Lateral Torsional Buckling of Steel I-Section Cellular Beams

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ABSTRACT

Cellular beams are usually desirable in places where there are services below the ceiling and the openings allow services to pass through without increasing the floor height or building height. Architects also prefer this type of members due to their aesthetic look.

After the cutting, shifting and welding of these members, there will be changes to their cross sectional slenderness since due to the heat, they experience through the cutting and welding process hence they may be subjected to different types of failure modes.

In this study the lateral torsional buckling (LTB) failure mode of steel cellular beams is investigated. The LTB can cause partial failure or whole failure in the structure. An experimental steel section was verified using finite element software (Abaqus). The shell element for finite element (FE) modeling was used. FE analysis results showed a good agreement with the experimental test results. Based on the verified section, more members were modeled to study their behaviors against LTB. Some modifications were introduced to these sections in order to decrease the risks of LTB failure mode.

The aim of this study, is to find ways of reducing the risks of lateral torsional buckling on perforated sections. Instead of the usual beam stiffeners, T-shaped stiffeners were used as a substitute for the beam. This kind of stiffener is a very good way of simulating the secondary to main beam connection in real life. Furthermore, the stiffener thicknesses of different values were used to see their effects on displacements. It was found that the use of T-shaped stiffeners with the increase in the thickness of stiffeners, significantly reduce the lateral displacements as well as the occurrence of lateral torsional buckling.

Keywords: Finite element, Cellular beams, Lateral torsional buckling, Stiffeners.

ÖZ

Tavan altında tesisat borularının bulunduğu yerlerde dairesel delikli kirişler bu boruların geçişini sağlamakta ve bu uygulama binanın kat yüksekliğini artırmadığı için tercih edilmektedir. Dairesel delikli kirişlerin mimarlar tarafından tercih edilmesinin en önemli nedeni de bu tür kirişlerin daha estetik görünmeleridir.

Elemanların doğrudan üretimi yerine, piyasada mevcut I enkesitlerin belli şekillerde kesilip kaydırdıktan sonra kaynaklanması neticesinde elde edilmesi nedeniyle bu aktivitelerden kaynaklı olarak enkesit narinliklerinde değişimler oluşmakta bu da üretilen kesitte kesite bağlı farklı kopma modlarını oluşturabilir.

Bu araştırmada celik dairesel delikli kirişlerin yanal burulmadan dolayı kırılma modları incelenmiştir. Kirişlerde yanal burulma bir yapının bölgesel veya tümden çökmesine neden olabilir. Sonlu elemanlar (Abaqus) kullanılarak önceden deneysel verilerle elde edilmiş bir celik kiriş kesiti doğrulanmıştır. Sonlu eleman modellemesi için kabuk eleman kullanılmış ve sonlu elemanların analiz sonuçları deneysel verilerle iyi bir uyum sağlamıştır. Doğrulanmış kiriş kesitine dayanarak, farklı kirişler modellenmiş ve yanal burkulma davranışları incelenmiştir. Bu modellerde yanal burkulma riskini azaltmak için değişiklikler de yapılmıştır.

Bu çalışmanın amacı delikli kesitlerde yanal burkulmayı azaltmak için çözüm bulmaktır. Normal kiriş güçlendiricileri (dikdörtgen plaka) yerine T-şekil güçlendiriciler kullanılmıştır. Bu tür güçlendiriciler, gerçek hayatta, ikincil kirişlerle ana kirişler arasındaki bağı benzeştirler. Buna ilaveten, farklı kalınlıklarda güçlendirme plakaları kullanılarak kiriş sehimine olan etkisi gözlemlenmiştir. Bu işlemlerin sonucunda T-sekil güçlendiricilerin kullanılması ve kalınlığının artırılması sonucunda yanal deplasmanların ciddi şekilde azalmasi yaninda yanal burkulma riskinin de azaldığı belirlenmiştir.

Anahtar kelimeler: sonlu elemanlar, dairesel delikli kirişler, yanal burkulma, güçlendiriciler.

Dedicated to

Palestine

&

My Family

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First I want to thank his majesty Allah for all the things I am having in my life. Without Allah's mercy and generosity nothing can be achieved in life. Alhamdullah, always and forever for everything.

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σ: Stress

ε: Strain

h: Height or Depth of the parent beam section

H: Height or Depth of the Cellular beam section

b: Width of beam

S: spacing

$t_{w:}$ Web thickness

$t_{f:}$ Flange thickness

E: Modulus of elasticity

d: Depth of the web for parent section

d_{cell}: Depth of the web for parent section

t_{weld}: Thickness of welding

a_o: Circular diameter

L: length of section

n: Number of perforations

$\rho_{a:}$ Density

$W_{y,z}$: Modulus of elasticity

$W_{pl.y}$: Modulus of plasticity

$\sigma_{true:}$ True Stress

Iy,Iz : Second moment of area (Moment of Inertia)

$\sigma_{nom:}$ Nominal stress

$\varepsilon_{true:}$ True strain

$\varepsilon_{nom:}$ Nominal strain

$i_y, i_{z,}$: Radius of gyration

E: Modulus of Elasticity

r: Radius

q_u: Ultimate load

G: Dead Load

Q: Live load

Chapter 1

INTRODUCTION

1.1 Introduction

Construction industry has been one of the leading fields among many others in the world. Hospitals, commercial, residential and educational buildings, bridges, dams and many others types of structures are essential needs for humanity that they cannot live without. Structural engineering has a major role in the construction field which every day becoming more widespread and sophisticated.

One of the main materials used by structural engineers is structural steel. In recent decades its usage increased, particularly in developed countries due to its recyclability, which makes it environmentally friendly, easy methods of erection, provision of economical solutions and optimum choices for many requirements, such as, high rise buildings and sky scrapers and many others. The history of structural steel industry is over one hundred years old. Design codes, such as, Eurocodes, British Standards and American Institute of Steel Construction (AISC) standards were introduced to make the design of steel structures simple, practical but yet safe.

The AISC was the first to develop the standard specifications for design, fabrication and erection of steel structure.

As the technology of steel structures progress, more types of steel sections were produced to improve the structural steel's mechanical properties and also to obtain sections that allow usage for more aesthetic applications by satisfying the architectural needs. Perforated sections, such as, castellated, cellular and sinusoidal beams are good example to such newly developed sections. Castellated beam section was the first that developed in the past (Figure 1). The main aim in producing such sections was to increase their resistance against bending due to the increased height. This approach would also cause an increase in the second moment of area (moment of inertia) leading to sections that better meet the serviceability and aesthetic requirement. Researchers and designers keep trying to develop these kinds of members with the aim of achieving steel sections with better mechanical properties, more economical and lower risks for failure. The smooth rounded edges of the openings in cellular beams (Figure 2) resolved one of the main problems in castellated beams which is the sharp edges of the hexagonal opening. In most cases, these sharp edges caused some failure modes in the beam web due to accumulation of high shear stresses around the perforations. Then cellular followed by the development of sinusoidal perforated beams (Angelina beams) to provide better performance with aesthetics (Figure 3). Around 15 years ago, cellular beams were not known and it was solely produced by Westok in UK. Then more producers joined in and they became more widely available and they are used for variety of applications. Nowadays, cellular beams with circular openings are becoming more common in developed countries where the cellular beam technology exists. Cellular beams has wider use than the Angelina beams which require a different technology than the cellular beams. Currently Angelina beams are trademarked and only manufactured by one of the leading steel producer in Europe and in the world. As the researchers get to know more about the behavior of Angelina beams, it is expected that in near future it's production technology will also be more widely available, which will increase the Angelina's usage. One needs to look at the possible advantages and disadvantages of using Angelina and these comparisons will affect the usage in future. There is need for more research into both cellular and sinusoidal beams to establish design approaches and limitations.

Comparing the cutting pattern of castellated members, cellular members have more flexibility in their finished depth, perforation diameter and spacing. In addition, cellular members need less infill plates and easier infill cut parts compared to castellated members. Moreover, cellular members can be fabricated as asymmetric sections while castellated members can be constructed only as symmetric sections Ellobody (2011).

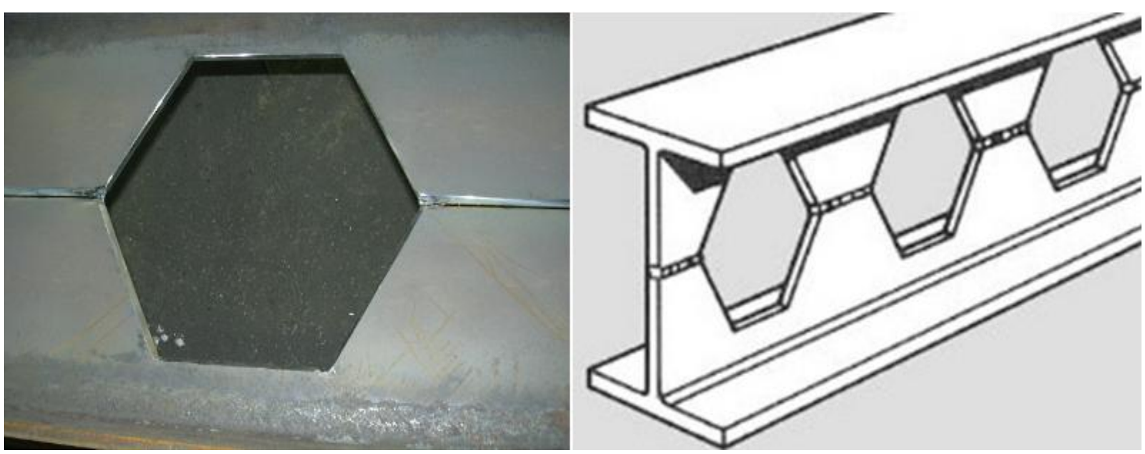

Figure 1 Castellated beam with hexagonal openings **(Macsteel, 2012)**

Figure 2 Cellular beams with circular openings **(Bouwenmetstaal, 2008)**

Figure 3 Angelina beams with sinusoidal openings **(ArcelorMittal, 1996)**

1.2 Related Terminology

In order to make it more clear for the reader, the main terminologies used throughout this thesis are briefly explained in this section.

- **Stiffener (Normal Stiffener):** It is a rectangular piece of metal plate used in structural steel members to increase the local strength of the section against bending, buckling (Figure 21).

- **Cellular Beam:** It is a rolled steel I-beam with circular perforations in the web. Cellular beam is an improved version of the castellated beam (Figure 2).

- **Castellated Beam:** It is a rolled steel I-beam the web of which is first divided by a lengthwise zigzag cut, then welded together. Thus achieving an increase in depth and strength (Figure 1).

- **Steel I Beam:** Also known as Universal beam. It is a steel beam with I- shape cross section made of two flanges and one web part (Figure 4).

- **Welding:** It is a fabrication process that joins materials, usually metals , by causing coalescence. This is often done by melting the work pieces and adding a filling material to form a pool of molten material that cools to become a strong joint (Figure 27).

- **T-shape Stiffener:** It a stiffener with two rectangular pieces that are connected together perpendicularly to form a T shape (Figure 28,29,30).

- **Perforations:** Is a cut in the beam's web that enables the passage of services through the beam section (Figure 6).

- **Major Bending Axis:** It is the axis that has greater bending resistance. Usually it is in the longitudinal direction.

- **Bending Resistance Strength:** It is the material's ability to resist deformation under loading.

- **Secondary Beams:** Steel beam which carries the load from the floors and roofs to the main beams.

- **Parent Section**: The word 'Parent' is used to distinguish between the original beam (parent beam) and the cut and welded section (Cellular beam).

- **Shear Forces:** Forces pushing one part of a body in one direction and the other part of the body in the opposite direction.

- **Connections (Steel Connections):** Steel parts that are used to connect the beam to a column, secondary beam to a primary beam and hanging rod to a beam.

They are one of the main structural parts in the steel design as most of the failures of steel structures are due to connection failures. Some of the common examples of steel connections are web cleat, flush end plate, extended end plate.

- **IPE and HE sections** : Designation of beam and column I-sections produced in Europe(Europeans profiles).

- **Resistance**: Is the ability to keep the section member at equilibrium state without failure under loading. Resistance is enhanced by the material of the section.

- **Restrained and unrestrained length:** Restrained length of the beam is the length that is prevented from rotating and twisting and therefore deflection in the weak axis of the beam. Unrestrained length is the length which is free to rotate and twist and therefore can be subject to lateral torsional buckling. Lateral Torsional Buckling: Rotation, twist and deflection of the unrestrained length of a beam when subjected to loads in the strong axis.

- **Critical Part :** The main part that is prone to buckle and twist.

- **Boundary Conditions:** The limitations introduced via the type and method of the connections used to connect beams and columns (Beam's end supports can be restrained in either of the x,y,z directions or combination of these directions).

- **Slenderness Ratio:** Slenderness ratio is an assessment of a structural member's ability to withstand buckling pressures. It can be calculated by dividing the unrestrained length of the beam or column by the radius of gyration (second moment of area divided by the area of the cross section under the square root).

- **Stability of the Section**: The ability to keep the member stable and at equilibrium and not to buckle, twist or rotate.

- **Plastic Hinges:** Deformation of a beam section where plastic bending occurs at critical or weak locations of the section.

- **Butt Welding:** It is a welding technique used to connect parts which are nearly parallel and don't overlap. It is an economical and reliable way of jointing without using additional components.

- **Hot Rolled Steel:** In metalworking, rolling is a metal forming process in which metal stock is passed through a pair of rolls. Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal is above its re-crystallization temperature, then the process is termed as hot rolling.

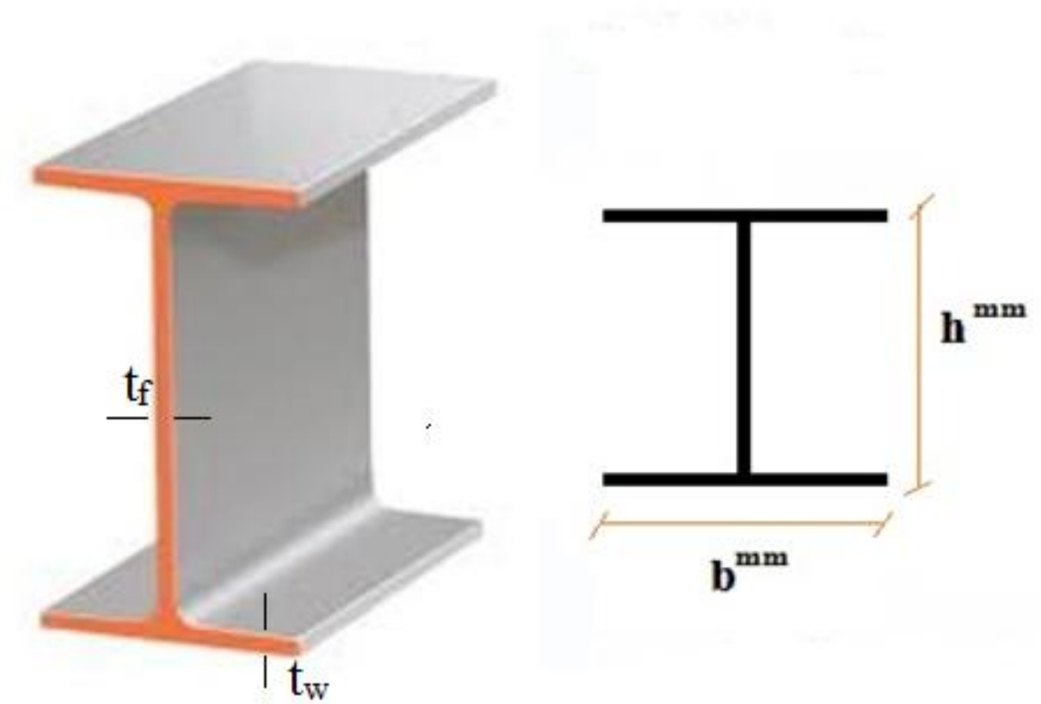

Figure 4 Steel I-Beam Section

Chapter 2

LITERATURE REVIEW

2.1 Cellular Beams

Cellular beams originally come from the steel I- beams (such as universal beams and European sections) which are cut in a certain pattern so that when welded together and end up in a deeper form, (around 50% deeper than its original section). This increase in the depth gives the cellular beam the advantage to have better properties than its parent section and it becomes more resistant to bending too (Westok, 2013).

Cellular beams are made from hot-rolled or cold-rolled steel I-sections. The parent beam section are re-manufactured by cutting process using a computerized system. The new cut section contain circular perforation in the web at equal spacing which are done by cutting the parent beam section into two halves as shown in the figure 5 and shifting them simultaneously to give the circular perforation shape, then at last welding the two halves together (Sonck D., Boissonnade N. , Van Impe R., 2012).

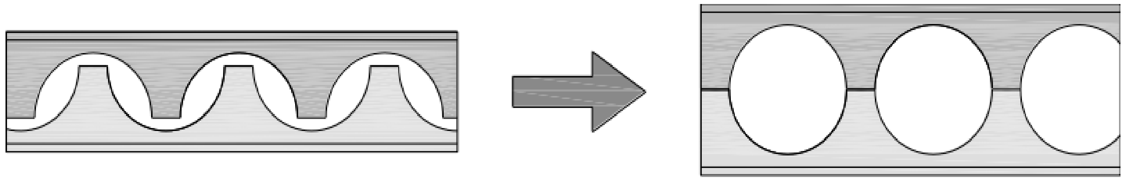

Figure 5 Fabrication of cellular beams (Sonck D., Boissonnade N. , Van Impe R., 2012)

2.1.1 Advantages of Cellular Beams

A deeper beam section means increase in the moment of inertia which makes the cellular beams much stronger in the major bending axis.

Cellular beams compared to their parent section of the same weight, their stiffness and bending resistance will be much higher as the moment of inertia will considerably increase leading to better mechanical properties. Compared to normal sections, span to weight ratio of cellular beams are much lower which indicates that cellular members have less weight and therefore, more economical (Sonck D., Boissonnade N. , Van Impe R., 2012).

Cellular beams are one of the most sought after steel sections that architects prefer in steel framed structures (e.g. industrial and commercial buildings) since it has a unique shape and lighter (slender) appearance that attracts the user's sight and make the internal and external look of the building more aesthetic.

As stated by Macsteel (2012), the usage of the cellular beams (figure 2) significantly increased within the last decade due to its useful advantages. Some of the advantages of cellular beams are given below:

- Good solution and more economical for the long spans.

  Cellular beams can span up to 20 meters long with no extra costs.

- Shorter time in erection and fabrication.

- Their unique and economical CURVED shaped (Figure 6).

  Bending of beam member (curved shape) and handling the cellular members are easier due to its lighter weight.

- Access for serviceability. As shown in Figure 6, the perforations allow the passage of service ducts like mechanical, electrical and in some cases structural.

- Higher moment of inertia, which means higher bending resistance.

  After the beam is cut and shifted accordingly, the height will increase by around 50% more than the parent section which makes a significant increase in the Second moment of area (moment of inertia).

- Aesthetic look. Architects often prefer the steel members as it can bend and drawn into favorable shapes that enable most of the architects to show their creativity. Cellular beams along with the perforations give a unique and aesthetic look for the structure.

- Shallow construction. There is no increase in construction depth of any structural cross section due to services being passed through the openings with the web.

2.1.2 Serviceability of Cellular Beams

The perforations in the web help the services to be accommodated in the building. The usage of these perforations makes it easier for the commercial and industrial buildings to let the pipes and other services to pass easily and without creating clash problems with any other members.

The passage of the service ducts through the perforation and not under, gives the advantage of these ducts to look better arranged and also helps in decreasing the overall height of the building (Sonck D., Boissonnade N. , Van Impe R., 2012).

The main structural members in steel construction are the steel I- shaped Sections. The perforations in the cellular beams result in an obvious reduction in the total volume of steel and at the same time, allow the passage of electrical and mechanical canals without affecting the design plan. (Sweedan A.,, 2010).

According to Westok (2013), cellular beams are widely used in more than 25 countries and it is still increasing due to its high advantages and more economic solutions for high spans and aesthetic point of view. In United Kingdom, the use of cellular beams exceeds 25 thousand tons per year and all around the world it exceeds 50 thousand tons per year where the rest amount of steel are used to fabricate the traditional structural members such as beams, columns, connections and other structural steel members.

Figure 6 Cellular beams facilitating the passage of services (Westok, 2013)

During the manufacturing process, when the cut section is separated into two T-sections, it is easy and not-costly to bend the cellular beams to make it look like curved shape. For some cases; cellular members can easily be curved to meet the structure and the architectural needs. Figure 7 below shows the curved shape of the cellular beam which give it a unique architectural shape and good resistance against bending. The bent up process in cellular sections are mainly used in long span beams as in some cases this process is required in order to have more bending resistance strength (Westok, 2013), (Macsteel, 2012).

Figure 7 Curved Cellular Beams (Westok, 2013)

2.1.3 Usage of Cellular Beams

The use of cellular beams has been gradually increased through the past decade. It is widely used in almost all types of buildings due to its structural and architectural advantages.

They are mainly used as secondary beams. Moreover, cellular members can be used as roof beams, floor beams, tapered and cantilevers beams, normal and tapered columns and beams. One of the most important advantage is that the curved beams can be obtained through the manufacturing process without extra costs (Macsteel, 2012).

Cellular beams are widely used in:

- Multi storey car parking structures,
- Stadiums,
- Transportation facilities such as metro stations and bus stops,
- Hospitals,

- Bridges and high rise buildings,
- Industrial buildings,
- Arches,
- Galleries.

Macsteel, Westok, Arceloarmittal, Graitec, Fabsec and New Millennium are the main manufacturers of cellular beams and they have their own design manuals, which are based on Eurocodes and other design standards. These manuals enable the designers to understand the design procedures of cellular beam sections. The design procedures related to this study are discussed in the literature review section.

2.2 Design of Cellular Beam According to Eurocodes

2.2.1 Introduction

The design of cellular beams follows the design of I-steel beams according to Eurocode 3 for steel structures and Eurocode 4 for the composite structures. On the other hand, there are some additional formulas in the design procedure to be considered and followed. These are due to changes in height, slenderness, web area (perforations) and welding.

2.2.2 Selecting the Perforation's Spacing and Diameter

According to Eurocode 3 (2004), and the cellular beams design manual of ArcelorMittal (1996), the diameter of the web perforations in cellular beams has to be decided by the architect with respect to the structural height and the size of the serviceability that will pass through these perforations. Moreover, there are some limits for choosing the adequate sizes and spacing length in order to get an optimum section for the selected case. Figure 8 shows the recommended method for finding the height, spacing and diameter of the perforation for the cellular sections.

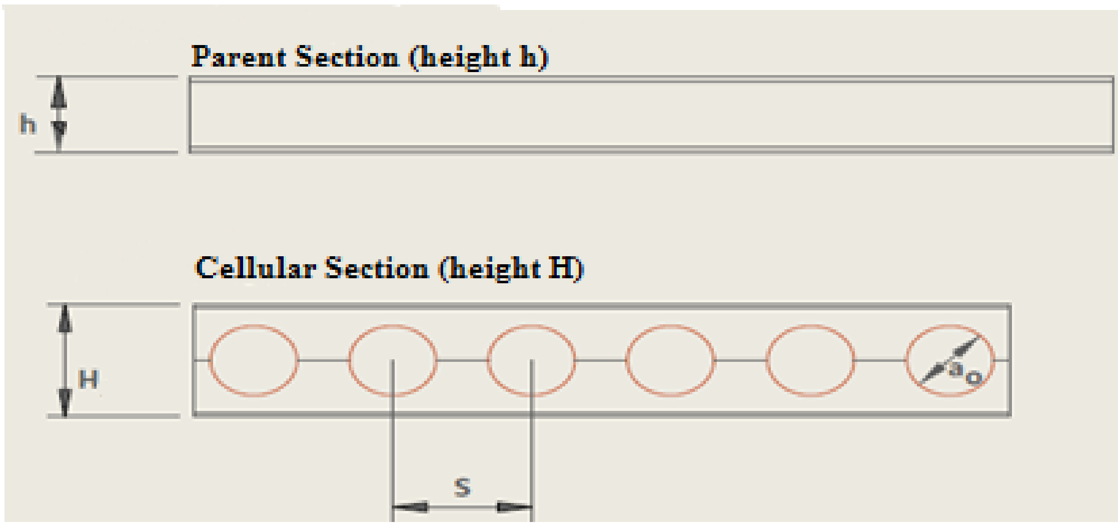

Figure 8 Recommended method for finding cellular beams dimensions (ArcelorMittal, 1996)

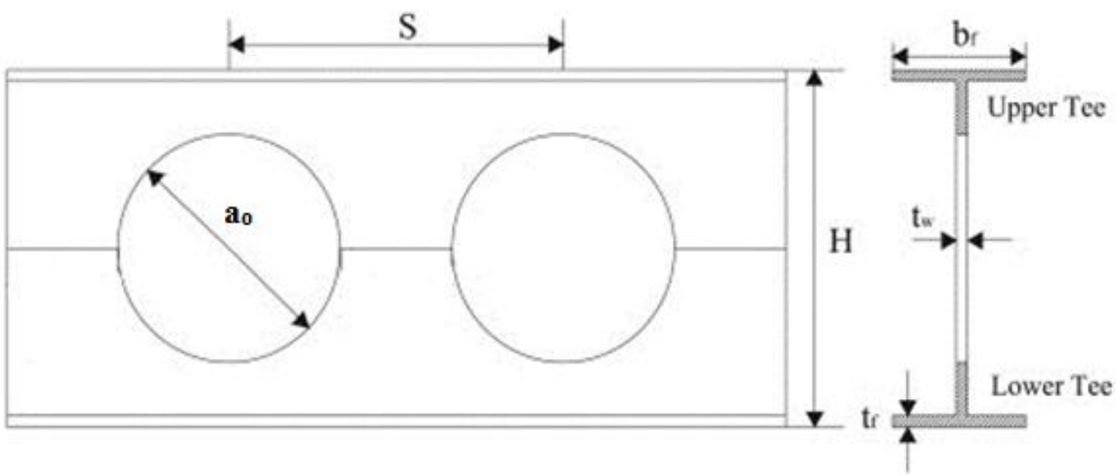

Figure 9 Cellular beam dimensions

where:

$$0.8h \leq a_o \leq 1.1\,h \quad (1)$$

or

$$1.25\ a_o \leq H \leq 1.75\ a_o \quad (2)$$

$$1.2\ a_o \leq S \leq 1.7\ a_o \quad (3)$$

or

$$S = L + a_o / (n+1) \quad (4)$$

$$1.3h \leq H \leq 1.4h \quad (5)$$

where L is the length of the sections and n is the number of perforations in the web.

The above equations are recommended for the structural applications in columns, car parks, offshore structures and floors with steel grades of S355 and S460 by (ArcelorMittal, 1996).

2.2.3 Closing of Perforations Next to High Shear Locations:

In long spans and high loaded members, the sections are subjected to high shear forces next to the connections that will make the member more prone to failure modes. Moreover, for the safety against fire it is recommended to close some of the perforations near the connections and this can be performed by placing circular steel plates that have the same perforation's diameter along with the same web's thickness and welding it from both sides. The welding type and the plate thickness are to be decided by the designer according to the local stresses of the section.

2.2.4 Welding Type

After the cutting and shifting procedure of the cellular beams, the welding stage plays a major role in the design of cellular beams. It is recommended by the European

Standards that the Butt welding type should be used for cellular beams (ArcelorMittal, 1996).

2.2.5 Height to Span Relations of Cellular Beams

Figure 10 is recommended by ArcelorMittal (1996) for choosing the adequate span length according to the total height of the cellular section and vice versa.

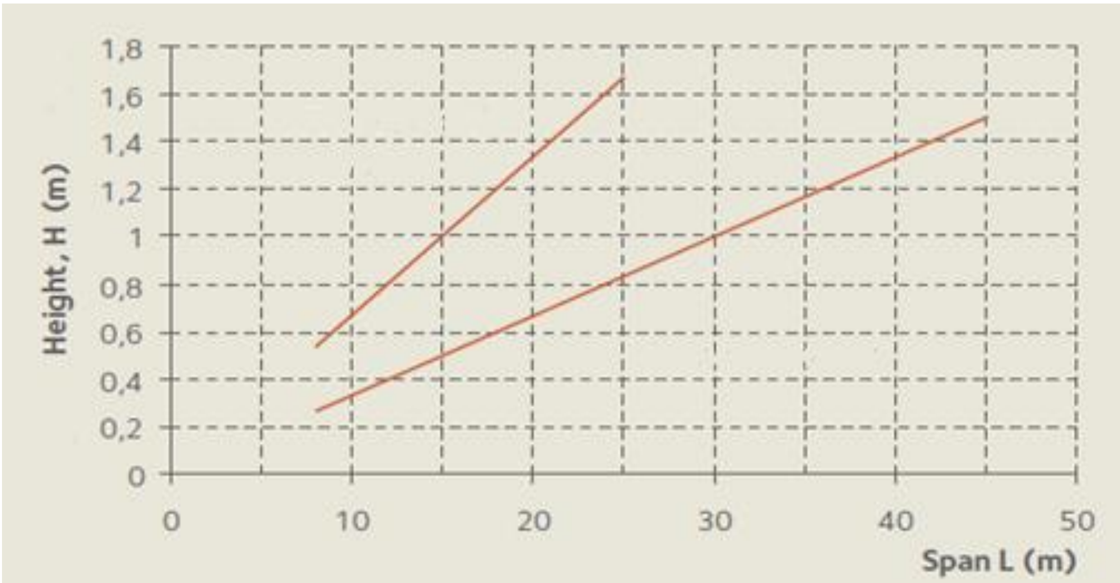

Figure 10 Height to span relations of cellular beams (ArcelorMittal, 1996)

2.2.6 Performance Data for Cellular Beams with IPE Sections

The following data are recommended by ArcelorMittal (1996) which are collected from experimental tests data according to Eurocodes Standards. The below data are for IPE sections with steel grade of S355 and S= 1.25 a_o.

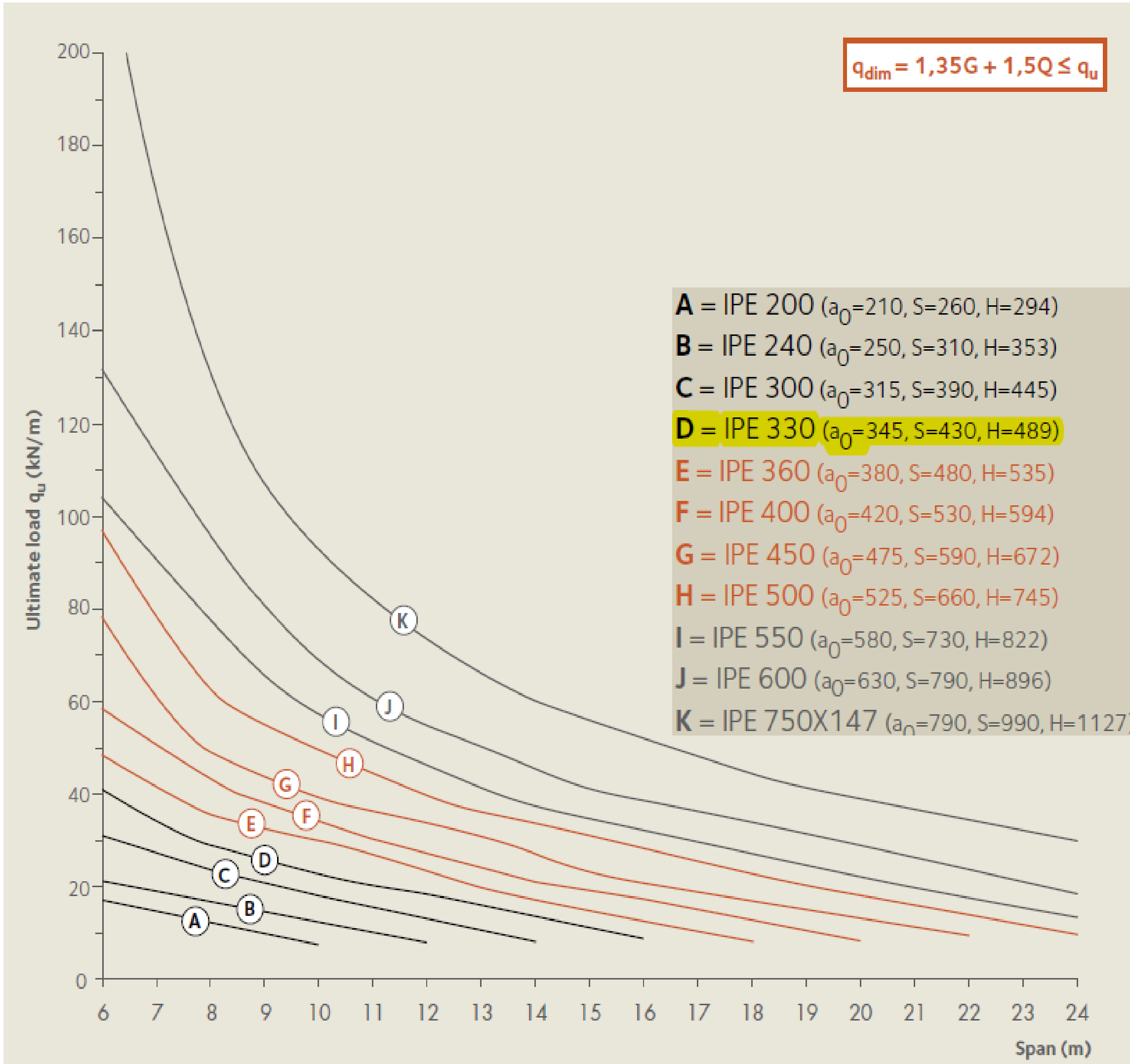

Figure 11 Performance data for cellular sections (ArcelorMittal, 1996)

2.2.7 Design Formulas for Cellular Beams Sections

According to steel design of Eurocode (2005), the equations for finding the dimensions (e.g. section area, web depth, mass per unit length, second moment of area (moment of inertia), radius of gyration, elastic section modulus) of cellular beam sections are illustrated below.

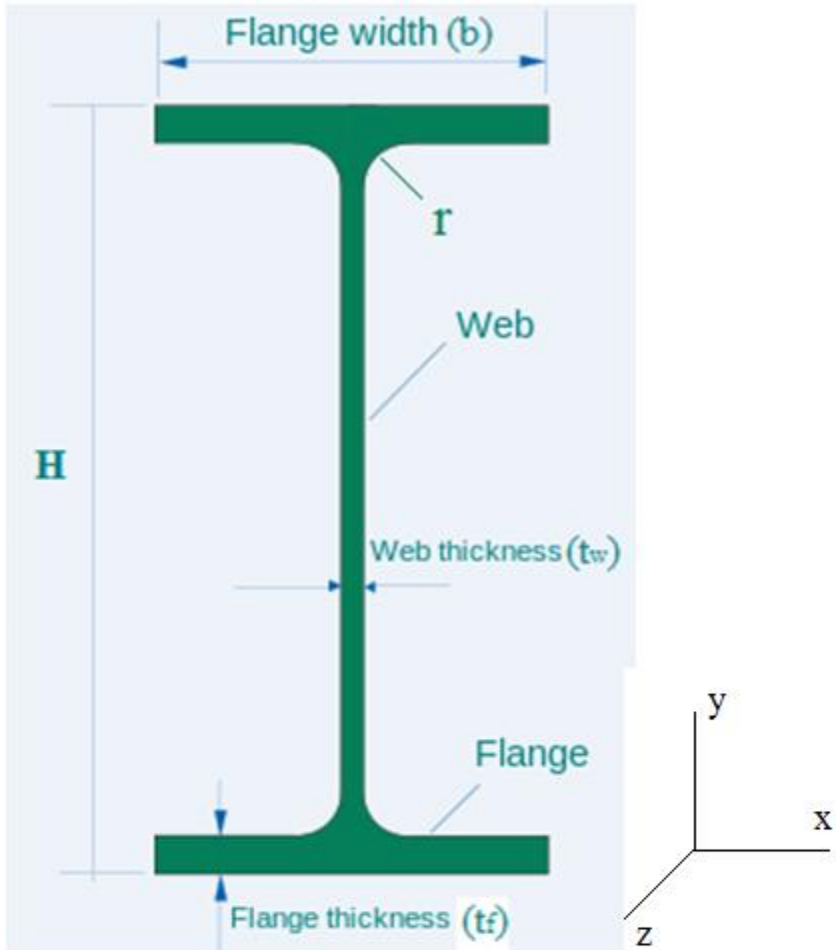

Figure 12 Cellular beam geometry

1) Area of the Section

$$A = 2\, t_f\, b + (H\text{-}2\, t_f)\, t_w + (4 - \pi)\, r^2 \quad (6)$$

2) Web depth

$$d = H - 2\, t_f\; - 2r \quad (7)$$

3) Mass per unit length

$$G = A\, \rho_a \quad (8)$$

4) Second moment of area

$$I_y = \frac{1}{12} [b H^3 - (b- t_w) (H- 2 t_f)^3] + 0.03 r ^4 + 0.2146 r^2 (H - 2 t_f – 0.4468 r)^2 \qquad (9)$$

$$I_z = \frac{1}{12} [2 t_f b^3 + (H- t_f) t_w^3] + 0.03 r ^4 + 0.2146 r^2 (t_w + 0.4468 r)^2 \qquad (10)$$

where, r is the radius, ρ is the density and π (PI) is A MATHEMATICAL CONSTANT.

5) Radius of gyration

$$i_y = \sqrt{\frac{I_y}{A}} \qquad (11)$$

$$i_z = \sqrt{\frac{I_z}{A}} \qquad (12)$$

6) Elastic Section Modulus

$$W_y = \frac{2.I_y}{H} \qquad (13)$$

$$W_z = \frac{2.I_z}{b} \qquad (14)$$

7) Section's Plastic Modulus

$$W_{pl.y} = \frac{tw\, H^2}{4} + (b- t_w) (H-t_f) t_f + \frac{4- \pi}{2} r^2 (H-2 t_f) + \frac{3\pi-10}{3} r^3 \qquad (15)$$

2.3 Lateral Torsional Buckling (LTB)

Extra loading of the steel members pushes them to a stage that the member start to lose its equilibrium, when the member reaches to this stage, the modes of failure start to take place. Lateral torsional buckling is one of the major modes of failure that the beams face due to over loading and lack of resistance at that point. In steel members, LTB has special calculations and considerations as it is a critical issue for steel sections that can cause part or whole of the structure to collapse in some cases.

When the length or the span of the beam increases, the beam will be more exposed to lateral torsional buckling as the increase in the unrestrained length of the beam makes the resistance against LTB mode of failure lower. The critical part in this mode of failure usually is the compression flange as the load will be exerted directly on that surface pushing it to the non-equilibrium state.

Figure 13 shows the Lateral torsional buckling failure mode for a cellular section loaded above the stiffeners in a four-point bending test. Loading on the beam started to be applied in increments till the beam reached to its maximum load and the LTB failure mode start to take place as shown in Figure 13.

According to Eurocode 3 (2004), without lateral restraint along the beam section, the sections are prone to buckle and twist around the major axis. This mode of failure is called Lateral Torsional Buckling.

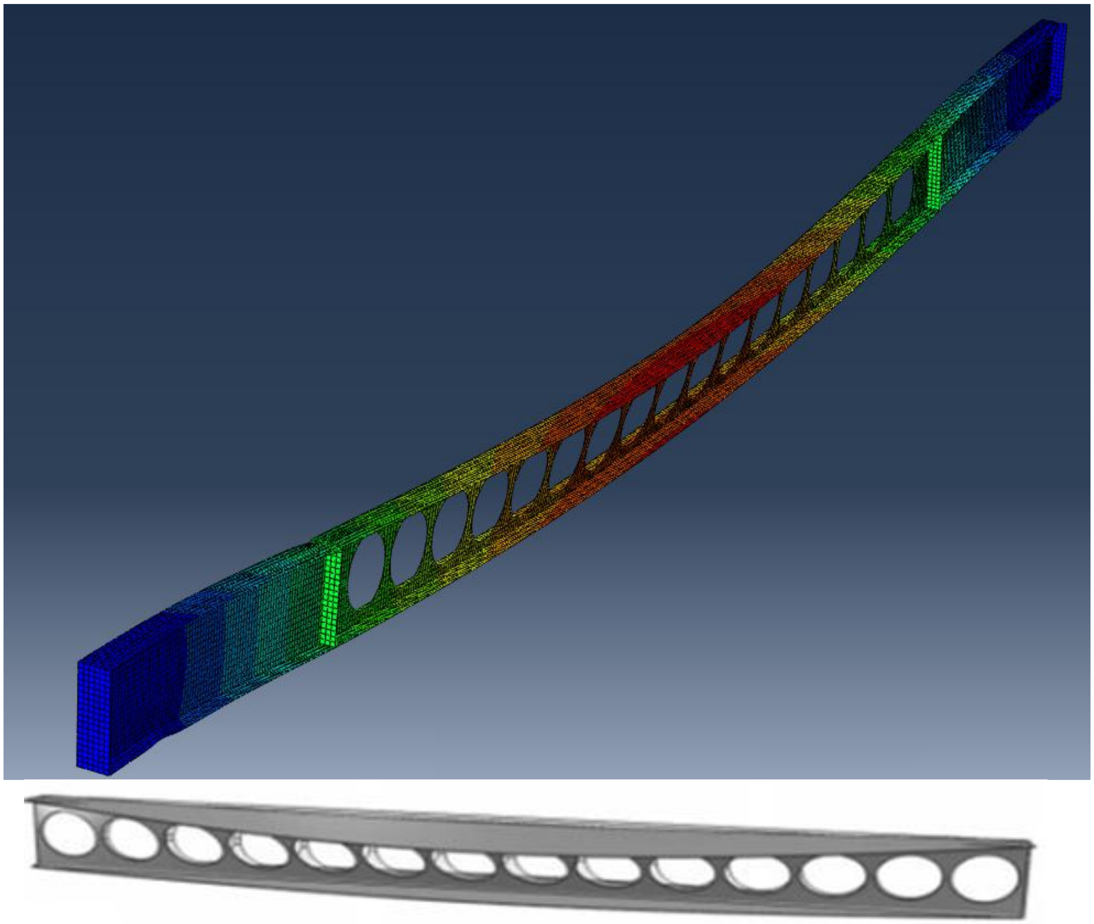

Figure 13 LTB of Cellular Beam shown by FE Analysis

Technical guidance of structural engineers (2012) stated that, steel members tend to buckle along their unrestrained length. This mode of failure can be prevented or reduced by restraining the compression part of the beam. LTB should be treated carefully by designers as it is a critical issue in the structural steel design, otherwise the structure will be at risk and the possibility of failure will significantly increase.

The beam will be unrestrained when the compression flange is free to rotate and move along its axis. Applying the load and increasing it to reach the non-equilibrium point cause vertical, lateral and torsional displacements which causes the lateral torsional buckling failure mode as shown in figure 13 (Technical, 2006).

2.3.1 Lateral Deflection

When the load is applied perpendicular on the upper flange of the beam, the force applied will be resisted by the compression flange and tension flange. The critical part in LTB mode of failure is the compression flange. After a while of the load application, the compression flange tries to buckle and deflect laterally away from its original axis while the tension part tries to stay at its original position. This conflict between the two flanges causes higher stresses to be exerted along the beam section which at last lead to the beam failure. Figure 14 shows the LTB behavior of the tension and compression flange under loading (Technical, 2006).

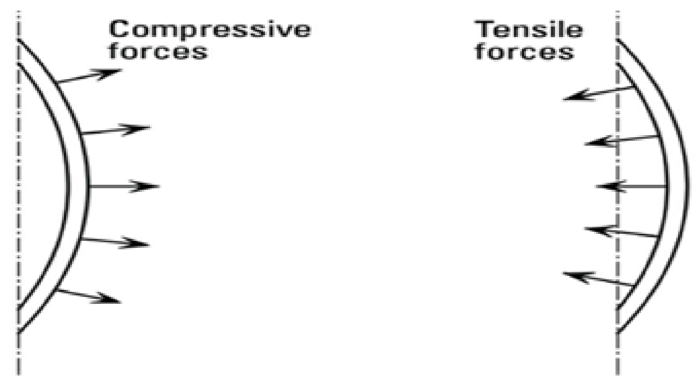

Figure 14 "LTB" of Cellular Beam **(Barrett Byrd, Associates, 2013)**

Furthermore, other stresses can be exerted on the beam that comes from the twisting of the section around its longitudinal axis. This twist can be resisted by the section's torsional stiffness which is mainly governed by the flange thickness of the beam. If the two beams with the same depths but different flange thicknesses are compared, the beam with the thicker flange will have more bending strength. (Technical, 2006).

The beams boundary conditions and its restraining methods (e.g. type and location of connection, the welding and the use of bolts) play a major role in controlling the lateral displacements and the failure mode too. Moreover, imperfections might also have a significant effect on the lateral displacements and twisting of the beam as they affect the accuracy of the load and displacements results. In addition, imperfections play a major role in the beam's failure as it affects the residual stresses and also cause the lateral bending stiffness of the beam to be reduced just like the slenderness. There are many types of imperfections that the steel sections might face and some of these imperfections happen during:

- Manufacturing,
- Transportation of the sections,
- The process of cutting and welding (for beams that have perforation e.g. cellular members),
- The erection phase of the steel members.

Imperfections cause the steel members to have additional residual stress patterns to change. This would contribute to the failure modes like lateral torsional buckling as the bending resistance and the strength of the section itself will be affected and reduced as a result of the imperfections. Figure 15 shows the measured and the obtained imperfections of the beam, the IPE 330 section is the section that is verified numerically in this study.

Base profile	h_{left} [mm]	h_{right} [mm]	b_{up} [mm]	b_{lo} [mm]	$t_{f,up}$ [mm]	$t_{f,lo}$ [mm]	$t_{w,up}$ [mm]	$t_{w,lo}$ [mm]
Angelina	518.6	517.9	160.8	160.2	11.9	11.9	8.1	8.1
HEA 340	465.8	472.1	297.1	297.7	16.0	16.0	10.4	10.3
IPE 330	446.0	446.5	161.4	161.7	10.8	10.7	7.9	7.6

Figure 15 Measurement of imperfections **(Nseir et. al., 2012)**

2.3.2 Effect of Slenderness

One of the most important advantages of cellular beams is the increase in the depth when the section is cut, shifted and welded. This cut along with the perforations in the web part causes a significant increase in the height, around 50 to 60 percent, which reinforces its bending resistance as the moment of inertia will dramatically increase.

As discussed before, lateral torsional buckling is a critical issue in the steel structural design and special calculations and checks should be considered for it in order to ensure a safe structure.

Many factors are affected by the slenderness of the section, and many factors can affect the section's slenderness and in both cases this is a disadvantage for the beams. Some factors that affect the section's slenderness are as follow (Technical, 2006):

- beams length,
- thickness of the flanges,

The thickness of the flanges affect the torsional and lateral movement as thicker flanges have better resistance that minimize the torsional and lateral bending. In cellular beams, the height is increased while the flange thicknesses stay the same which makes it more prone for LTB due to increase in slenderness.

2.3.3 Factors Affecting the Lateral Torsional Buckling of Beam

The main factors that cause the cellular beams to experience LTB failure mode are the beam's geometry, spacing between the perforations, diameter of the perforations, web slenderness, loading type, unrestrained length, section's boundary conditions and the quality and the type of the weld used (Ellobody, 2011).

For some cases, two identical beams with the same dimensions might not behave similarly due to boundary conditions or loading locations and other factors as mentioned above. In this study the main objective is to verify a section which was tested against lateral torsional buckling before (Nseir et. al., 2012). Using the finite element model sections having the same properties of the original test should be defined numerically for LTB results to achieve the verification.

The following are some of the factors which may have serious influences on the lateral torsional buckling,

- **Load Location:** According to new steel construction technical report (2006), the load location may have a significant influence on the LTB failure mode. The most critical case is when the load is applied above the shear center of the beam where it makes the section more prone to LTB (destabilizing load). On the other hand, if the load is applied at the shear center or below it, this will help in reducing the susceptibility for LTB (non-destabilizing load).

- **End Support Conditions:** One of the main problems during the verification process was the boundary conditions which are the same as the end support conditions. End support conditions affect the results in a significant way and in order to get accurate and realistic results, the end support conditions should be precisely assigned in the finite element software. However, in real life, the FEM won't give the same results as the experimental one since for FE software the support condition might be stiffer than the one in the real life which leads to a stronger section with higher resistance. Moreover, imperfections and geometric nonlinearity have a significant influence on the failure load and in order to get accurate failure load and displacement, they should be considered more precisely.

In the design of steel structure, the types of connections considerably affect the LTB failure mode. For instance, if one considers that the web cleat connection restrains the web, then as the technical report of new steel construction (2006) states, the web cleats help in reducing the lateral deflection and twisting of the web.

The flange thicknesses also play a major role in the lateral displacement and twisting resistance. In other words, the beams with thicker flange would have lower slenderness ratio and better resistance to **LTB**.

End plate thickness also has significant influence on the **LTB**. According to the tests carried out by Marco Santarelli (2010), increase in the buckling load was achieved by increasing the plate thickness.

2.4 Lateral Torsional Buckling of Cellular Beams

2.4.1 Residual Stresses

For a section, changing its physical characteristics or the geometrical shape and adding a new material like welding for cellular members might have a big influence on the mechanical properties like bending strength resistance, moment resistance, stiffness, etc. A residual stress is an important factor for structures, as it may help in the failure modes at earlier stages. In cellular beams residual stresses will be affected by the cutting process specially as it include cutting and welding, where the welding process generate extra heat on the section. Also, adding a new material on the section, such as weld, can obviously affect the residual stresses of the section. According to Delphin Sonck et al (2013), residual stresses are internal stresses which can exist in the section without any external disturbance like loads and can be obtained using Eurocodes standards in Figure 16. It has a noticeable influence on the behavior of the buckling failure. However, according to authors, the effect of the cellular beam production process on the residual stresses is still unknown and researchers are trying to investigate this critical phenomenon.

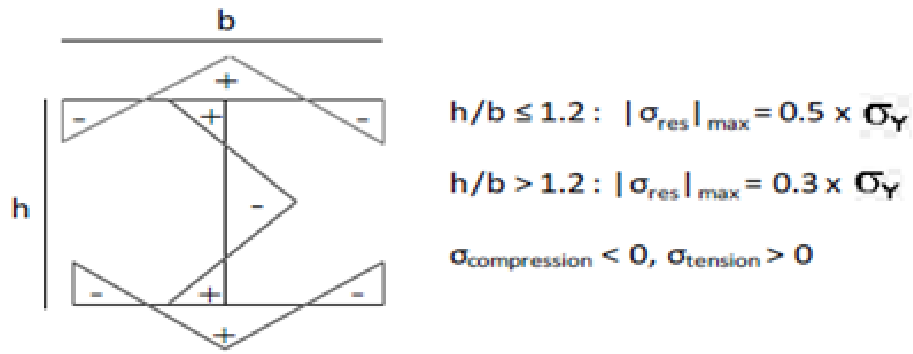

Figure 16 Typical Eurocode residual stresses pattern (EuroCode3, 2004)

2.4.2 Influence of the Perforations on Cellular Beams

There are many advantages and disadvantages for the cellular beams as a consequence of having perforations. The web openings affect the behavior of the cellular beams since part of the section is removed and also the total geometrical shape changes. In addition, the presence of the openings can cause more than one mode of failure like web post buckling and other failure modes.

According to Chung et. al. (2000) and Kerdal et. al. (1984), cellular beams can face many failure modes due to the perforations in the web and its slenderness, which is affected by the beam's depth or height. The failure modes that are related to the stability of the section are as follow:

1. Lateral Torsional Buckling,
2. Web post buckling,
3. Lateral distortional buckling.

It is found that the yield caused by the shear stresses in the steel sections with circular perforations is very effective as it promote the formation of the plastic hinges near the high moment side of the web openings (Chung et. al., 2000).

Some studies were done by Mohebkhah (2004), which were proven through some quantitative data. These studies state that, the change in slenderness of the perforated sections has a significant influence on the moment gradient coefficient which is mainly used for the flexure calculations in the design of beam which in turn, affect the stability and the strength of the beam.

2.4.3 LTB Design Rules for Cellular Beam

When the loading is increased and LTB mode start to take place in the beam, the lateral displacement of the compression flange is restrained (prevented from twisting and moving laterally) by the flange itself or the part of it in tension. This conflict between the tension and compression results in a combined torsion and lateral movement of the section. Currently there are two design rules for calculating the critical moment of the LTB mode of failure for the cellular beams. The first design rule comes from the European pre-standard ENV3 (European Committee for Standardization,, 1992). According to this rule, the critical LTB failure moment for the perforated beam can be obtained in the same way it is obtained for the parent section; the only difference is that, the properties of the cross sectional should be used at the center of the castellation rather than the plain webbed cross sectional properties. The other rule was introduced by the Centre Technique Industriel de la Construction Metallique (2006). This design rule was more conservative; where the cellular beam resistance is only dependent on the lateral buckling resistance of the compressed T-Sections at the openings (Sonck D. et. al, 2011).

Further research was in accordance to the above two rules. It showed that the first design rule "European pre-standard ENV3" is safer (Sonck D. et. al.,, 2010).

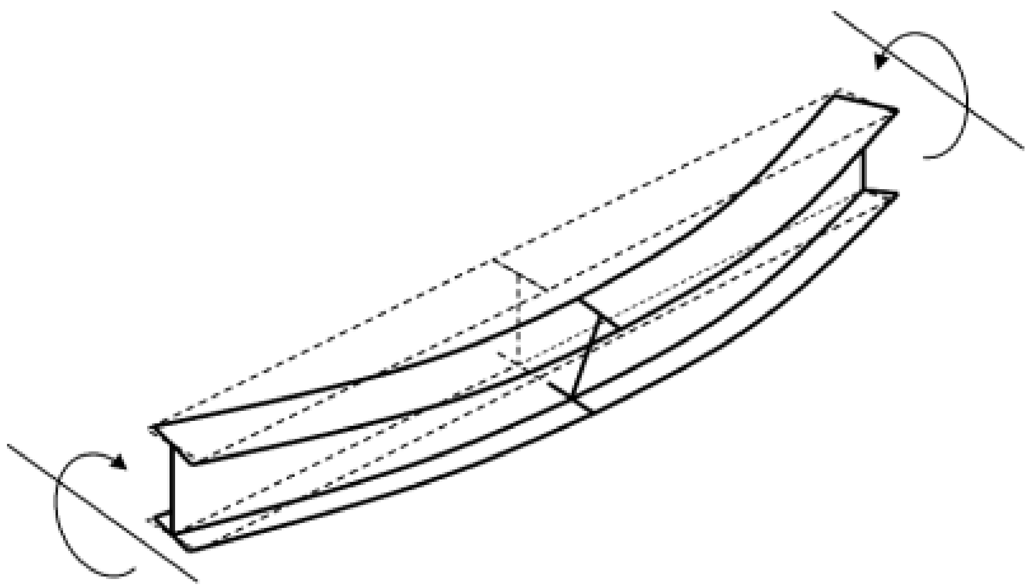

Figure 17 LTB of steel beam

Chapter 3

METHODOLOGY

3.1 Introduction

The usage of cellular beams has been increasing during the last decades due to its advantages. However, these kinds of beams also have disadvantages that affect the structure in a significant way and can cause more than one mode of failures. Furthermore, these beams also need special machines and software to perform the cutting, shifting and welding procedure under the supervision of trained staff. The welding and shifting process should be done very carefully otherwise failure modes may be observed at earlier stages. The machinery required are expensive and not widely available, therefore, the whole process is more costly. Accordingly, researchers have been studying the effects of this type of beams through experimental and numerical work where the failure modes for the cellular beams are investigated. Moreover, the lateral torsional buckling of steel cellular beams recently started to be investigated by researchers. Few of the most important research about lateral torsional buckling were carried out by Sonck et. al., (2010), Sonck et. al. (2011), Sonck et. al. (2012) and Ellobody (2011).

Researchers proposed new theories and introduced some solutions for reducing the risk for this critical mode of failure (LTB). It all started when the era of castellated beams

(Figure 1) started to shift to the era of cellular steel beams (Figure 2) since the castellated beams have sharp edges. Nowadays, there is another type of castellated beams which is sinusoidal beam (Angelina beam). These developments are due to engineers and researchers that are continuously trying to improve the perforated sections in order to enhance the strength of the member and to reduce the possibility of failure modes. There are few scientific work on this subject and the researchers are trying to find solutions to problems relating to this new type of beam.

3.2 Choosing the Finite Element Software

3.2.1 Introduction

Experimental tests are generally performed to get realistic data, to observe the possible behavior of members in real life and to identify the risks for a specific member under various loading conditions. Another way of testing members and getting realistic data is via the use of sophisticated finite element software. A researcher can perform numerical analysis by modeling a member that was already tested experimentally by other researchers. Same boundary conditions, load magnitude, and location, material properties, member imperfections and all the relevant experimental parameters should be used to achieve accurate results. This approach is known as verification of experimental results.

Verification of an experimental member is said to be successful if the results (e.g. displacements, stresses, etc.) obtained from the numerical tests reasonably agrees with the ones obtained from the experimental tests. Verifying members by using FE programs should be repeated many times in order to get accurate results that are very similar to test results. In this research, the number of simulations "Runs" for the tested member was 1000 in order to verify the section and to get accurate results. Every time the parameters, such as boundary conditions and location of loading nodes were changed until the most adequate case was obtained, the verification was successfully achieved and the results were close enough to those one obtained from the experimental tests.

3.2.2 Abaqus Software

Abaqus is designed to meet the engineering analysis and design requirements. The program contains 3 model databases selections for different design purposes which make it easier to meet the designer's requirements. The 3 model databases explained in the coming paragraphs.

In this study, the database with standard-explicit model was selected to model and analyze the cellular beam sections which are related to mechanical and structural components (Dassault Systèmes,, 2006).

1) Database with computational fluid dynamics "**CFD**" model

- It is used to model and analyze problems that deal with fluid dynamics (Dassault Systèmes,, 2006).

2) Database with electromagnetic model

- It is used to model and analyze the sources of electromagnetic interference and the interaction of electromagnetic fields with physical objects (Hubing, 1991).

Abaqus is used by many researchers in order to model and verify various sections. Abaqus software has many parameters and variables, such as imperfections, and designer can properly define these parameters to get accurate results. Abaqus software can also handle members with perforations in the beam web for instance, to get accurate values for parameters, like stresses , displacements, reactions and other output results by using special types of analysis and a right mesh structure which will be discussed in the coming sections.

3.3 Selection of Experimental Section IPE 330 Cellular Beam for Verification

The aim of this numerical study was to find methods of reducing LTB for cellular beams. However, experimental test results are needed to verify such numerical study. During the literature review process the experimentally tested sections that might be useful for such study were identified, after careful and detail consideration the most appropriate one was selected. First of all the section was selected, modeled and verified against the experimental results. Then some modifications were applied to these members in order to improve their behavior against lateral torsional buckling that will be discussed in the following sections.

3.3.1 Experimental Test

The experimental tests were done by Nseir (2012) for three perforated sections of which, one of them was chosen to be verified (IPE 330). Tests were performed in the structural engineering laboratory of Fribourg Faculty of Engineering and Architecture.

The beam consisted of 4-points of bending test where the load was applied at two locations away from the edge supports, as shown in Figure 18.

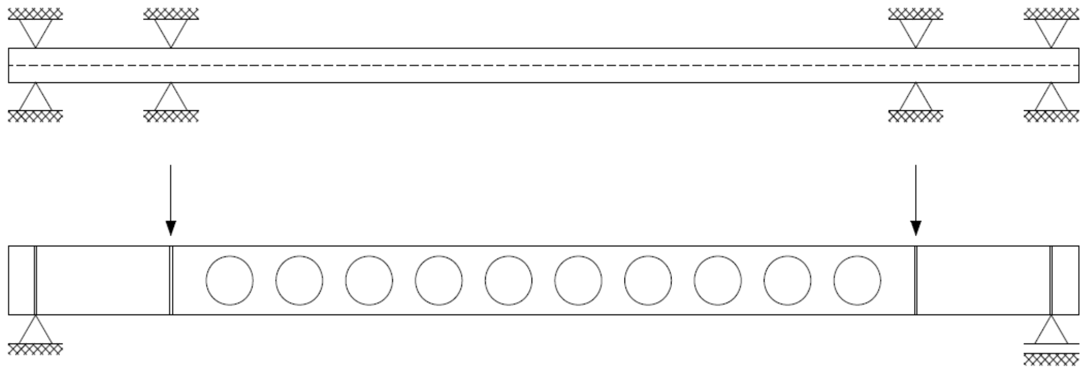

Figure 18 Locations of applied load for cellular beams (Nseir et. al., 2012).

The middle unrestrained length between the loads had a constant bending moment distribution while the adjacent segments supported linearly varying bending moments.

Accordingly, the mid-length between the load application points is unrestrained, whereas the outer part was restrained laterally at the end supports and at the loading locations.

3.3.2 Section's Specifications

After carrying out detailed research and reading many different sources on lateral torsional buckling and cellular steel beams, the paper of Nseir (2012) was chosen as the reference to this research. Some parts of this article were not clear enough. The information on the length of beam and the stiffener thicknesses were missing in this paper. It is mentioned in the article that the length of the tested members varies from 7.5 m to 11.0 m. This made it hard to use trial and error for these dimensions. Eventually, this problem was resolved when there was personal contact with Mrs. Delphine Sonck who is one of the researchers who performed these experiments that took place in Nseir (2012).

The length of the unrestrained middle part which is between the two loading points was 7110 mm and the distance from the loading points to the end supports (outer part) was 1945 mm which in total makes the total length of the beam to be 11 000 mm (Figure 19).

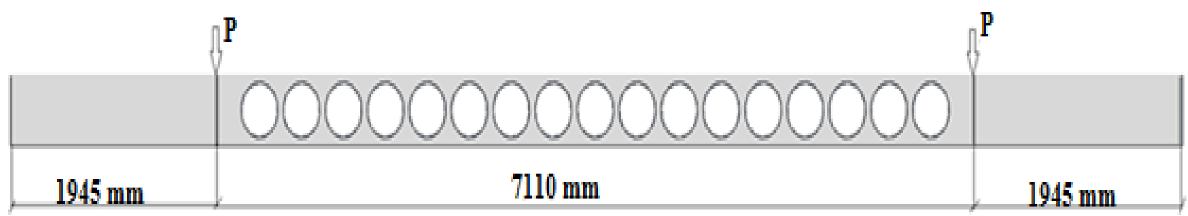

Figure 19 Dimensions of cellular steel beam (IPE 330)

3.4 Section's Properties

3.4.1 Material Properties

In order to get accurate results on the stress-strain values, coupon tests were done. From each member, two coupon specimens have been tested through a loading protocol. Figure 20 shows loading protocol and Table 1 gives the results from the coupon tests.

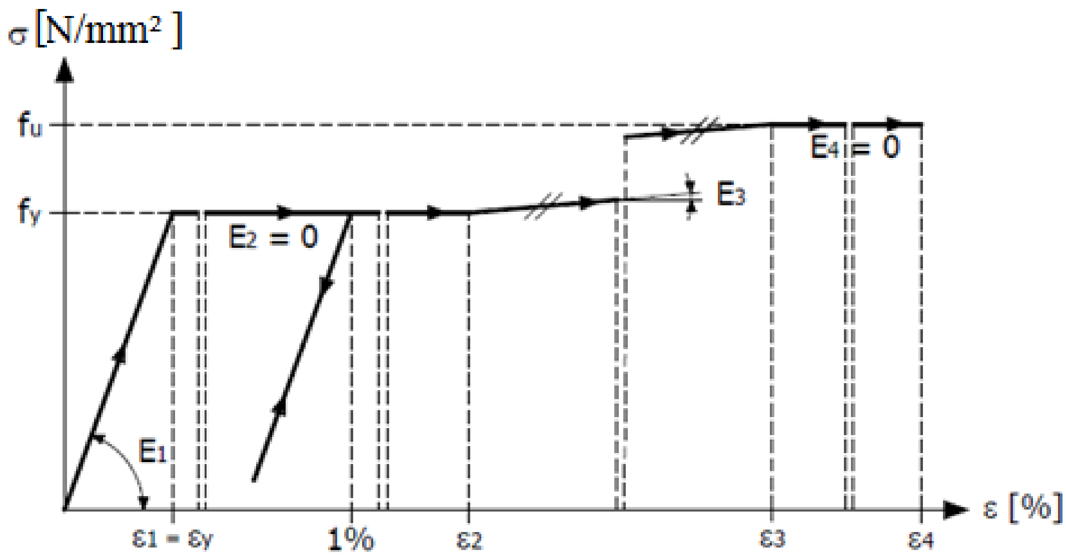

Figure 20 loading protocol for the Coupon tests **(Nseir et. al., 2012)**

Table 1 coupon test results for IPE 330 section **(Nseir et. al., 2012)**

Coupon # (base profile)	1st slope			2nd slope	3rd slope			4th slope
	f_y [N/mm²]	ε_1 [%]	E_1 [kN/mm²]	ε_2 [%]	f_u [N/mm²]	ε_3 [%]	E_3 [N/mm²]	ε_4 [%]
1 (IPE 330)	373	0.21	177.6	2.00	481	5.03	3564	30
2 (IPE 330)	372	0.22	169.1	2.00	480	5.10	3484	25
Average	*373*	*0.22*	*173.4*	*2.00*	*481*	*5.07*	*3524*	*28*

According to the above coupon tests specimens, the average results were considered during the preparation of the model. The values given in Table 1 are nominal values and in order to define these values in Abaqus, they should be changed to true values using the equation recommended in Hibbitt (2008).

The behavior of the material in Abaqus allows the use of a non-linear stress-strain and since the analysis of buckling modes includes large plastic strains, the nominal stress and strain are changed to true stress and strain using the equations (16) and (17) as given below:

$$\sigma_{true} = \sigma_{nom} (1 + \varepsilon_{nom}) \quad (16)$$

$$\varepsilon_{true} = \ln (1 + \varepsilon_{nom}) \quad (17)$$

The exact value of the Modulus of Elasticity can be found by true yield stress and strain using the following equation:

$$E = \left(\frac{\sigma}{\varepsilon}\right) true \quad (18)$$

The modulus of elasticity was calculated from the true stress and strain. Related to the strain, Abaqus subtracts the Elastic stage from the plastic one to find the true nonlinear behavior of the member. This means that, the first elastic strain value in Abaqus will be set to zero and all other plastic strains will be subtracted from the value of elastic strain of the original true strain value.

3.4.2 Initial Imperfections

Imperfections play a very important role in the design and modeling process. The general view about imperfections being not important is misleading. In reality they do have significant effect on the results and on the behavior of the section (e.g. failure load). Members may have imperfections due to a number of reasons. These imperfections often affects its physical and mechanical properties, The followings are the main reasons of imperfections:

- **During Manufacturing**

The temperature may change through the manufacturing process and this might affect the mechanical properties of the section.

- **Transportation of the Section**

During transporting, handling and placing of the sections, the member might hit somewhere or being bent at specific location along its span which might change the section's properties.

- **Cutting and Welding of Cellular Beam:**

One of the main factors affecting the mechanical properties of the section is the temperature. During the process of cutting, shifting and welding of cellular beams the section will face changes in the temperature and this might affect the behavior and properties of the section.

All these imperfections can cause change or deviation in residual stresses. More information on imperfections can be found in the following references; Dubina et. al. (2001), Mathur et. al. (2011) and Zdenek (2005).

The measurement of the actual dimensions in Nseir et. al. (2012) after the changes of the imperfections on the section was measured using 3 sophisticated techniques that can detect the change in dimensions in small areas providing a level of accuracy for the measured imperfections by around ± 0.30 mm.

The first technique was done by global scanning using theodolite devices. The second technique was done by means of optical system. It is done by putting the light source on the edge of the flange over a longitudinal moving trolley. Finally, refined scanning of the local areas for the section in which the surfaces of the web are measured and after some numerical treatment, an optimum average surface will be defined for the Finite Element Model.

3.4.3 Estimated Dimensions

After using the imperfection measuring techniques, Table 2 shows the results of the section's dimensions.

Table 2 Dimensions after imperfections

Base Profile	h_{left} [mm]	h_{right} [mm]	b_{up} [mm]	b_{lo} [mm]	$t_{f,up}$ [mm]	$t_{f,lo}$ [mm]	$t_{w,up}$ [mm]	$t_{w,up}$ [mm]
IPE 330	446.00	446.50	161.40	161.70	10.80	10.70	7.90	7.60

The section properties of the verified Cellular steel beam (IPE 330 base profile) was calculated from the table above by finding the average dimension of each part of the section and are illustrated in Table 3:

Table 3 Actual dimensions of IPE 330 cellular steel beam

Base Profile	H [mm]	b [mm]	t_f [mm]	t_w [mm]	D [mm]	S [mm]
IPE 330	446.25	161.55	10.75	7.75	345.00	395.00

For cellular beam with base profile IPE 330, stiffeners were used at 4 locations, two at the end supports and two at the loading locations. The thickness of each stiffener used in the experimental test was 20 mm.

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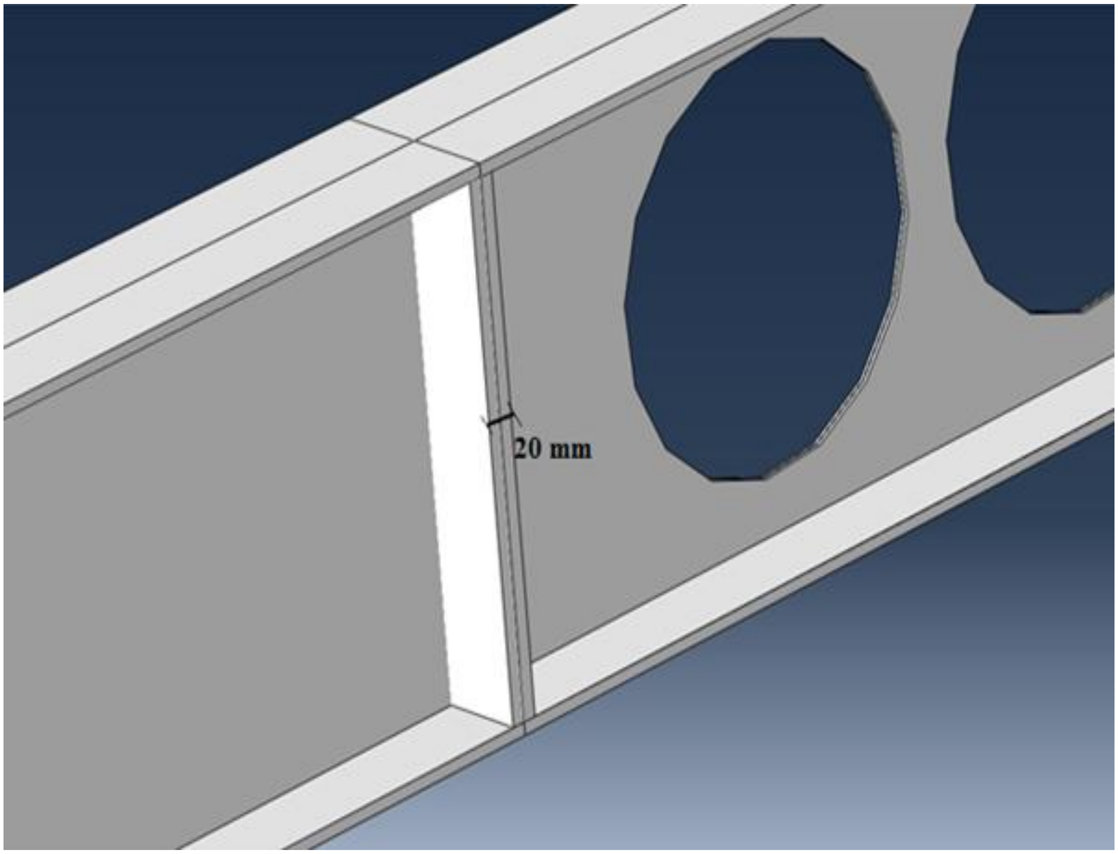

Figure 21 Stiffener at load introduction

3.5 Finite Element Model

3.5.1 Modeling the Parts for Cellular Beam IPE 330 Base Profile

Modeling the parts were the first step in the analysis and design process. There were two parts to model, the first part was the beam profile along with the perforation in the web and the other part was the stiffeners. In order for these two parts to act as one part, the beam was merged with the stiffeners at the specified locations. After merger, this part became the main part of the analysis.

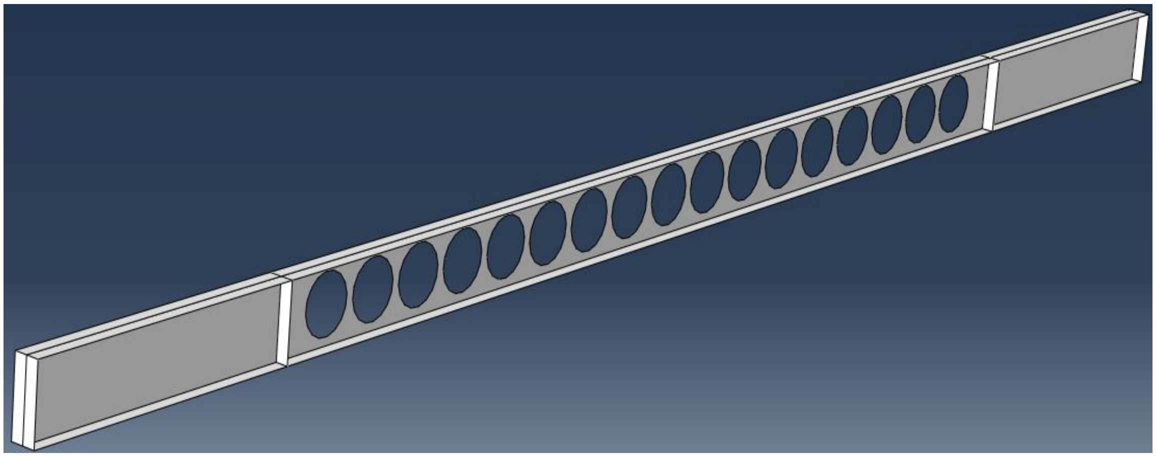

Figure 22 Cellular beam merged with the stiffeners

The parts were modeled using shell element method rather than solid elements method (Abaqus software) since shell elements have more accurate solutions to most of the buckling applications. Modeling of complicated sections, such as, beams with web perforations need careful selection of the types of elements to get accurate results and realistic behavior. According to lluk et. al. (2013) the advantages and disadvantages of using shell element method are given below:

Advantages:

- Can solve sections that have precise details (e.g. web's perforations),
- Proper Mesh shape can be easily created which will produce high quality elements,
- Analysis using shell element will have less problems in stability,
- Shell element needs much less memory space for simulations,
- Shell element needs less time to run a simulation.

Disadvantages:

- Have problems in connection design for precise connections and multi layered connections,
- Have less realistic boundary conditions than solid element has and this is because shell element boundary conditions are applied to the surfaces instead of edges,
- Shell element needs more steps to create a model as most of the details should be modeled separately.

The beam parts (flanges, web and stiffeners) were modeled using a 3D modeling space with a deformable element type. The base features were shell element with extrusion type while for the stiffener part the base feature type was planar.

After the merged beam is modeled, a partition process was performed on it. The main purpose of creating partitions was to enable the mesh criteria to be in the right way so that the stresses will be uniformly distributed without any disturbance and also to have a uniform number and sizes of the mesh elements. There were 60 partitions in the section where most of them were around the web's perforation due to the non-regularity of the web section.

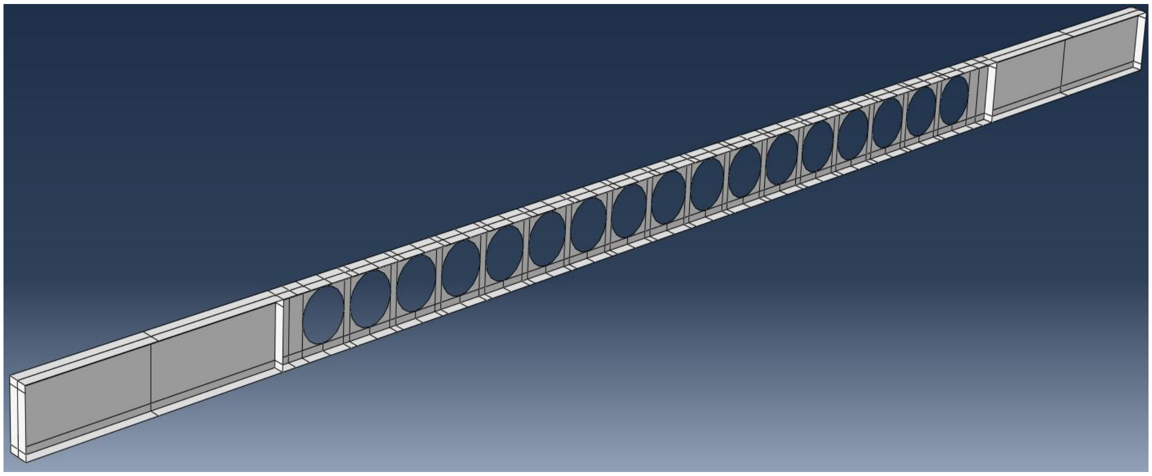

Figure 23 Partitions for the cellular beam

3.5.2 Section Assignments

Unlike solid element, Shell element has no thickness with regards to section's parts (web and flange). In order to define the thicknesses of the section's parts in Abaqus, the parts should be assigned and defined separately. Each part of the web, flange and stiffener were selected and assigned, and then the thickness of each part is defined. Figure 24 show how the section's parts are assigned and then the thicknesses was defined.

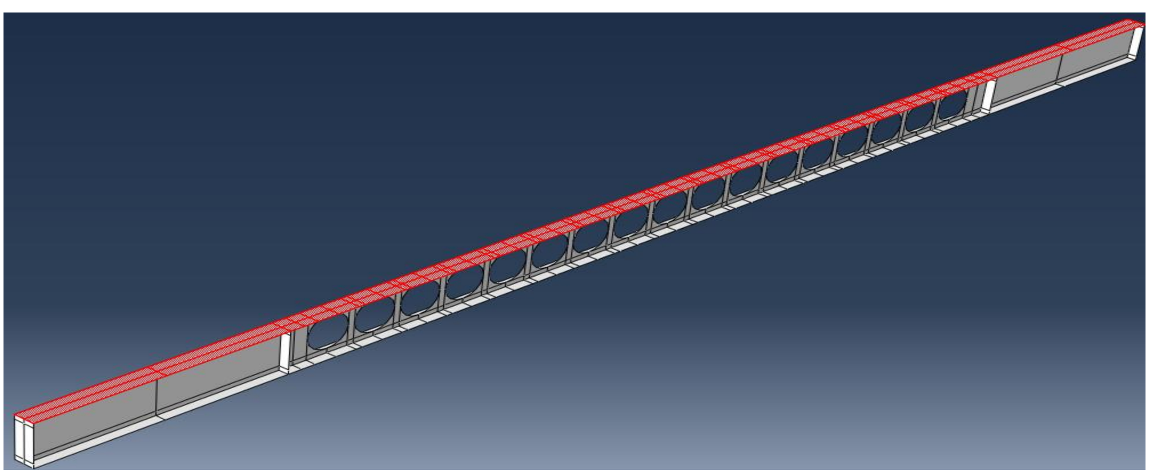

Figure 24 Assigning the top part of the flange section

3.5.3 Mesh and Element Type

The finite element type was selected in such a way that, it would be adequate for the lateral torsional buckling failure mode cases. A combination of 8-nodes doubly curved thick shell elements with reduced integration S8R was used to model the beams section's parts (flanges, web and stiffeners).The S8R element have 6 degrees of freedom per node and provides precise solutions for lateral torsional buckling cases.

For the mesh, the size of global seeds was adjusted to meet the adequacy of the section and in each section the size was changed in a way to have no warning and errors in the mesh criterion. The curvature control box was activated to control the curves due to the web perforations. Moreover, the partition of the sections which was discussed in the previous sections gave the advantage for the mesh shape to be linear and adequate. Figure 25 shows the mesh shape for the cellular steel beam IPE 330 base profile section.

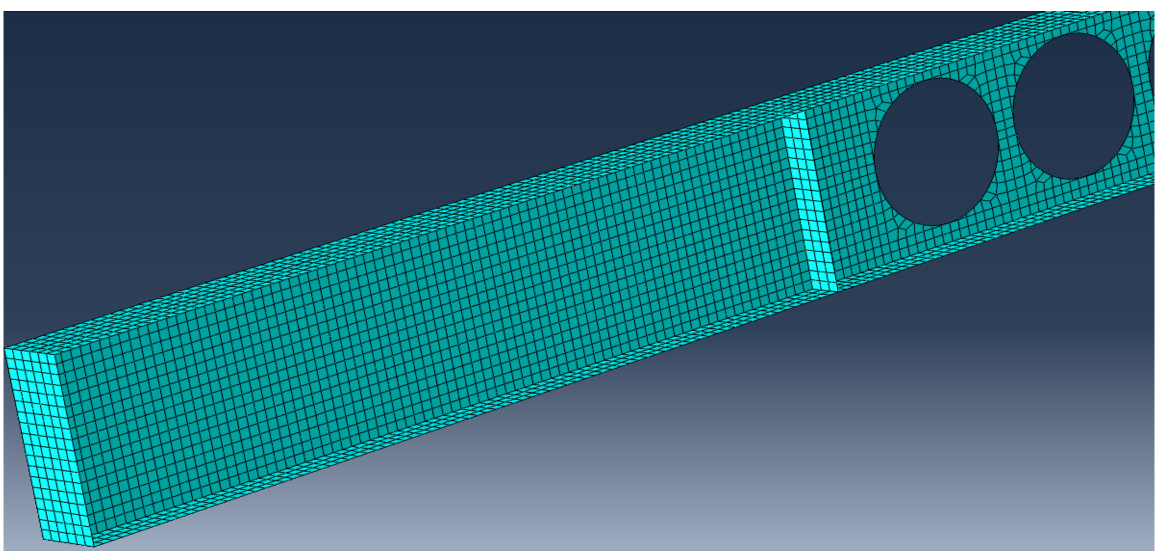

Figure 25 Finite elements mesh for cellular beam - IPE 330

3.5.4 Assigning the Material

One of the important parts of the modeling process is defining the material properties. It enables the software to detect the sections mechanical properties (e.g. strength, yield stress and strain) and make it more precise for the realistic results.

The stress-strain properties were obtained from the coupon tests and changed from nominal values to true values as explained earlier in section 3.4.1. The density of steel grade S355 according to Eurocode, is 7850 kg/m^3. Poisson's ratio is 0.29-0.3 and the calculated modulus of elasticity is 177600 N/mm^2.

3.5.5 Boundary Condition and Load Sets

Shell element is not a solid part, instead its thin surfaces and location needs to be specified and this was done by creating sets of nodes and assigning them to the boundary conditions. Other sets of nodes were created in the beam for the loading locations. Assigning load and boundary conditions as sets of nodes in shell elements are easier and more accurate. Loads were applied at a distance of 1945 mm away from the end supports and were located above the stiffeners. End supports were fully restrained in such a way that both lateral and vertical displacement and also rotations were all prevented. At the loading points (stiffeners locations), the beam was constrained in the direction of the lateral displacement. Additional sets were assigned at the middle part of beam as the maximum displacements were observed at that location. Assigning a set and running the analysis save time and work and also can give accurate results as the sets are assigned per node.

3.5.6 Analysis Steps

Analysis steps are the part where the designer controls the type of output variable desired to be studied. There are two analysis steps. The first one is the field output step where the domain model of analysis is the whole model and from the output variables section, the desired types of output can be chosen. For this research only the behavior of the lateral and vertical displacements were studied. The second analysis step is the history output step where the middle part set is selected in order to study the behavior of that specific location, which is at the middle of the beam. The analysis step used in this research was static-general procedure type, therefore material and geometric non-linearity were not fully considered and this might affect the failure load and the sudden increase in displacements specially in the non-elastic stage. The static-general analysis step was adequate for the analysis and it gave accurate results. However, static-riks method has extra parameters that can deal more accurately with buckling modes than other analysis. The Riks method was not used in this research, due to the lack of details and parameters related to this method. This affected the failure load since in this research the maximum load was obtained at partial failure rather than full failure stage. If Riks method was used, then the full failure stage would have been obtained at the maximum load . This do not mean that the results obtained in this research are not accurate or different than the one in Riks method, because including the material and geometrical non-linearity will give the software the information where the beam totally fail and might affect the results with a small percentage deviation.

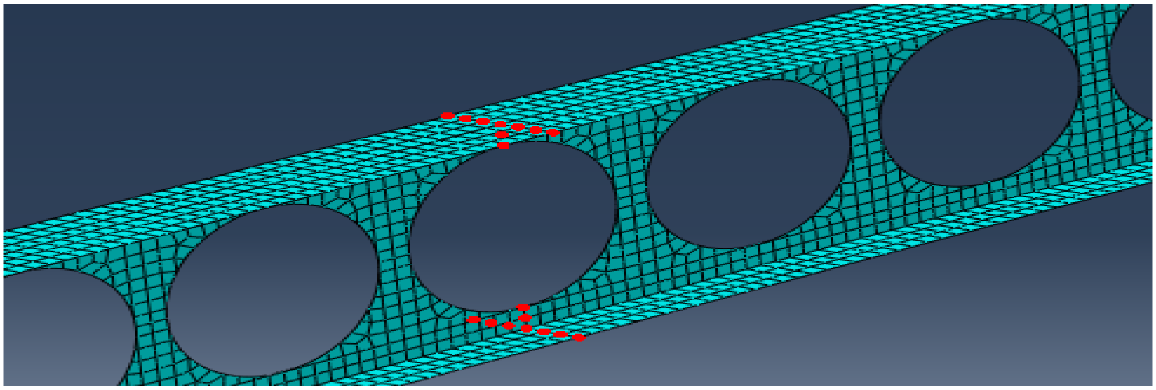

Figure 26 Middle part set

3.6 Parametric Studies

3.6.1 Investigation of IPE Beam Sections for LTB

The verified finite element cellular beam-IPE 330 model was used to investigate the lateral torsional buckling behavior of two cellular beams with base profile IPE 300 and IPE 360. The cases used in the verification of the cellular beam-IPE 330 were also used for both of these cellular beams. Boundary conditions, load locations, stiffener thickness and location, diameter and spacing of the holes and the total length of the beam were assigned to be the same as the Cellular beam-IPE 330. Other dimensions like beam's flange width, web and flange thicknesses were obtained from the European standards manual (European Standards, , 2004) of I-Beams. The only missing dimension was the total height of the beam after cutting and welding. In order to calculate the cellular beam's total height the below given equation was used.

$$H = d + a_0/2 + t_{weld} \quad (19)$$

where t_{weld} is the thickness of the weld in the middle part of the beam's web as shown in Figure 27.

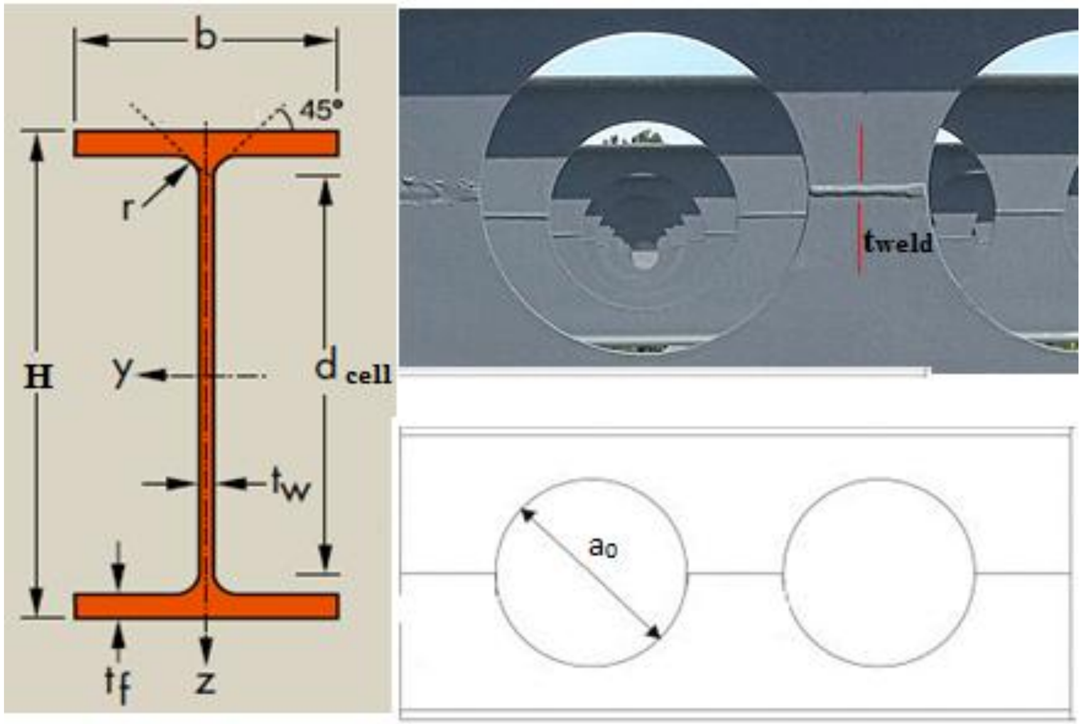

Figure 27 IPE Cellular beam profile **(European Standards, , 2004)**

For the imperfections, the percentages of error related to each dimension (e.g. % of error for the web thickness of IPE 330 Cellular beam = 3.33%) that was measured in the test were considered for the other two modeled beams (IPE-300 and IPE-360) as well (Nseir et. al., 2012). Table below show the calculated dimensions for the two finite element beams:

Table 4 Dimensions for Cellular Beams IPE-300 and IPE-360

Base Profile	h [mm]	b [mm]	t_f [mm]	t_w [mm]	a_0 [mm]	S [mm]
IPE 300	423.85	151.45	10.00	7.34	345.00	395.00
IPE 360	473.85	171.65	11.87	8.27	345.00	395.00

3.6.2 T-Stiffener Approach

In real life one of the jointing methods used to connect secondary beams to main beams is via a kind of T- shape stiffener. Therefore, this connection also acts as a restraining point for the main beam. In this research a T-shape stiffener (Figure 28) was added to the verified IPE-330 cellular beam section instead of the normal stiffener in Abaquas. Analysis results showed significant improvements in the strength resistance of the section. Figures 28,29,30 Show some details of the T- shape stiffener.

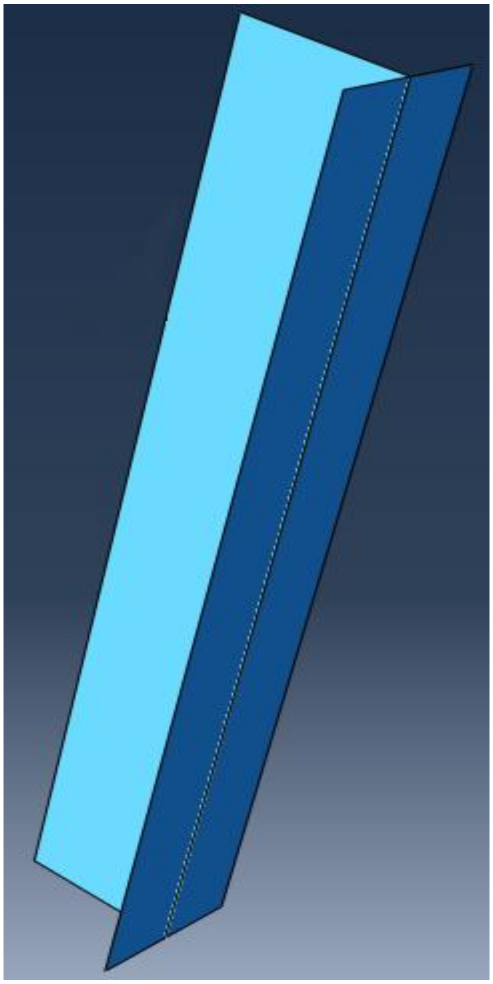

Figure 28 T-shape Stiffener

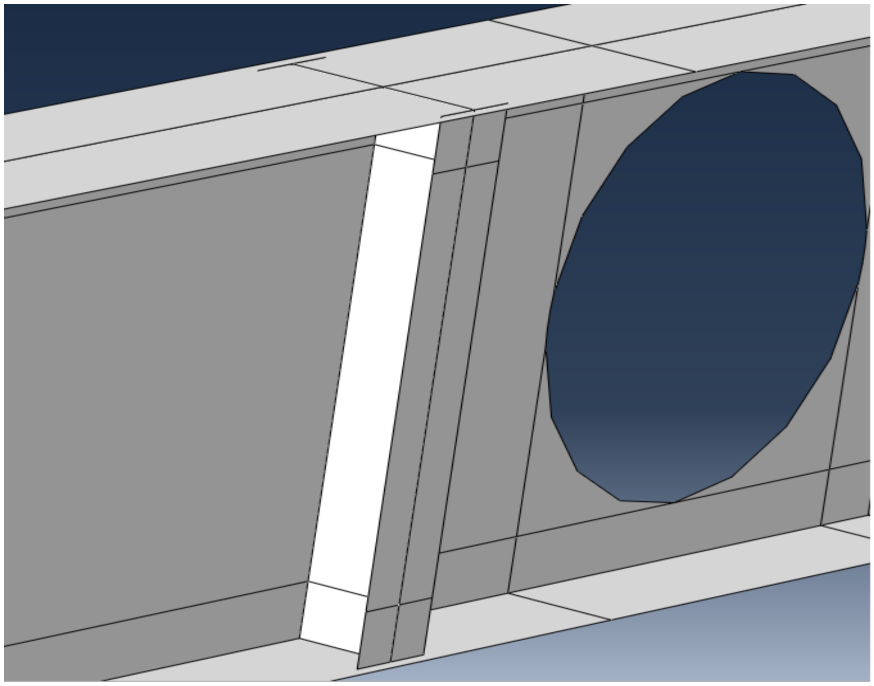

Figure 29 T-Shape Stiffener merged with the beam

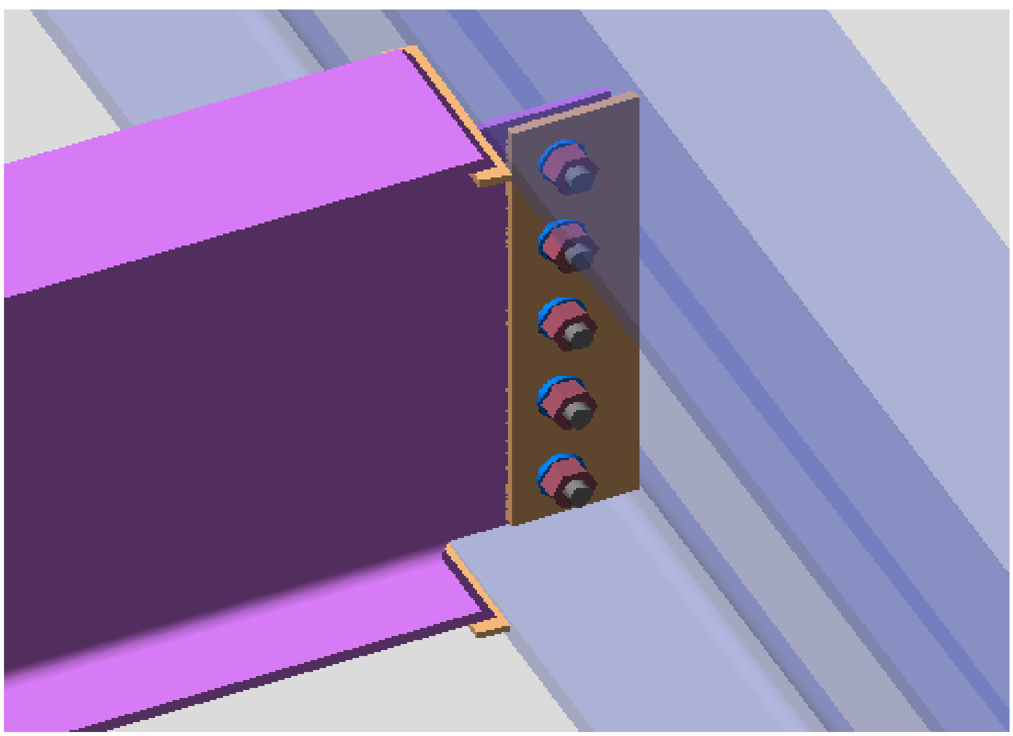

Figure 30 Real life beam to beam connection (T-Shape Stiffener)

Chapter 4

RESULTS & DISCUSSIONS

4.1 Introduction

When there are difficulties in carrying out experimental research due to lack of funding or laboratory facilities then it is convenient to use finite element analysis to verify previously tested steel beam sections so that these verified sections can be used to investigate new cases. In this research this approach was used to verify the previously tested cellular beam-IPE 330 and then two more cellular beams- IPE 300 and IPE 360 were modeled and analytically tested for lateral torsional buckling where the vertical and lateral displacements were studied. Then, the parent section IPE 330 was modeled to compare it with the cellular beam of the same section to observe the effects of increases in depth. Furthermore, the cellular beam IPE 330 was modeled with closed perforations along the web so as to compare how the spacing of web perforations can affect the performance of the beam and the behavior of the failure modes, such as, lateral torsional buckling.

Six IPE 330 cellular beam sections were studied with different stiffener thicknesses to show how it will affect the behavior of the displacements.

In addition, the verified IPE 330 cellular beam section was modified by adding one normal stiffener on each side of the middle part of the beam where the maximum lateral and vertical displacement occurred. Finally, T-shape stiffeners were placed at the same location of the normal stiffeners in the verified IPE 330 cellular beam section and the behavior of the beam was studied.

4.2 Verification of IPE 330 Cellular Beam Section

The verification of test results were obtained after 1000 simulation runs. Table 5 shows the results for the vertical and lateral displacements obtained from the finite element model using Abaqus software.

Table 5 Finite element analysis results for Cellular beam IPE-330

Vertical Load [P_{FE}] (kN)	**Beam mid span displacements**	
	Vertical (mm)	**Lateral (mm)**
0	0	0
50	20.307	0.262
80	32.501	0.303
110	44.674	0.375
140	56.808	0.531
170	68.958	1.235
185	77.434	14.836
190	83.233	30.836

The load was applied at 22 increments. The results obtained from the finite element analysis showed a good agreement with the experimental test results. For the experimental test results, the lateral and vertical displacements at the maximum load **P_{test}= 176.6 kN** was **24.5 mm** and **62.3 mm** respectively. On the other hand the finite element analysis results were found to be **30.84 mm** and **83.23 mm** for the lateral and vertical displacements respectively at the maximum load of $\mathbf{P_{FE}}$ **=190 KN**.

The mean value or the difference ratio **(P_{test} / P_{FE})** between the test and the finite element results was **0.8** for the lateral displacement and **0.75** for the vertical displacement and **0.93** for the maximum load.

Figures 31 and 32 show the comparison of vertical displacements obtained from the finite element analyses and test. Figure 31 gives the vertical displacement results obtained from the finite element analysis using Abaqus software. Figure 32 gives the vertical displacement and FE results of (Nseir et. al., 2012).

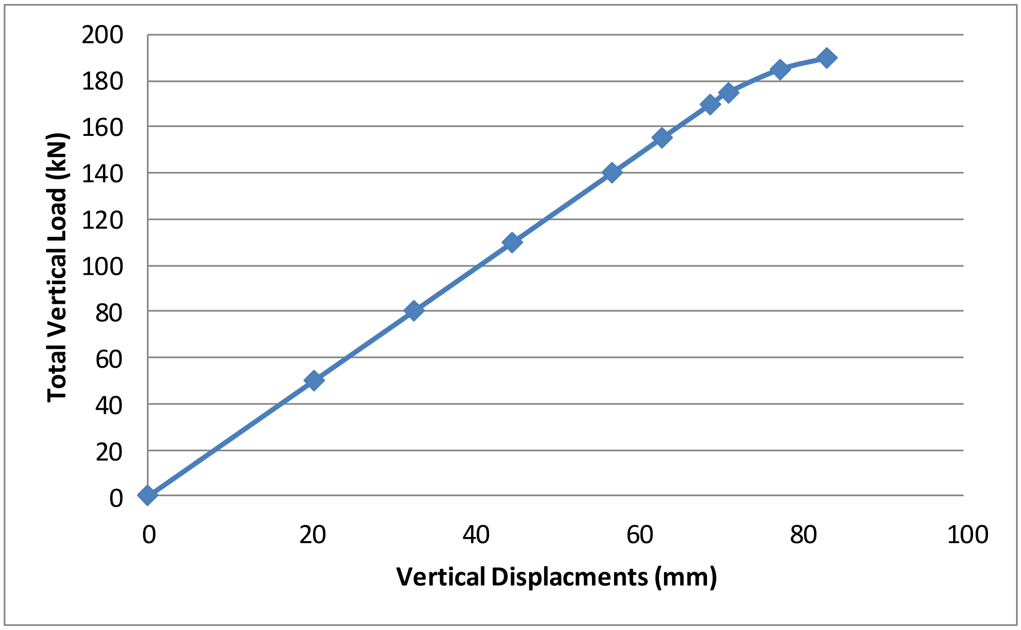

Figure 31 Finite Element vertical displacements

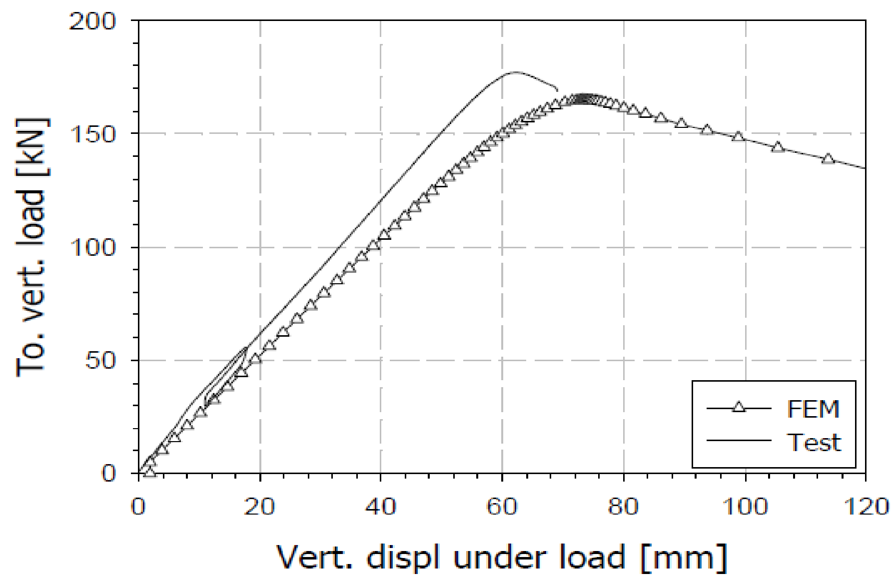

Figure 32 Vertical displacements obtained by Nseir et. al. **(2012)**

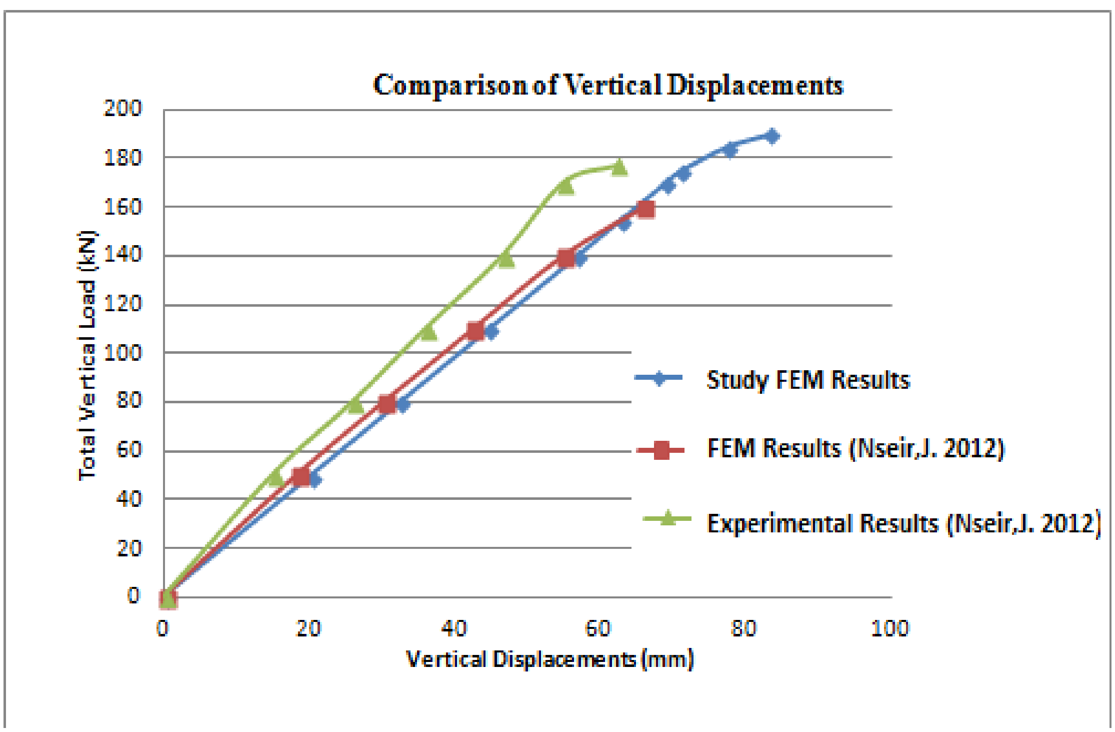

Figure 33 Vertical displacements obtained in this study are compared with the results obtained by Nseir et. al. **(2012)**

For the lateral displacements, the values obtained from the finite element analysis for the total load are shown in Figure 34.

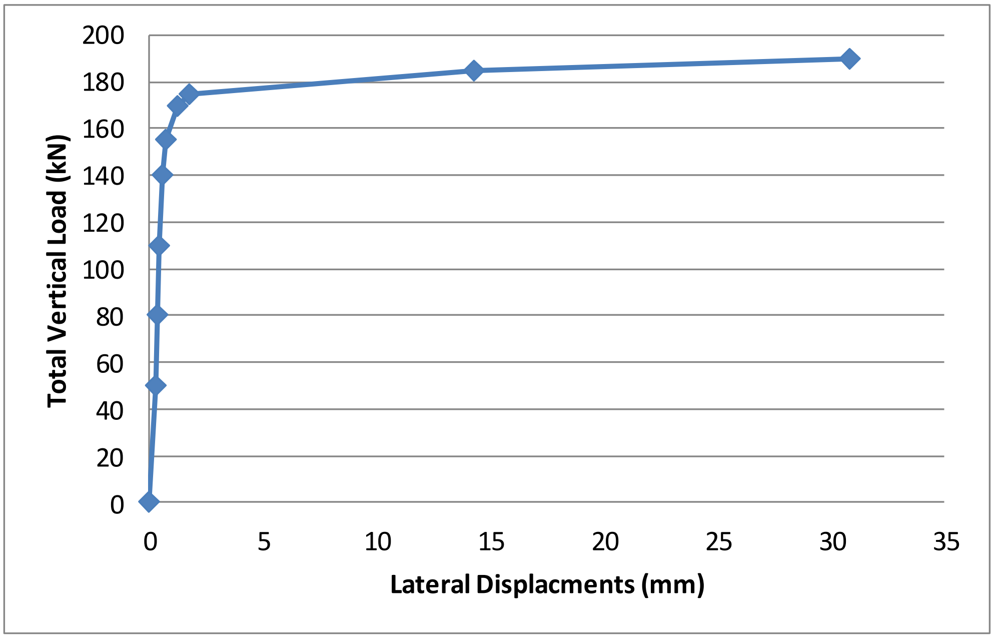

Figure 34 Finite Element lateral displacements

Figure 34 shows the lateral displacements of the FE results. The sudden increase in the displacement is because of the elastic stage being shifted to the plastic one. At that stage, the member is shifted to the plastic stage where the lateral displacement increase gradually and the resistance of the member start to decrease.

Figure 35 Experimental LTB failure mode shape at maximum load **(Nseir et. al., 2012)**

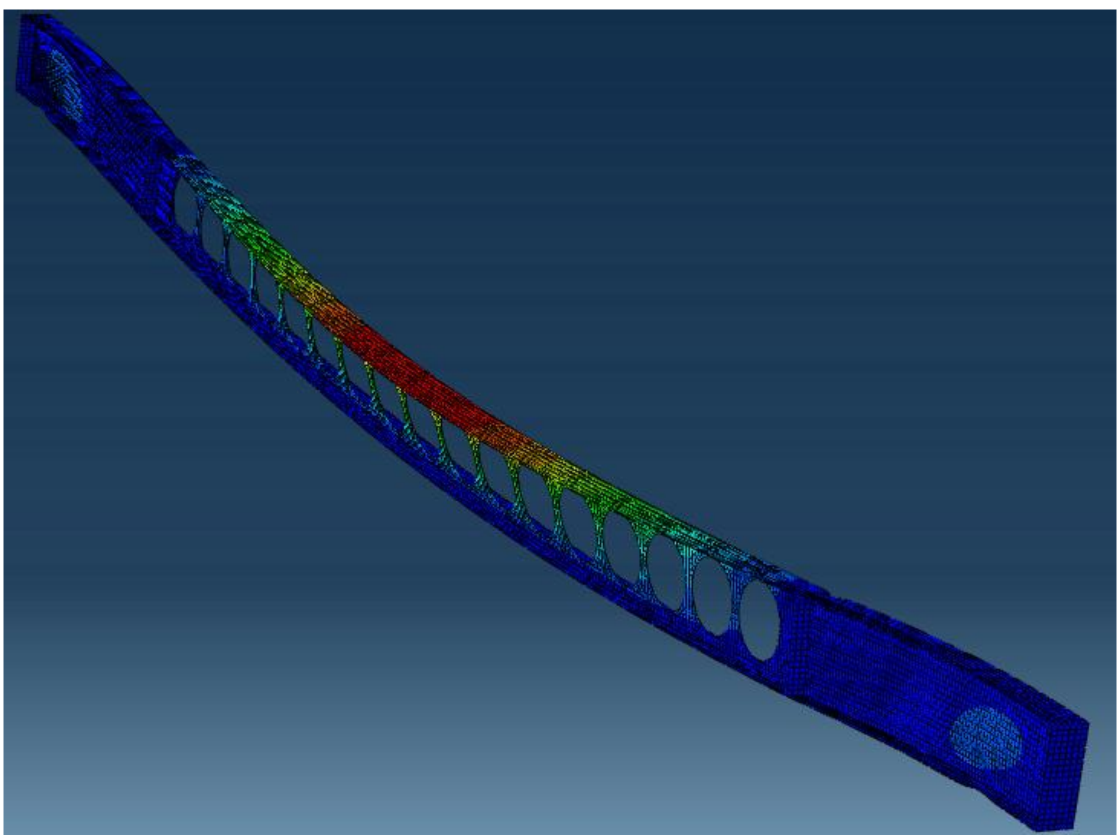

Figure 36 Finite element LTB failure mode at maximum load

4.3 IPE 330 Cellular Beam Section Without Perforations

To study the effects of the web perforations, a beam section having the same dimensions as the IPE 330-cellular beam given in Table 3 with no web perforations was modeled and the results were obtained by using finite element analysis (Figure 37). It was very clear from the results that the presence of web perforations have significant effect on the lateral torsional buckling and on the vertical displacement of beams. The lateral displacement at maximum load for the beam with no web perforation was **1 mm** compared to the same section with web perforations which was **30.84 mm**. These results are realistic. However, as it was discussed before in section 3.5.6, the material and geometric nonlinearity are not fully considered in the modeling. If it was used, then it would have affected the maximum failure load (lower) of the section and might have a slightly lower displacement values.

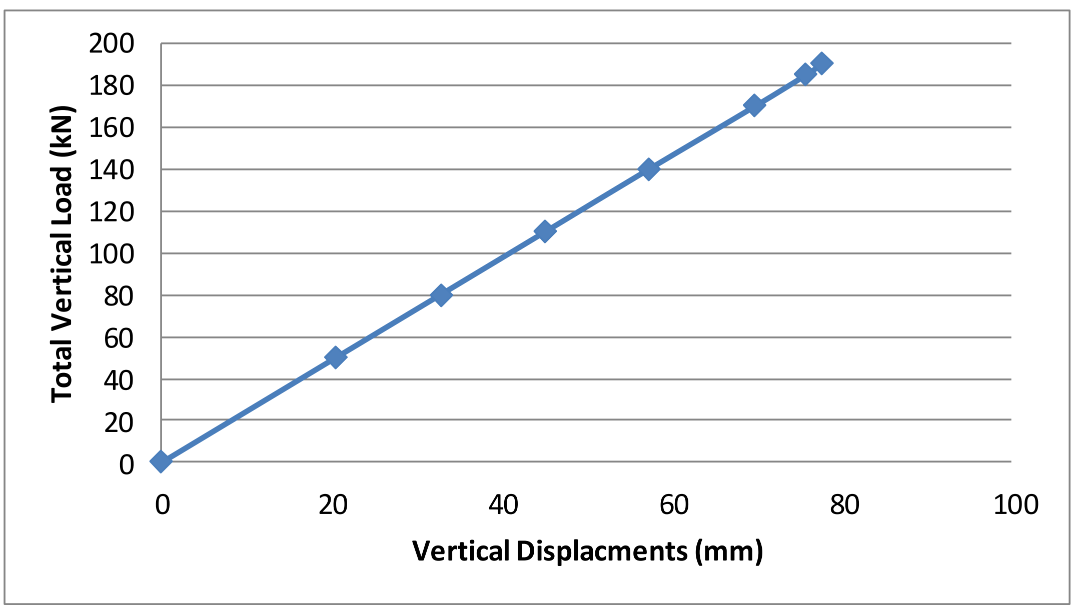

Figure 37 Vertical displacements for closed web section

4.4 Parent Section (IPE 330)

The IPE 330 parent section was modeled and analyzed in order to compare and show the main advantage of cellular beam which had a significant increase in the strength resistance due to the increased height. In addition, it was aimed to show how the lateral torsional buckling behavior of the section will be affected after its increase in height with the presence of the web perforations. Table 6 gives the comparison of displacements between the IPE 330 parent section and IPE 330 cellular beam. For lateral displacements the cellular beams showed a higher bending resistance due to the increase in height. The difference in vertical displacement was **50.68 mm** less for the cellular beam section. On the other hand, the parent section showed a better resistance against lateral displacement with difference in lateral displacement of **27.53 mm** less for the parent beam section.

Table 6 Comparison of the Vertical Displacements and Lateral Displacements

	Vertical Displacement		Lateral Displacement	
Vertical Load (kN)	IPE-330 parent section (mm)	IPE-330 Cellular beam (mm)	IPE-330 parent section (mm)	IPE-330 Cellular beam (mm)
0	0	0	0	0
50	36.936	20.541	0.268	0.262
80	58.798	32.875	0.312	0.303
110	80.186	45.185	0.382	0.375
140	100.95	57.45	0.519	0.531
170	121.031	69.72	0.925	1.235
185	130.943	77.623	1.82	14.328
190	134.511	83.827	3.309	30.836

4.5 IPE 300 and 360 Cellular Sections

The sections IPE 300 and IPE360 were modeled to study their behavior regarding lateral torsional buckling and vertical displacement. Table 7 shows the results obtained from the finite element analysis.

4.5.1 Results for IPE 360 Beam Section

Table 7 FE lateral and vertical displacement values

Vertical Load (kN)	Beam mid span displacements	
	Vertical (mm)	Lateral (mm)
0	0	0
50	16.019	0.251
80	25.649	0.277
110	35.279	0.337
140	44.896	0.393
170	54.491	0.447
180	57.684	0.489
190	60.873	0.546
200	64.061	0.624
220	70.452	0.968
250	80.559	4.786
380	122.662	12.131
381	159.934	114.673

4.5.2 Results for IPE 300 Beam Section

Table 8 Vertical and lateral Displacement for IPE 300 Cellular beam section

Vertical Load (kN)	Beam mid span displacements	
	Vertical (mm)	Lateral (mm)
0	0	0
50	28.717	0.284
80	45.882	0.368
170	96.078	0.481
185	104.113	0.502
190	106.776	0.509
200	112.067	0.523
202.5	138.515	104.116

4.6 Variation of Stiffeners

4.6.1 Introduction

In most cases of cellular and no web perforated beams, stiffeners are widely used as part of the section since they increase the resistance of beam section. Stiffeners are usually added at critical locations, such as, load application and high stress locations, where the maximum displacements occur. The thickness of the stiffener also plays a major role in the strength, thicker stiffeners providing higher strength, but also a higher cost.

4.6.2 Use of Stiffeners at the Maximum Displacement Location (Middle of the Beam)

Two T-shaped stiffeners were applied, one on each side and at the mid-span of the beam, to study their effect on the lateral and vertical displacements of beam. There was no improvement of vertical displacement but the lateral displacement was improved.

Table 9 shows the results for IPE 330 cellular beam with and without the mid-span stiffeners.

Table 9 Comparison between IPE 330 – cellular beams with and without -span stiffeners.

Vertical Load (kN)	Lateral Displacement of cellular beams	
	Without mid-span stiffeners (mm)	With mid-span stiffeners (mm)
0	0	0
50	0.262	0.263
80	0.303	0.305
110	0.375	0.377
140	0.531	0.533
170	1.235	1.2
185	14.328	10.697
190	30.836	28.577

Table 9 shows the comparison of the lateral displacements. The sudden increase in displacements are because of the elastic stage being shifted to the plastic one. At that stage, the member is shifted from the elastic to the plastic stage where the lateral displacements increase gradually and the resistance of the member start to decrease.

4.6.3 The Effects of Stiffener's Thickness

A six identical beam sections **(IPE-330 cellular beam)** with different stiffener thicknesses were modeled to study the effects of stiffener thickness on lateral torsional buckling and other failure modes. Table 10 gives the results of the analysis for different stiffener thicknesses.

Table 10 Beam's mid-span displacements for different thicknesses of stiffeners

Vertical Load	Stiffener Thickness	Beam mid span displacements	
		Vertical	Lateral
(kN)	(mm)	(mm)	(mm)
190	12	86.351	39.394
190	14	85.465	37.176
190	16	84.713	35.218
190	20	83.233	30.836
190	24	81.876	26.293
190	26	81.21	23.866

From Table 10, increase in the thickness of the stiffeners showed good improvements. A difference of **5.141 mm** in vertical displacement between the maximum and minimum stiffener thickness was observed. Moreover, a difference of **15.528 mm** in lateral displacement between the maximum and minimum stiffener thickness was observed respectively. As the stiffener thicknesses increased from 12mm to 26mm, the values of vertical and lateral displacements reduced by **5.14 mm** and **15.53 mm** respectively. These are **5.95** percent and **39.42** percent reductions for vertical and lateral displacements. This would reduce the possibility of lateral torsional buckling failure.

4.6.4 T-Shape Stiffeners

The increase in thickness of stiffeners showed significant improvements in lateral displacement of the beam in the previous sections. The T- shape stiffeners were modeled in this study to represent the real life detail for beam to beam connection. The IPE-330 cellular beam was modeled using T-shape stiffeners instead of the normal stiffeners that were used in the experimental tests. Table 11 and figures 38, 39 show the improvement of this approach. Introducing the T-Shape stiffener as oppose to the normal beam stiffener reducing the vertical and lateral displacements by **9.597 mm** and **24.19 mm.** These are **11.53** percent and **78.46** percent reductions for vertical and lateral displacements.

Table 11 Comparison of the vertical displacement between normal stiffeners and T-shape stiffeners.

	Vertical Displacement		Lateral Displacement	
Vertical Load (kN)	IPE-330 with normal Stiffener (mm)	IPE-330 with T-Stiffener (mm)	IPE-330 with normal Stiffener (mm)	IPE-330 with T-Stiffener (mm)
0	0	0	0	0
50	20.541	19.187	0.262	0.26
80	32.875	30.697	0.303	0.298
110	45.185	42.181	0.375	0.36
140	57.45	53.626	0.531	0.485
155	69.72	59.331	0.715	0.598
175	71.039	66.956	1.235	1.032
185	77.434	70.864	14.328	1.884
190	83.233	73.636	30.836	6.643

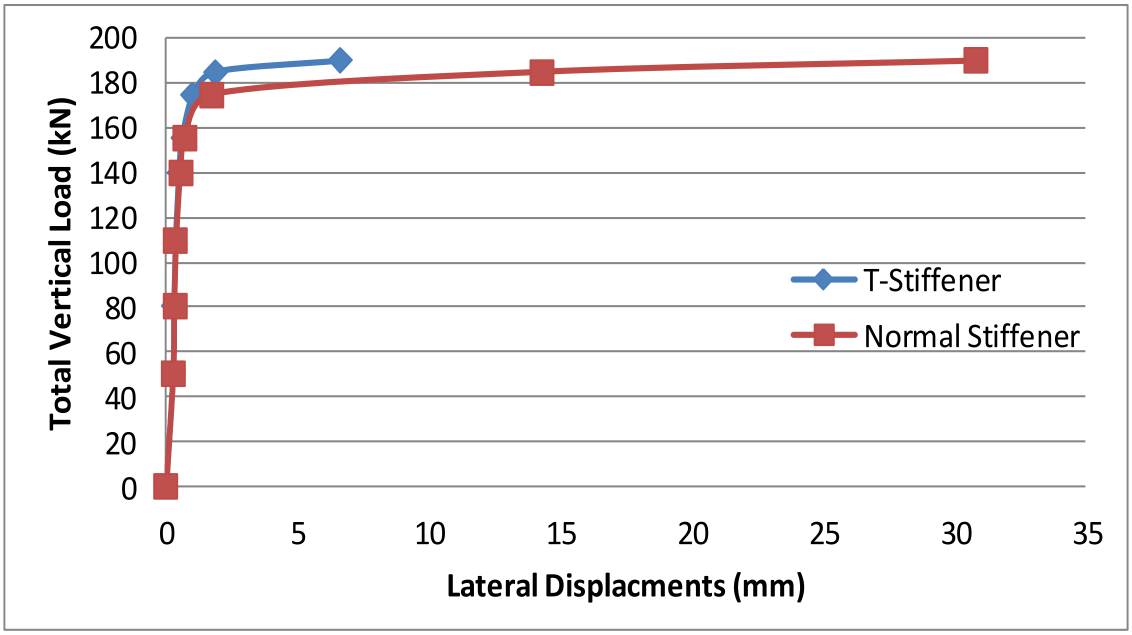

Figure 38 Lateral displacements at maximum load of 190 kN

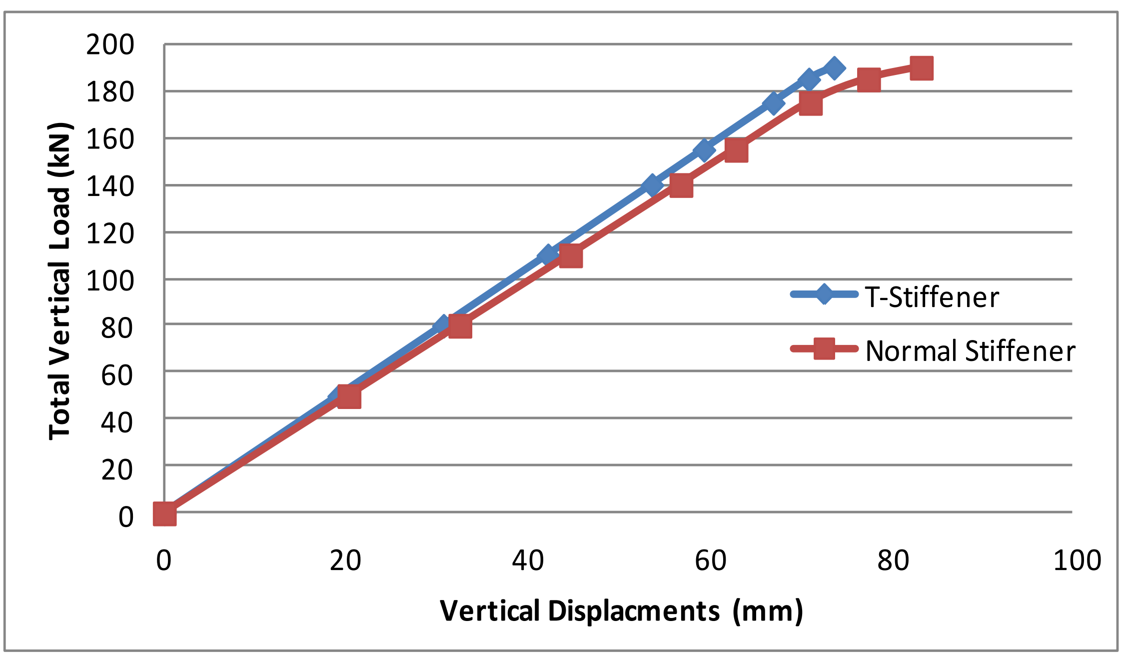

Figure 39 Vertical displacements at maximum load of 190 kN

Chapter 5

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

5.1 Introduction

Cellular beams are widely used nowadays but still this subject is wide open for further research to find possible optimum solutions for the sake of decreasing the risk of these members due to the changes in their mechanical properties during fabrication process and changes in geometrical dimensions as a result of this process The following points summarizes the work done in this study:

- Investigation of the history of steel industry and the development of steel members with the help of researchers and designers according to the requirements of construction market.

- Investigation of cellular beam sections, their production and fabrication process, cutting, shifting and welding.

- Verification of a pre-tested steel section by using ABAQUS finite element program and through the process getting to know the procedures needed for verification process.

- In order to get realistic data modeling and analyzing more members with ABAQUS FE program based on the verified model.

- Finding out the advantages and disadvantages of the normal sections when redesigned to be cellular beams. The main advantages were the increase in the bending strength resistance due to the increase in the second moment of area, passage of services through the openings in the web and without increasing the beam depth. The main disadvantage is the high risk of lateral torsional buckling failure.

5.2 Conclusion

- FE analysis carried out on the verified model (which is addressed as the original model) and the modified model to find out about LTB behavior of cellular beams. Various thicknesses of stiffeners used for this purpose and the results indicate that increase in the thickness had positive effect on the vertical and lateral displacements of cellular beams. As the stiffener thicknesses increased from 12mm to 26mm, the values of vertical and lateral displacements reduced by 5.14 mm and 15.53 **mm** respectively. These are **5.95** percent and **39.42** percent reductions for vertical and lateral displacements.

- Introducing the T-Shape stiffener as oppose to the normal beam stiffener reducing the vertical and lateral displacements by **9.597 mm** and **24.19 mm.** These are **11.53** percent and **78.46** percent reductions for vertical and lateral displacements.

5.3 Recommendations for Future Work

After obtaining the results from the original and modified sections it became clear that more modifications can be done to explore other possibilities which may reduce the possibilities of LTB failure.

The modification done by using T-Shape stiffener in this study gave good results and improvement when compared to normal stiffeners. This was applied on one verified section only. It is recommended that more experimental sections to be verified by using finite element modeling and subject to modifications used in this study and other modifications, such as, change in steel grade, to see the effect on LTB behavior. In this way some of these modifications may found to be consistently giving positive results for cellular beams, as they became more widely used in application.

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