started after excessing the maximum load in the elastic zone. Though more load is carried if post – buckling process is regarded, the structure transmits to plastic zone and permanent deformation is observed. So, it should be kept in mind that the final failure is unavoidable at end of the plastic deformation zone. This maximum load carrying capacity in the post – buckling region is simply named as crippling failure. Hence, the necessity of a review article is realized to present a perspective about the crippling phenomenon of the bodies for laminated materials.

Mainly, post – buckling process deals with the beginning of the plastic deformation till the failure of the members. When assessing the crippling strength for composite materials, firstly the effective parameters are tried to be determined by regarding the experimental studies. It is found that stacking sequence, geometrical properties and boundary conditions are assessed to be significant factors for composite crippling behavior. Moreover, a brief information about the experimental procedure is stated.

When considering the stacking sequence, it is stated that post – buckling strength of the parts are increased by locating the 45° fiber from the midplane of the laminates as far as possible. However, it is proven that flange width has more effect on crippling strength with respect to composite layup. Therefore, it might be better to improve the geometrical factors before assessing the stacking sequence. Furthermore, loading and displacement constraints have also valuable influence on crippling. It is remarked that no – edge – free bodies are able to carry more loads when comparing with the one – edge – free cases.

Generally, experimental studies are preferred due to the complexity of the anisotropic properties of the composites. However, there are some theoretical approaches to find the crippling strength of the composite materials. In the future studies, it is possible to expand the development of the formulations by taking into account the effective parameters. Hence, the requests of the tests might be reduced.

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