Dynamic Characterization and Modelling of Metallic Foam Material

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To my Family

Declaration

I hereby declare that all parts of the research work has been achieved according to the academic rules. Moreover, I declare that, all results which are not obtained originally are fully cited. The dissertation includes around 15000 words, 35 figures, 10 tables, 30 equations and 32 references.

Acknowledgements

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Sasan Farhadi

Abstract

The objective of this research project is providing an experimental investigation of the structural dynamic properties and examining the damping ratio for steel foam sandwich beam specimens and mathematical modeling of this particular structures, along with the reviewing of the state-of-the-art for the structural manufacturing and applications. The sandwich samples are comprising a mild steel plate and hollow sphere foams which are bonded with thermosetting epoxy. Specimens comprise a single-phase and two-phase (semi-filled by solid particles which here is sand) sandwich foam structure. Three different test experimentally were performed, in particular, random noise, sweep sine, and impact test over a range of frequencies. Moreover, by using ANSYS the specimens were modeled for the finite element analysis. Regarding having a better correlation for two-phase the random noise results have been used and compared with the finite element model. The final results represent an appropriate evaluation of the harmonic frequencies and vibration damping for different specimens in single-phase specimens and by some improvement for two-phase structures.

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Chapter 1

Introduction

At present metallic foam materials are new, and insufficiently characterized, however, during the last decades, metallic foam materials in particular aluminum and steel foams have been improved rapidly and are developing in use as a novel class of porous metals. At this moment, there are methods exist for foaming some metals such as steel, aluminum, zinc, lead, bronze, titanium, and even gold [2].

These ultra-light metal materials based on their low densities possess unique physical and mechanical features, such as high specific stiffness and strength, ideal plastic energy absorption at low weight, excellent corrosion resistance as well as high damping ratio and their identical properties in all directions giving tolerance to differing direction of loading, reliable deformation mode and adaptation to loading condition during deformation, etc. [3].

Nevertheless, utilization and products based on metallic foams are almost inexperienced and unknown. The reason is that they are still not extensive and prevailing, even though they have a very noble potential, and multitude applications already exist on the market; despite that, in the last few years, these materials offer significant potential applications in different industries based on their properties which are documented in Table 1.1, moreover, they are non-toxic materials, have the capability to recycle, and a resistance capability to blast, shock and impact loads more than those monolithic structures with equivalent mass [4, 6].

Depending on the different characteristics of applications, sandwich composite structures may be constructed in a different manner; however, polymer laminates form is the most common lay-up made up of face sheets with stiff cores. Regularly, the cores made in the honeycomb structures or formed by foams by using different materials. In accordance with intense research activity and developing process, it is expected that available foam ranges will expand rapidly through following years. In the next following chapters, it will deeply discuss in what ways metallic foam sandwich structures materials are fabricating [7].

Table 1.1: Potential Application for Metal Foams

Application	Comments
Lightweight Structures	Excellent stiffness-to-weight ratio when loaded in bending
Sandwich Cores	Metal foams have low density with good shear an fracture strength
Mechanical damping	The damping capacity
Vibration Control	Foamed panels have higher natural flexural vibration frequencies than a solid sheet of the same mass per unit area
Acoustic Absorption	Reticulated metal foams have the sound-absorbing capacity
Thermal Management	Open cell foams have a large accessible surface area and high cell-wall conduction giving exceptional heat transfer ability
Bio-compatible Inserts	The cellular texture of bio-compatible metal foams such as titanium stimulate cell growth
Electrical Screening	Good electrical conduction, mechanical strength, and low density make metallic foams attractive for screening

The motivation for this investigation came from the hypothesis that steel foam sandwich structures are special types of composites, which can be ideally applied as lightweight stiffeners against buckling that can also exhibit multi-functionality by passively attenuate vibrations in aerospace industries, civil infrastructures such as steel bridges, offshore structures, and wind turbine towers and armor for both military and civil uses [1, 2]. The unique trend of composites in different industries bring about the interest in developing the new NDT techniques to monitor and examine these structural components.

This investigation was conducted on specimens (Figure 1.1 developed during the EU FP7 Project INSIST [1] [2], where the static compressive and shear properties of the steel foam were determined as well as their shear fatigue life.

[1]INSIST is an experimental investigation on the structural integrity and stability of novel steel foam sandwich panels (SFSPs) under monotonic and cyclic loading.

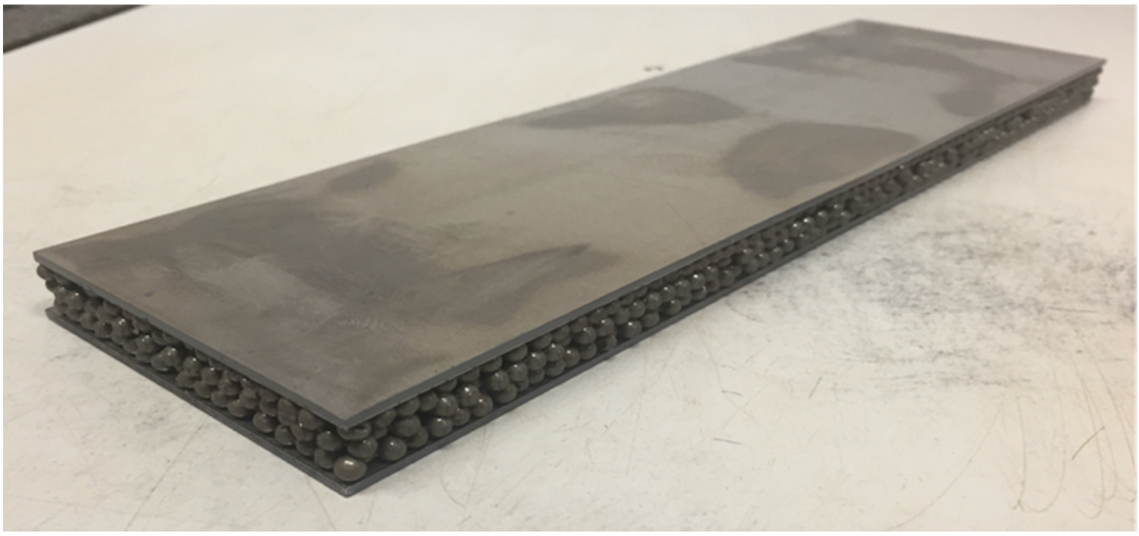

Figure 1.1: Hollomet Specimen

In recent years, researchers have investigated the energy absorbing characteristics of sandwich structures subjected to a wide range of loading conditions. The sandwich structures mechanical response is widely subject to several parameters, comprising the strength and stiffness characteristics, skin features, the wave impedance ratio and the thickness ratio between the core and skin and so on [3]. Although there are some researches about investigating of damping coefficient of metal foam materials, there is yet a wide variation in the final results based on the nature of the used materials and the utilized method.

1.1 Purpose of the Work

The main aim of the present project is: to determine the dynamic characteristics (damping ratio) of the steel foam sandwich structure with three different test types such as Sine Sweep, Random Noise and shaker impact testing and evaluate the damping characteristics of the single-phase material over a spectrum of frequencies as well as evaluate the effect of adding solid particles like sand in the steel foam core (2-phase core) and evaluating the damping ratio increase. In addition, this research applied mathematical method in order to determine the error function between experimental and analytical results comparison. Besides, for this research purpose experimental measurements, FEM by using ANSYS and MATLAB were developed. Currently, the research on metallic steel foam has not been advanced and investigated as much as other types of metallic foams but the scientific community has certainly made great strides since a few decades ago.

1.2 Outline of the Thesis

In this project, which represents the first nine months of progress, we first present a brief review of the current state-of-the-art with respect to steel foam manufacturing and processing by studying of the mechanical properties of metallic foam materials. Next, reviewing of the structural application for the metallic foam structures. After that, dynamic properties of the physical systems for these types of structures deeply discussed. Thereafter, finite element modelling for metallic foam material considered with explaining the process and different aspect of view for this specific research. It continues with experimental setup description in detail. Finally, preliminary results that indicate the effect of different damping ratio on this particular specimen presented.

Chapter 2

Characterization and Manufacturing

Metallic foam materials have been formulated from basic materials comprising polymers, ceramics, and metals such as aluminum, copper, steel, titanium and even gold. This kind of materials has been utilized to solve different engineering problems mainly in the structural and aerospace domains. Notably, steel is one the most applied material in engineering; however, steel foam is not widely implemented which can be the lack of commercial availability.

Since the last 10-15 years, the diverse investigation has started to reveal that it can be possible to produce steel foams at the laboratory scales and have desirable properties. Nowadays, metallic foam structures can produce in laboratory scales employing various approaches to implement and develop materials with different morphology.

The features of different steel structures have been mainly invariant for the last decades. Modifying the yield stress which has seen an increase over the past several decades and even the elasticity's elastic modulus has not changed as much as is regularly thought — "the Eads Bridge in St. Louis, Missouri was designed and manufactured with 345 MPa yield stress steel in 1874" [8]. In engineering, the development of novel components and structural foams with their higher performance are vigorously linked to the introduction of new materials such as steel, iron, and reinforced concrete which allowed engineers to make new extreme structures by decreasing cost. However, many of the advanced materials of the last decades have not propagated to the engineering.

Generally, metallic foam materials offer a particular possibility to utilize in different structural and non-structural applications. Foaming the metals means implanting voids in the structures and increasing the apparent thickness and decreasing the density (ρ). The final result with respect to the solid steel can obtain lower weight and higher plate bending stiffness ($\sim Et^3$) based on the design accuracy. Moreover, the resulting component ordinarily has a severely improved physical and mechanical characteristics and expanded energy dissipation capability. "A steel engineer working with steel foam has a new degree of freedom: density (ρ)" [8]. Indeed, the density is an essential variable in design applications which covered by steel. Initially, applications may be highly individualized, however, once the volume of production increased and costs decrease, widespread utilizing of metallic foams become possible.

There are considerable researches which have been performed regarding have optimal manufacturing methods to apply for metallic foams, suchlike aluminum, steel, copper, and titanium, however, among them, steel presents some unusual challenges, contacting high melting point which requires new technology for its processing.

In this chapter, the most significant methods for the manufacturing process of this particular material reviewed therewith, different material properties features.

2.1 Manufacturing Process

In order to understand the advantages and applications of hollow sphere steel foams, it is imperative that the different manufacturing processes be understood for different metal foams, to make way as to how hollow sphere steel foam came to be. The structural characterization of metallic foams is established by its cell topology (whether it is the open or closed cell), relative density, cell size, shape, and anisotropy [2]. In general, the method of manufacturing consists of dispersing air into the solid metal matrix and thus reduces the relative density of the metal and introduces other advantages. Some of these advantages include its light weight and low density, its high strength to weight ratio, and its exceptional capabilities of energy dissipation.

Contemporary techniques for producing steel foams are classified into open-celled[1] (permeable voids) or closed-celled[2] (sealed voids) foams which have variable isotropy, uniformity, and density. Besides, various producing metallic foams methods are summarized in Table2.1. In the last 40 years, there were many efforts to foam metals or to produce porous metallic structures. In the present review, some of the most important and successful procedures are described. Three known manufacturing methods and a new method which recently discovered and published are pointed up here: powder metallurgy as it is still using successfully to produce structural steel foam prototypes, hollow spheres as it has been used effectively in active commercial manufacturing, and to have low-cost production method necessarily Lotus-type is using as it has high ability for continuous casting processes [8]. although there are some different methods exist, the newest metal foam type invented by prof. Rabiei is discussed further.

There has been a substantial amount of research published on foams made of other types of metals such as aluminum, titanium, and copper, with aluminum being the most prevalent today in applications and research. Some of the published research on it for dynamic loading will be much of what this thesis will be referencing back to. Steel has not been the subject of as much research as the rest and

[1]Open-celled foams are those that contain a continuous network of metallic struts and ligaments and the enclosed pores in each strut frame are connected, are weaker, and are mainly used in functional applications where the continuous nature of the porosity is exploited. Open-celled foams permit the fluid flow, in growth, and thus in addition to impact applications there is a potential for orthopedic solutions.

[2]Closed-cell foams are different from open-celled in the sense that the cells are individually separated from each other by cell walls and they can be filled with gas.

this is because of the manufacturing difficulties that it poses due to steel's high melting point that requires new technologies [8]. Despite these difficulties, research on different types of steel foams is in the early development stages. Today, there exists research topics within steel foams that encompass cell morphology, material characterization, finite element analysis, mechanical properties, quasi-static loading behavior, and current and future applications.

Table 2.1: Potential Application for Metal Foams [8].

Manufacturing processes for steel foam							
Process	Essential Variables	Min. Density	Max. Density	Cell Morphology	Morphology Notes	Major Advantages	Major Disadvantages
Powder metallurgical	Foaming agents (e.g. $MgCO_3$, $CaCO_3$, $SrCO_3$), cooling patterns	0.04	0.65	Closed	Anisotropic if not annealed for long enough, or with some mixing methods	High relative densities possible	
Injection molding with glass balls	Types of glass (e.g. IM30K, S60HS)	0.48	0.66	Closed	Glass holds shape of voids, and increases the brittleness of the material	High relative densities possible	Potential chemical reactions with glass; some glass can break in forming process
Oxide ceramic foam precursor	Ceramic/ cement precursor materials	0.13	0.66	Open	Polygonal shapes on small scales, residues of reactions remain	Foaming at room temperatures; complex shapes possible; standard equipment	
Consolidation of hollow spheres	Sphere manufacture, sphere connections	0.04	0.21	Either	Two different cell voids: interior of the spheres, and spaces between spheres	Very low relative densities possible; highly predictable and consistent behavior	High relative densities not possible
Working and sintering of bimaterial rods	Types of working before sintering, filler materials	0.05	0.95	Open	Anisotropy is controllable	Wide range of relative densities possible; anisotropies are controllable	
Composite PM/hollow spheres	Matrix material used, casting may be done instead of PM	0.32	0.43	Closed	Powder metallurgical region may be foamed or a semi-solid matrix	Behavior is both predictable and strong; no collapse bands until densification	
Slip reaction foam sintering	Dispersant, bubbling agent, and relative quantities	0.12	0.41	Open	Highly variable cell diameters are produced	Many optimizable manufacturing parameters; foaming at room temp.	
Polymer foam precursor	Polymer material used	0.04	0.11	Open	Cells take on whatever characteristics the polymer foam had	Low-density open-cell structure for later and sound absorption applications	Too weak for most structural applications
Powder space holder	Filler material used, shapes and gradation of material	0.35	0.95	Closed	Porosity may be graded across the material	Porosity may be graded across a wide range across the material	
Lotus-type/ gasar	Partial pressure of gas, which gas to use	0.36	1.00	Closed	Highly anisotropic but aligned cell shapes are unavoidable	Manufacturing by continuous production techniques; high relative densities are possible	Isotropic cell morphologies are not possible

2.1.1 Powder Metallurgy

Primitively developed for manufacturing of aluminum foams, it is the first method used to make steel foams and still, it is one the most popular method [9]. Initially, the powder metallurgy method is capable to develop notable anisotropic cell morphologies by producing closed-cell foams. Inasmuch as the relative densities are amongst the highest by using this method, up to 0.65, which make these materials a strong applicant for diverse engineering.

The process of the powder metallurgy is accomplished in three main steps: mixing, compacting and foaming at various temperature up to the materials' melting point. The powder metallurgy process for producing lightweight metal foams is shown schematically in Figure 2.1.

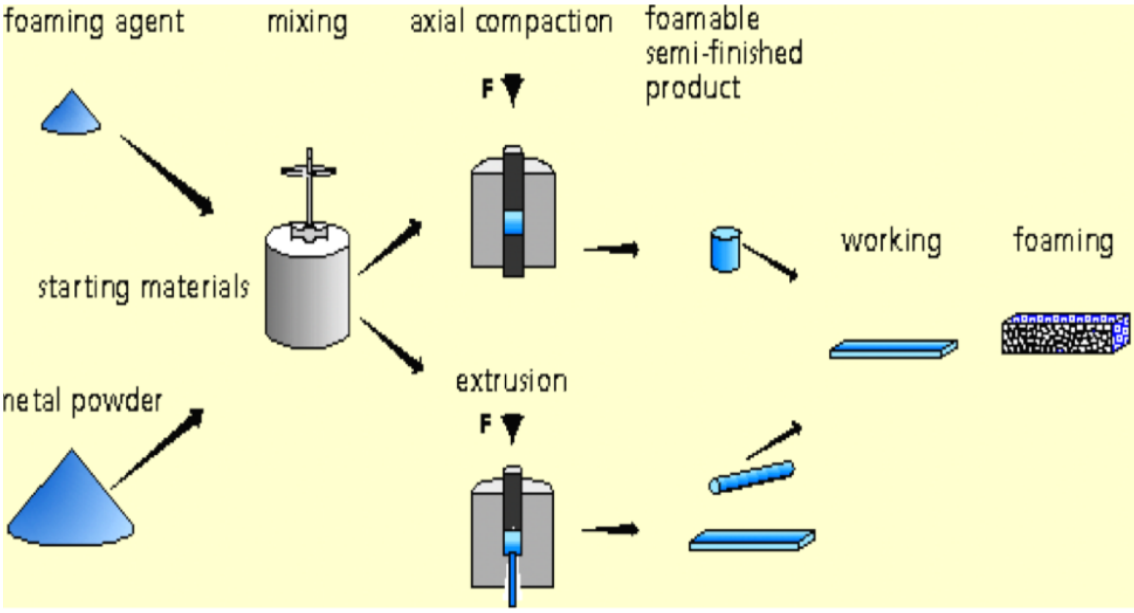

Figure 2.1: Fraunhofer Powder Metallurgy-Based Metal Foaming Process [10].

- ## Mixing

To synthesize the foam, commercially available steel powder (a Fe 2.5C blend) is mixed with a foaming agent, usually strontium carbonate ($SrCO_3$) and magnesium carbonate ($MgCO_3$). The mixing time is usually about 90 minutes at 58 RPM which is an essential speed and condition for homogenization mixture especially when "balls cascading fall", was taken place. Up to 45% of the container volume is occupied by the powders and balls.

- ## COMPACTING

After mixing, the blend is compacted by uniaxial cold-pressing to yield a virtually non-porous, semi-finished steel sample. Subsequently, the steel is melted to effect foam expansion, volumetrically. At this point, the metal softens and the released gasses infiltrate the pores to a size 2.5x the initial volume. The range of pressure between 900-1000 MPa applies to the samples. To have a free residual porosity the required pressure was fixed empirically by compacting the samples.

- **FOAMING**

The compact material was located inside the electric furnace just about 17 minutes under the existence of an atmospheric nitrogen with 1250°C. Then when the melting temperature which is related to the sample compositions was reached the sample can take out from the furnace [9].

The process is most highly developed for producing metal foams (suchlike aluminum and steel). Figure 2.2 represents a sample with porosity about 80% volume or the bulk density of 0.54 g/cc. Porosity levels in steel foams have been developed to about 50-60% volume producing a material with a density less than half that of solid steel [10].

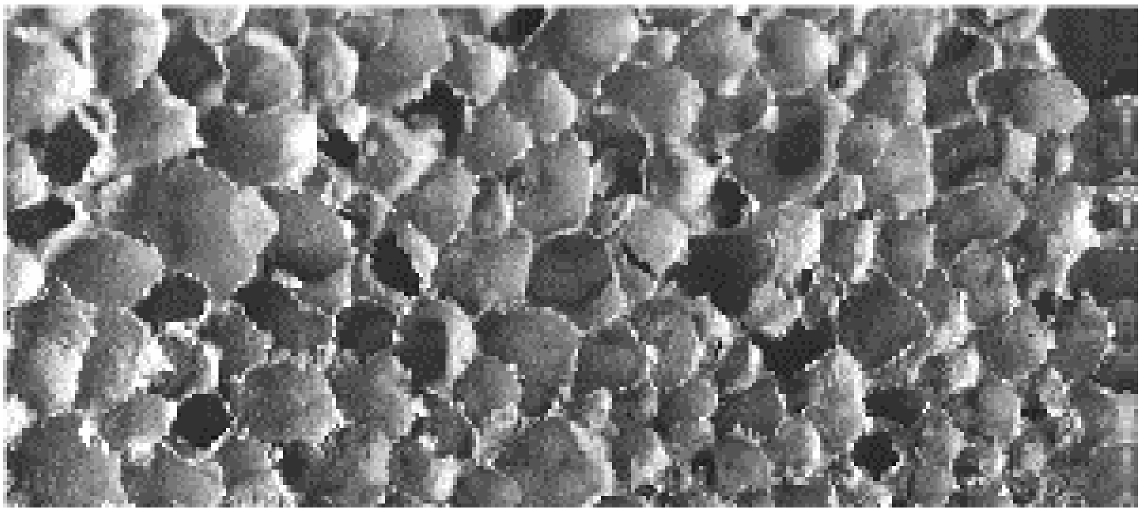

Figure 2.2: Pore structure of closed-cell aluminum foam with a bulk density of 0.54 g/cc [10].

2.1.2 Hollow Sphere

Hollow sphere is one of the most popular process in metallic foam manufacturing (in particular steel foam) and the most relevant method to this project. Indeed, hollow sphere steel foams consist of a spherical core which is packed together to make a structure that can be open- or closed- cell. Moreover, having exceptionally predictable physical and mechanical properties as cell size is accurately control and demanding minimal heat treatment [11].

W.S. Sanders and L.J. Gibson analyzed the hollow sphere foam's elastic moduli and initial yield strength and the outcomes indicate that their impractical values of moduli and strength are mediate to those for open- and closed-cell foams. Based on their research and by considering suitable manufacturing techniques hollow sphere foams have the potential for improved mechanical properties compared with existing metallic foams [12].

Recently, several techniques have been developed for synthesizing HS metallic foams. To form a HS metallic foam an individual hollow sphere can bond together. In a 3D array of HS, interstitial spaces can be percolated with bonding materials suchlike epoxy or a low melting temperature metal; these materials refer to a synthetic foam (Figure 2.3 a). This technique is not a sufficient way to make a metallic material with low relative density as the interstitial volume between the existence spheres considers for a considerable fraction of the total volume which is 26% in the closed-packed samples. Additionally, using a metal with low melting temperature point or a polymer in order to fill the voids diminish some of the metal benefits, suchlike high temperature properties or high specific strength.

In an alternative method, HS foams can also be produced by employing heat and pressure to an assembly of metal hollow spheres. The heat and pressure combined can flatten the contacts between the spheres, which then become diffusion bonded. Most commonly, the contacts cannot be fully flat; rather, they shape curved cell walls which are complex to model (Figure 2.3 b). Metallic foams which have been produced by using this type using hollow spheres created from metal powder slurries and gas atomized metallic powder. This technique has yet to fabricate good quality foams which has uniform and steady wall thickness and cell size.

Bonding hollow spheres by using a liquid phase is the last method developed for manufacturing of hollow sphere foams which make a bonded neck section between spheres and it next is the one of most interest and relevance to this thesis (see 2.3 c).

This can be carried out by two sub-techniques. In one such sub-technique, it comprises coated hollow spheres with a metal powder slurry and combined in a structure while the slurry is still in a liquid form and giving high uniformity to hollow metal spheres. The liquid forms the neck regions at contact points and is then dried to proceed to be sintered in the furnace. In the second sub-technique, the hollow spheres are coated with a material, for instance, a solder[3] or braze, that melts at a lower temperature than the sphere material. Then they are combined and heated to over the coating temperature of the melting point which makes the necks by flowing the liquid metal to the contact regions. HS metallic foams have been manufactured to make metallic foams like nickel, steel, and titanium via this method.

[3]Solder is a type of melted metal alloy which is usually consists of tin and lead. Although the use of lead based solders was banned in the European Union on the 1980s, conventional solders are widely using in different sectors.

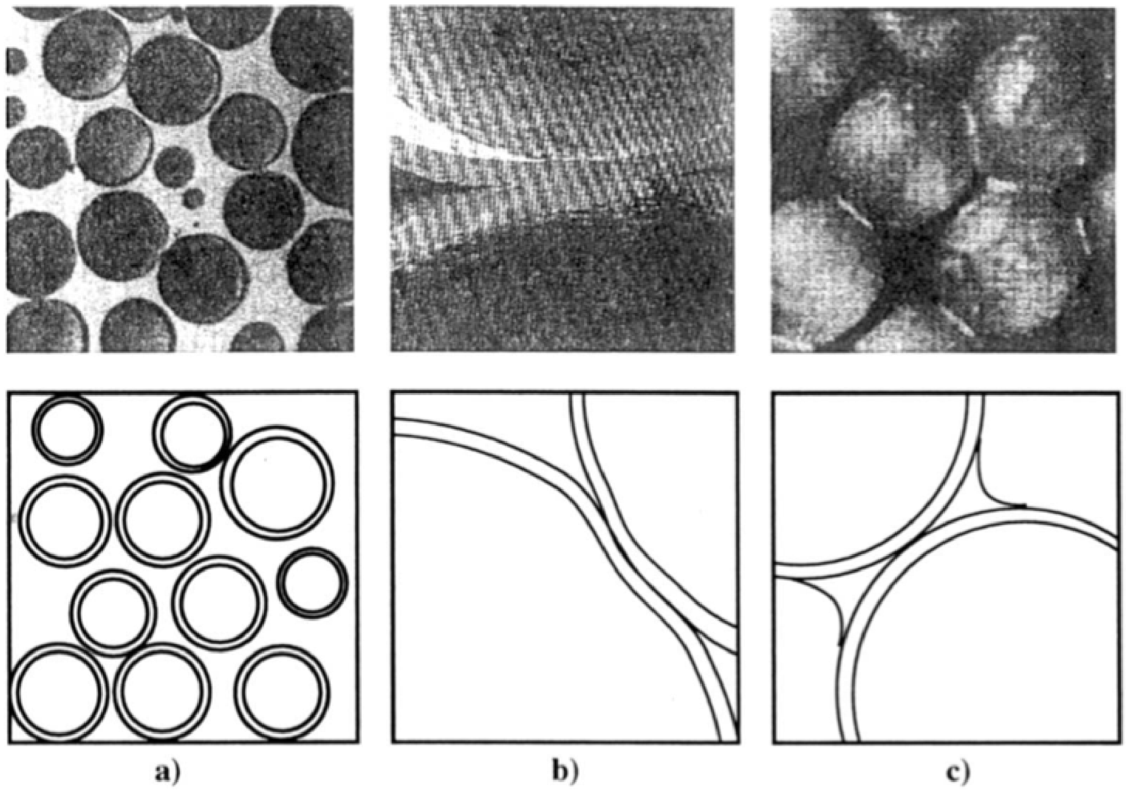

Figure 2.3: Three major types of the hollow sphere foams [12].

As mentioned, there are different methods for bonding the spheres together to one another, producing sintering necks between the spheres. Due to these, three different types of porosity are defined on a different scale:

- Macroporosity: volume inside the hollow spheres
- Mesoporosity: the cavity between the single spheres
- Microporosity: porosity of the cell wall itself

The morphology of the cell is important in determining the properties of the foam, just as is the types of porosities, due to the fact that porosity is what dictates the overall relative density of the material. The relative density could eventually be fitted during consolidation by differing the relative density of HS and densification extension [9]. Because porosity can be controlled and adjusted, density becomes a new design variable and, as a result directly affects the mechanical properties of the material such as elastic modulus and yield stress.

2.1.3 Lotus (Gasar)

The lotus-type (also known as Gasar) manufacturing method, is a very controllable method for steel foams in which long, cylindrical pores are aligned uniaxially alongside the length of solidification direction. In fact, this method is an efficient way to produce highly anisotropic foams with high density, ranging around 35% up to 100% with closed-cell morphology. Also, the method for a foam with 50% relative density allows a high tensile strength and ductility to 190 MPa [21].

There are two similar fabrication methods which incessantly have been developed, the continuous casting technique and the continuous zone melting technique. In continuous casting technique, the base metal is melted by an induction heating coil inside a crucible in the presence of the high-pressure gas, and then slowly drained and solidified. The gas is dissolved up to the equilibrium gas concentration into the molten metal, according to the Sieverts' law [4]. The melt saturated with gas is poured into the mold. When some part of the mold is cooled down by a chiller or circulated water, the melt can be solidified unidirectionally. The elongated pores can evolve and grow by the influence of the unidirectional solidification. Once the solidification is completed, the result is the foam with cylindrical voids along the length of the metal, and these elongated pores (Figure 2.4). Thus, multiple parameters can be controlled during the fabrication. These parameters include melting temperature, solidification velocity, the dissolving gas pressure during melting and solidification, the inert gas pressure during melting and solidification (Nakajima et al., 2006).

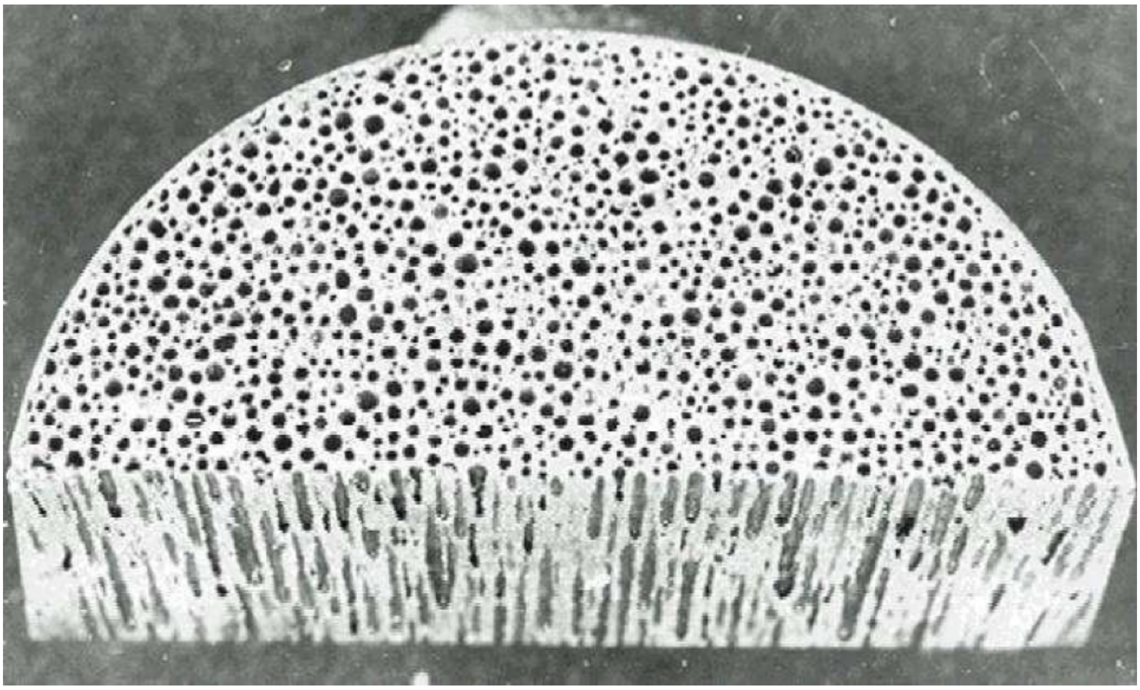

Figure 2.4: Gasar foam, showing largely elongated pores

Over the past decades, porous metals specifically whose have less than 30% porosity utilize for different industrial applications for instance filtration, battery electrodes, self-lubricating bearing, fluid flow control, etc. However, there are some serious disadvantages for using them as the pores are nearly spherical and arbitrarily distributed and then there are some detrimental effects to mechanical properties suchlike ductility and strength.

[4]"Corresponding Sieverts' law, the soluability of gases such as H_2, N_2, and O_2 in metals is proportional to the square root of the partial pressure of the gas in thermodynamic equilibrium (Gupta, 2003)"

2.1.4 Other Methods

As table 2.1 shows multitudinous other methods which exist for steel foam producing. For instance, polymer or ceramic precursors can be used to set up the voids. The last steel foam's relative densities have been realized ranging from 4% to 23% depending mainly on the precursor on the same morphology. Foam sintering as a particular iron-based foams manufacturing has also used effectively to produce foams with moderate densities ranging from 12% to 41%.

Material scientists investigating numerous steel foam manufacturing methods such as, fibrous foams containing truss cores and injection molding bi-material rods, and sintered fibers. Truss cores comprise turning and welding the lean fibers to mesoscale trusses which has different shapes whereas fibre sintering involves setting out the fibres and sintering them together. These fibrous foams have low strength, but may work productively as core material in sandwich panels [8].

Vast majority of metallic foams have been produced with bulk shape model. By mixing blowing agent to the melted aluminum, Alporas is formed. In Canada, Cymat Corporation has been producing an aluminum foam by injecting gas. New sort of composite metallic foam (CMF) has been made by Rabiei's group in either powder metallurgy route or casting route.

Even though, these kinds of metallic foams have a good quality, they just support bulk shape foams. This new type of metallic foam named "metallic bubble wrap" (Figure **??**) which is manufactured in the shape of thin sheet metal structure specifically aluminum with more decisive properties and longer lifetime than current produced metal foams. Indeed, the current metal foams especially the closed cell ones are not uniform with higher porous and have unpredictable deformation behavior, specifically in the thin sheet form. Bending and tension test results have been showed improvements in mechanical properties of aluminum bubble wrap which can develop in other type of metallic structures manufacturing [13].

This new type of metal foams has been produced by way of the roll bending method. Indeed, As compared with aluminum sheets, the metallic bubble wrap has better bending resistant and it is lighter than aluminum sheets. Moreover, these properties can be improved by expanding the number of bubbles. Furthermore, bubble wrap can make some enhancement on the tensile strength (around 17%) and the bending strength (up to 30%).

Chapter 3

Application

Manufacturing of metallic foams just started at an early stage of the 20th century, especially for engineering applications. Indeed, the sintered powder was the first commercial porous metals which were available in the market and used for engineering applications. It was used for filters fabrications and batteries around 1920's [2] and it is still in use by high volume applications.

In 1925 a French patent was published as the first reference to the metallic foams corresponding to a fabricating process to create a high porosity expanded structures. Three decades later in the USA the commercial metallic foams have been started to develop for about ten years and after 1990's the second wave of research and development RD activities have been started which is still keep going for instance, there are some international and national RD programs which are focused on metallic foam materials: The US Multidisciplinary Research Initiative on Ultralight Metals (MURI) launched in 1996, different European research projects funded within the 4th and 5th EU Framework program and a research program funded by the German Research Council in the late 1990's. Thanks to these RD the metallic foams became commercially available for numerous of structures properties. This section presents some recent developments on applications and commercialization of metallic foams [14].

In the last two decades, there are several companies that are manufacturing metallic foams and bet on the future, however, there are two main issues: the price of these new materials and find an effective marketing. Some of the most important metallic foam manufactures are [1]:

- Alulight (Ecka Granules, Mepura, Ranshofen, Austria)
- Cymat (Mississauga, ON, Cananda)
- Aluinvent (Miskolc, Hungary)
- M-pore (Mayser, Dresden, Germany)
- Pohltec Metalfoam (Collogne, Germany)
- Recemat (Dodewaard, the Netherlands)

[1] A more detailed and regularly updated list can be found on the Internet at www.metalfoam.net

- Exxentis (Wettingen, Switzerland)
- Alantum (Seongnam-City, Korea)
- Mott Corporation (Farmington, CT, USA)
- Foamtech (Daegu, Korea)
- Alveotec (Venissieux, France)
- ERG (Oakland, CA, USA)

Besides the companies' names, some trade names have been established, being characteristic of the production method, such as:

- Fominal (Frauenhofer, Bremen, Germany)
- Alporas (Shinko Wire, now Foamtech, Daegu, Korea)
- Alusion (Cymat, Mississauga, ON, Cananda)
- Aluhab (Aluinvent, Miskolc, Hungary)
- Duocel (ERG, Oakland, CA, USA)
- Incofoam (Inco, now Alantum, Seongnam-City, Korea)

Steel foam applications compared to the aluminum foams are at prefatory level; though, higher yield strength and initial young modulus are essential advantages of base metal respect to aluminum [8]. The range of metallic foam materials applications are increasing and either a suitable porous metal or metallic foams depend on different conditions which are summarized below:

- **Morphology:** type of porosity needed (open versus closed), amount of porosity needed, size scale of porosity desired, total internal surface area of cellular material required
- **Metallurgy:** metal or alloy or microstructural state required
- **Processing:** possibilities for shaping the foam or cellular solid or for manufacturing composites between the foam and conventional sheets or profiles
- **Economy:** cost issues, suitability for large volume production

There are various degrees of "openness", ranging from "completely closed" for load-bearing structures to "very open" for high rate fluid see 3.1 shows what types of porosity the various application fields require. Normally, a difference is made whether an application is "functional" or "structural", the difference between these two notions, however, being rather gradual.

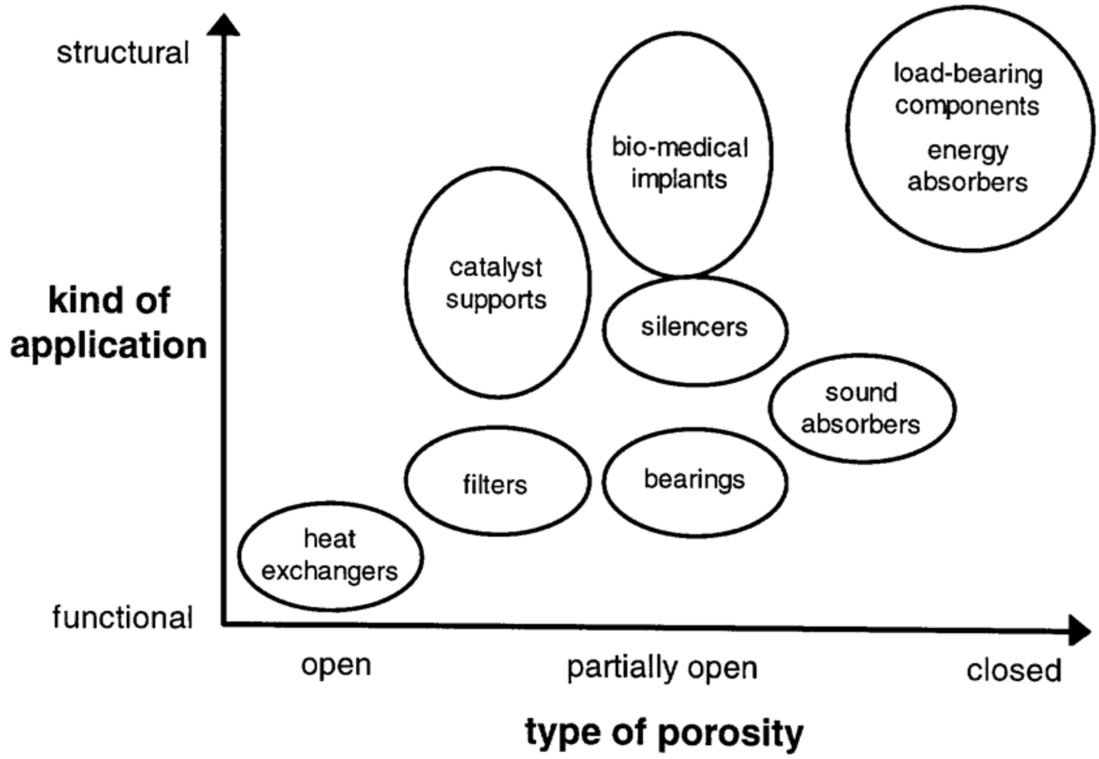

Figure 3.1: Applications of cellular metals grouped according to the degree of “openness” needed and whether the application is more functional or structural [24].

3.1 Structural Applications

Structural applications example for metallic foams are summarized in Table 3.1 based on stiffness, mechanical damping, energy dissipation, and vibrational frequency. Current applications are primarily existed in the aerospace, mechanical, civil and automotive domains. The potential for each application is also detailed in the Table 3.1.

Steel foams have superior stiffness-to-weight ratios, in particular, foam panels have higher bending stiffness than solid metal sheets with the same weight. Accordingly, for manufacturing, most of the structural application should either minimize weight given stiffness constraints or maximize stiffness given weight constraints. For instance, a sandwich panel with 1 mm steel face and 14 mm metallic foam core only at 35% of the weight has comparable bending stiffness with respect to the solid steel plate which has 10 mm thickness. In continuous chapters there are some specific utilization of metallic foams in different sectors.

Table 3.1: Example Structural Applications/Advantages for Metal Foams [8].

Prototype/In-Production Application	Improved Characteristics Explored in the Given Application					Importance to Civil Engineering
	W (Weight)	K (Stiffness)	En (Energy	c (damping)	F (frequency)	
Steel foam bars, rods, sandwich plates	X	X	X			demonstrates essentially all aluminum foam applications could be extended to steel foam.
Wall/floor foam sandwich panels	X	X				Mass production of metal foam panels is possible. Great varietyof bending stiffness-to weight regimes opened up by this possibility.
Balcony platform, parking floor slab	X	X				Metal foam panels may take significant, even localized, loads, thus appropriate forfloor slab, even heavily loaded parking garage.
Crane lifting arm and support	X	X				Metal foam beams can be produced that support high/typical structural loads andfatigue is not a unique problem as crane arms were fatigue tested.
Fabrication equipment		X		X	X	Metal foam panels can be tuned for desired vibration characteristics, could, e.g., be very important for high-speed rail applications.
Ariane 5 rocket cone prototype	X	X			X	Shell structures possible with metal foams, tight dynamic performance constraints can be met.
Race car crash absorber		X				Kinetic energy dissipation is one of the main strengths of metal foams. Load transfer to the support limited by the foam yield.

3.1.1 Automotive Industries

The requirement for automobiles safety has increased due to the higher weight in many samples, however, there are some contentions based on the further demand for decreasing the fuel consumption and vehicles weight reductions. Additionally, in Japan and European countries, vehicles with reduced weight ad lengths are demanded and this reduction should not effect the passengers area. The initial way was making a new compact engine or reduced the size of other structural parts in order to maintain the passengers comfort, but it creates other problems suchlike heat dissipation in the engine partition or even safety requirement decreased by reducing the length of structural parts in the crash zones. Lastly, the request for reducing the acoustic emissions from the vehicles held a new demand for the sound absorbers.

Figure 3.2 sums up three common applications for metallic foams. The ideal application can be the one which has an intersection of the three circles. Undoubtedly, these kind of applications which are able to perform many functions are tough to make, however, often it is satisfied to find an application where the light weight construction can serve as an energy absorber at the same time.

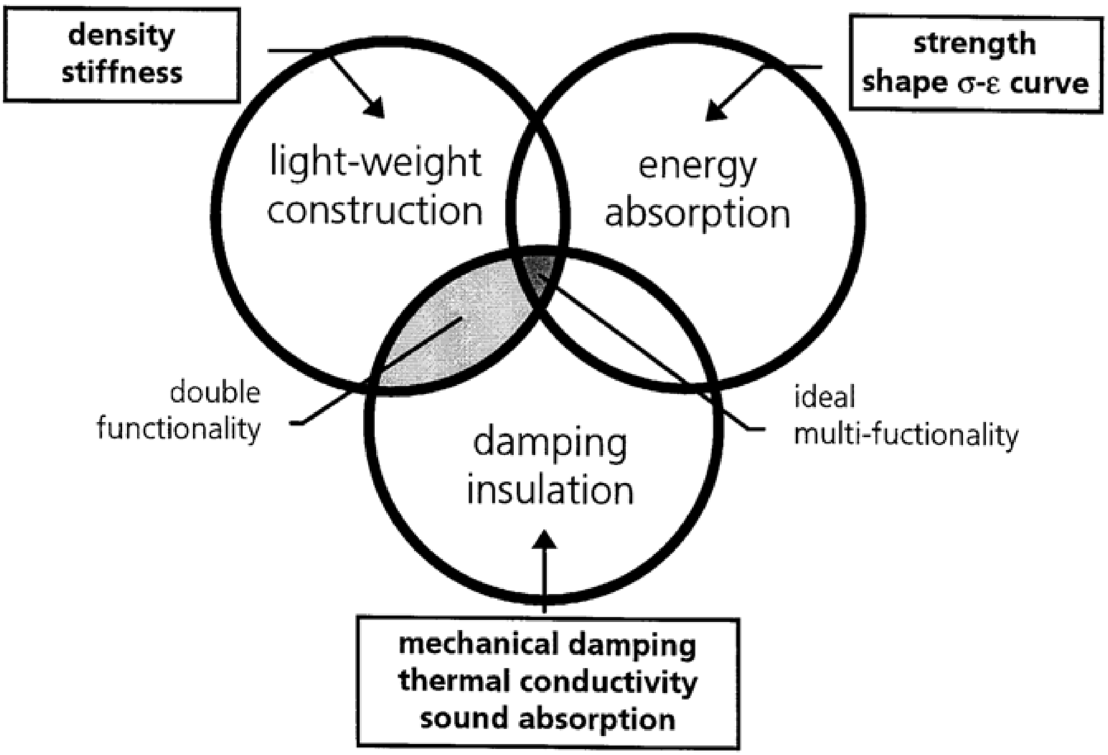

Figure 3.2: Main automotive application fields of structural metal foams [24].

3.1.2 Aerospace Industry

The main aim of the aerospace industries is to reduce weight keeping the same or more strength than the regular metals have. In this industry, high priced honeycomb structures replaced by metallic foam panel or foamed aluminum sheets with low cost and higher performance. In reality, a strong advantages of this kind of material is their isotropic mechanical characteristics and possibility to make the composite structures without using any adhesive bonding. As an example, the giant aerospace company Boeing (USA) has considered the utilization of metallic foam especially the one produced by the gas entrapment technique for manufacturing of 787 Dreamliner (Figure3.3) which from material point of view is on of the most advanced leap in the history of manufacturing.

The advantages of these structures are beyond the weight saving as there is increasingly practical methods to unify different functions to unique system. Utilizing the composite structures is growing cause it is not individually for structures , indeed, the structural systems can be part of acoustic damping, thermal transfer and electrical systems. Composite materials has higher lifetime respect to the aluminum materials, cause of the corrosion and fatigue advantageous along with fasteners reduction dramatically. The structure which applied to the 787 is a gigantic macro-molecule and all parts are fixed through across-linked chemical bonds that strengthened by carbon fibers.

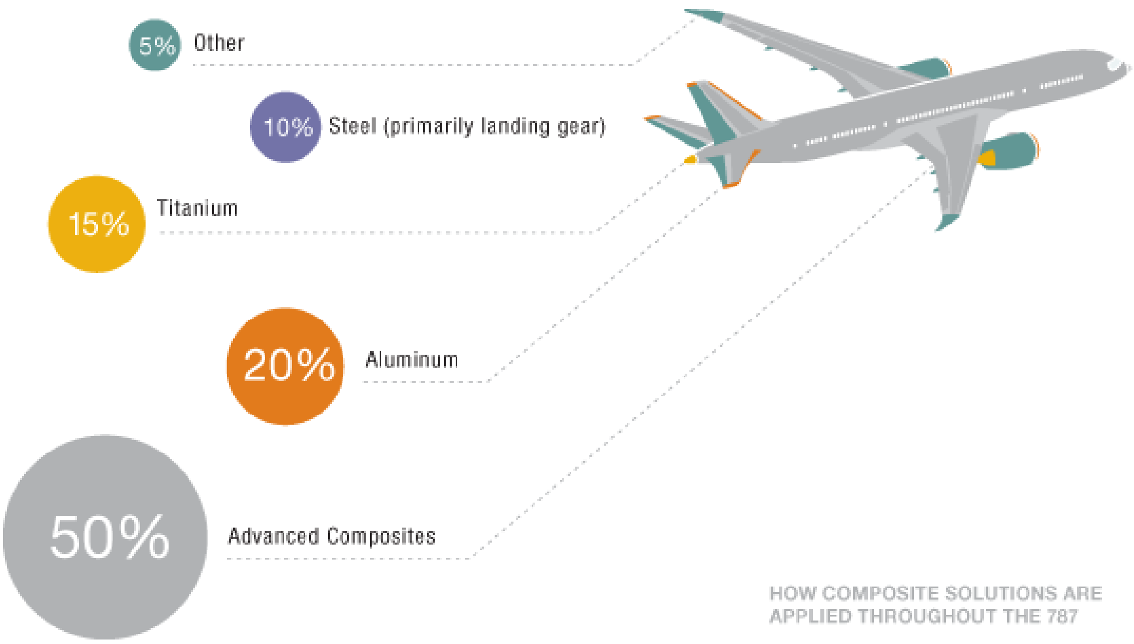

Figure 3.3: Composite applied throughout the 787 Dreamliner.

This kind of structures can be manufactured with curvatures and even in 3D shapes which is an essential advantage for them by comparison with flat honeycomb structures. Accordingly, the aerospace companies are seeking to utilize this kind of foam structures instead of the current honeycomb components. Another example of this is using metallic foam to make helicopters' tail booms.

Particularly in space technology, Aluminum foam has been classified as a crash absorber elements for space equipment, vehicles landing compartments and supportive equipment for load bearing structures for satellites. For space applications, the use of largely reactive but very lightweight alloy foams such as Li– Mg foams has been evaluated. These alloys, usually not appropriate because of their high reactivity, could be practical in a vacuum environment.

3.1.3 Ship Building

Light weight components and structures also are very prominence in ship-buildings. Large aluminum foam panels in particular, with aluminum cores are utilizing in modern passenger ships which built from aluminum sheets and extrusions. For ship-building applications, how the different element joining is an important technique and it can make a suitable fastening compartments during the manufacturing. Structural bulkheads, pyrotechnic lockers, elevator platforms, and antenna platforms are other cellular materials which are using in Naval applications.

3.1.4 Railway Industry

The applications of metallic foams in railway industry equipment are the same of automotive and aerospace industries and concerning three mail application fields. In addition, the benefits of utilizing light-weight elements are the same as in automotive sectors, the principal difference is railways products are much larger. In urban area where collisions can occur energy absorption is a challenge for the light trams and railways. For instance, there is a $2.3m^3$ block of "Alporas" foam in Japanese modern trains to enhance crash energy absorption.

3.1.5 Offshore Industry

From 1980's up to 1994, the U.S.A. oil and gas exploration dramatically decreased, driving a significant grow of the oil and gas production. For instance, the crude oil demand in 1994 was covered just by importing 50% which was the highest level for U.S.A. since 1990. For improving and developing the oil production in U.S.A. especially in deep water areas, the industries need a strong and lightweight materials to substitute the conventional heavy alloys that are used in the oil platforms. Additionally, the benefits of using that kind of materials are also include the cost reduction, weight reduction of the platform deck and decrease the maintenance cost.

Figure 3.4: Libra Oil Field, Santos Basin.

Recently, composite structures are being a considerable part in offshore industry and other marine structures. For instance, polymeric composites that hardened with carbon, glass, or aramids provide the capability of weight reduction, additionally, it can improve the fatigue and corrosion resistance. These properties along with decrease maintenance costs and uncomplicated manufacturing make the composite structures very appropriate for utilizing in the offshore facilities. Moreover, it is predicted that in the current years the use of this material and structures will increase spectacularly for the structures suchlike riser, drill pipe, storage tank, tubing and especially for platform decks [**?**].

For example the thermoplastic composite pipe (TCP) Riser that used in gigantic oilfield base in Brazil (Figure 3.4) could show a top tension reduction up to 45% compare to the conventional flexible pipes[2] by using a hybrid riser design. reducing the weight loading on the floating, production, storage and offloading (FPSO) vessel. Second, says Airborne, the TCP Riser itself is a simple monolithic wall pipe; while still flexible, it is inherently simple in its design leading to a cost effective solution for deeper waters.

Figure 3.5: Massive spools of Airborne Oil and Gas' thermoplastic composite pipe.

There are some factors that impressed the increasing demand of composite materials like the weight of the structures can dramatically decrease and the corrosion resistance of this new materials are much more higher than the conventional offshore structures. Weight reduction is a leading driver cause lower weight means less structure costs and make it possible to drill more and increase the pipelines length for oil production. Jerry Williams (Houston, Texas) mentioned "The cost differential narrows when installed costs are compared, and shifts in favor of composites when life-cycle costs are considered. We've seen life-cycle savings of up to 70% for fiber-reinforced plastic pipe."

In contrast with steel structures, where seawater can corrode faster, composite structures that made by chemical resins are nearly corrosion free. For column

[2]These pipes are using for the bottom and top of the riser section

pipe[3] as a platform component or firewater system[4] this corrosion resistance property causes maintenance service for years. There are some reports that mentioned a conventional steel pipe has been corroded only two or maximum three years after installation, while there are thousands of composite column pipes are in service more than twenty years.

Improving corrosion and controlling the weight are two principal factors that are driving the interest and increasing demand to use composites components and structures especially in oil and gas sectors like exploration and production. Controlling and preventing the corrosion is a big challenge in oil and gas industry and it costs huge amount of money in particular replacing the components periodically. Furthermore, composite components can utilize in order to resist and control corrosion and be suitable along with chemicals that are using in down-hole and offshore structures.

In addition, low dense composite structures give the best solution to reduce the weight of the structures in ultra deep water floating platforms that is one of the most important priority in this industry. Crucial structures safety as for example fire water piping besides the structures like grating and stairs that fabricated with fiberglass and polymeric resin are utilizing for offshore platforms. Moreover, there are some hybrid constructions that are using different materials in order to achieve the essential performance with minimizing the cost consideration.

Composite material characteristics give the requirement for having better flexibility design by introducing the unique physical and mechanical properties and provide a cost effective solution. Advanced composite structures that comprising the carbon fibers are regularly more expensive that the conventional steel metal components, however, weight reduction, decreasing maintenance costs can turn the cost differential and cause the less expensive solution for this new material. Moreover, the cost of the materials can be decreased based on the performance improvement capacity and decreasing the life cycle of the system.

"Beneficial Characteristics of Composites that are interested in oil and gas (offshore) industries are listed below" [18]:

- Corrosion Resistance.
- Weight Reduction.
- Excessive Strength and Stiffness.
- Fatigue Resistance.
- Low Thermal and electric Conductivity.
- Low to Moderate Flow Friction.
- Design Flexibility

[3]pipe that extends from the platform down below the water surface to supply seawater
[4]strategically placed pipes for fighting potential fires

Structural application in platform can be categorized due to the different load ranges. Heavily load range structures are like tendons, risers, and high pressure piping, for the lower load range or moderate loaded there are structures like helideck, flare tower, low pressure pipes and vessels. The structures such as grating, ladder, and living quarters are classified as secondary structures.

Composite Applications Categories [18]:

1. Sea Bed Platform: riser and mooring system
2. Processing Facilities: containers and pump
3. Secondary Structure (Topside): grating
4. Protective Structures: walls
5. Piping (Topside): firewater and waste water
6. Pressure Vessels: storage vessels
7. Platform structures: helideck
8. Downhole Structures: drill pipe
9. Subsea Structures: injection and flow lines
10. Ship Applications: pipe and mast

Particularly, deepwater oil and gas resources are proposing considerable potential to develop and improve the structural application, for instance, in the Gulf of Mexico or the west coast in Africa and other deepwater basins. Over the last ten years, major companies in different sectors worked together in order to make the composite materials a viable and feasible option for oil and gas applications. Currently, the oil price and some unstable economical situations can delay the offshore structures development, however, the composite structures expected to play a significant role for improving the performance and also make affordable offshore development.

Current Composite Applications: The new deepwater areas where the depth is higher than 1500m for instance the new explorations in Gulf of Mexico, Brazil, or in Africa presents tremendous opportunities in improvement and development of offshore platforms and also technical challenges. Particularly, for design a pipe with large diameter for over 2000m appertains there are crucial challenges in engineering design for rigid and flexible pipes technologies.

To address the mentioned requirements, RPSEA ("Research Partnership to secure Energy for America") along with the national energy department of U.s.A. have been started to develop the program due to fabricate and design flexible pipe (Figure 3.6) with 8″ internal diameter in order to use for ultra deepwater structures and applications. The research program is based on the flexible riser with a novel hybrid technology which is going to develop with performance analyzing, material testing and combination of the different designs.

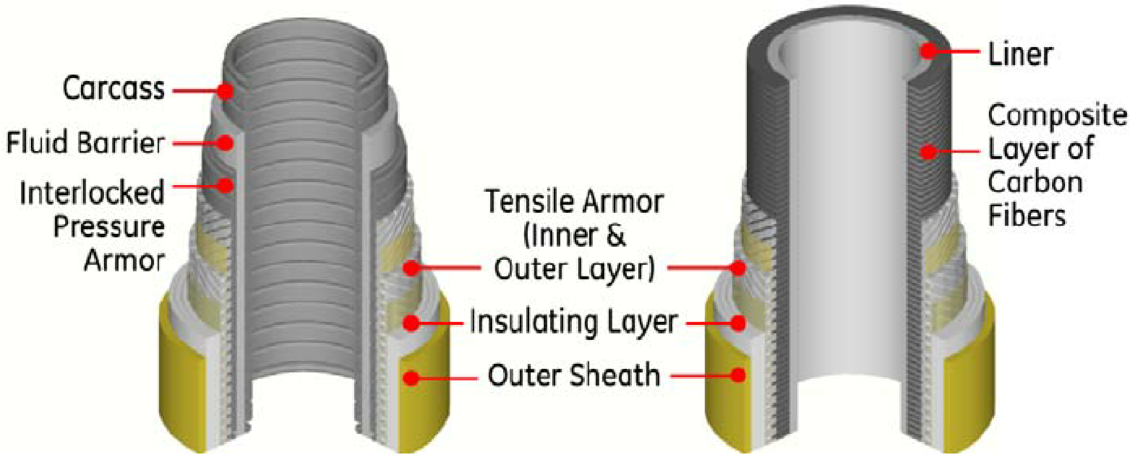

Figure 3.6: Cutaway schematic of composite pressure armor flexible pipe design.

As long as the oil and gas industry is moving to explore and invest on the ultra deepwater reservoirs, the weight of the structures and their performance become dramatically important. The risers are a very good example for saving weight on the deck structures. Some of the offshore platform structures are shown in Figure 3.7. The TLP (Tension Leg Platform) has been very common to use for the depth between 2000 to 4000 feet, however, recent research activities show the SPAR has better performance in particular for the depth greater than 3000 feet [18].

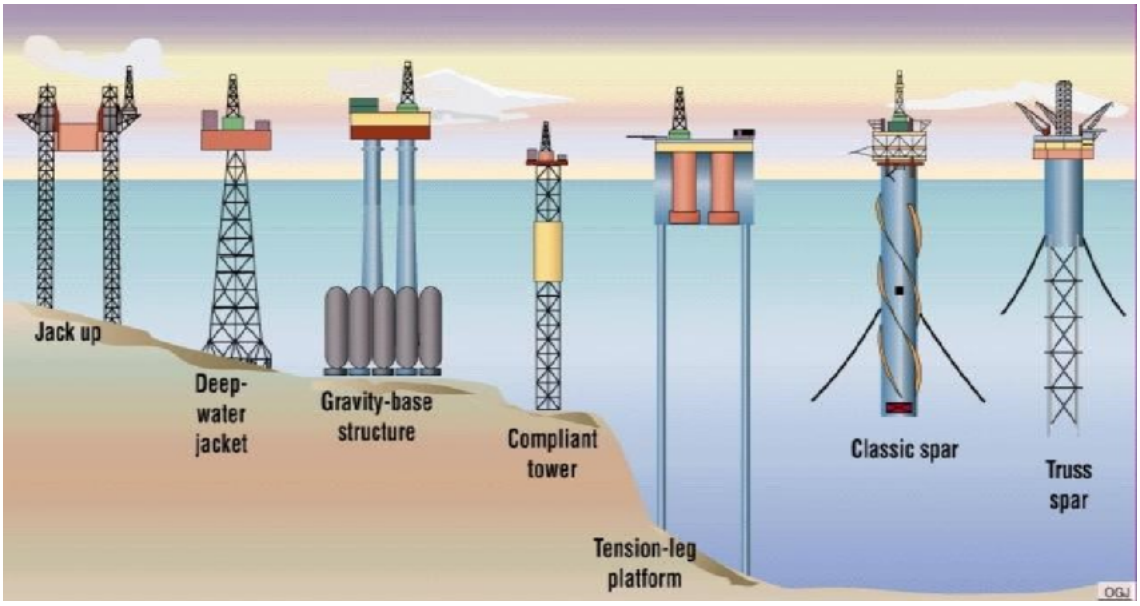

Figure 3.7: Deepwater production platform configurations.

3.2 Non-Structural Applications

Some essential non-structural applications for metallic foams are categorized in table 3.2. These applications are mostly use in the mechanical engineering sectors; accordingly, there is a description for the mentioned applications in structural engineering.

The technology of the metallic foamed applications is finding its place in the commercial markets. Scientific researches have a significant effect on this domain by sharing the relative knowledge about these complex structures name a few, developing homogeneity of the foams and the production methods. Thanks to the unique properties of these applications and some cost-effective production techniques, this industrial sectors would continue as the last years with fast development [9, 45].

Table 3.2: Example Non Structural Applications/Advantages for Metal Foams [8].

Prototype/In-Production Application	**Improved Characteristics Explored in the Given Application**					**Importance to Civil Engineering**
	α_t **(Thermal)**	**F (Fire)**	C_t **(Acoustic)**	**q (Transport)**	**h (shielding)**	
Industrial chill forms and generic foamed parts	X					Reduced thermal conductivity; could help solve thermal bridging problem in steel applications.
Metal-ceramic heat shield and bio-medical implants	X					Metal foams allow materials of disparate thermal expansion to be joined to great benefit.
Fire retarders	X	X				Potential for integral fire resistance in steel members. Modeling tools advanced in this application.
Heat exchanger	X			X		Open cell metal foams allow fluid transport, potential application for wall to be integrated with HVAC.
Sound absorber on bridge, in auto exhaust, and general use			X			Potential to integrate sound absorption and vibration frequency control into bridge/rail design.
Electromagnetic shield and radiation shield					X	Potential infrastructure applications for shielding buried structures, components of critical facilities, etc.

Chapter 4

Dynamic Properties of Physical Systems

Dynamics of a system like other scientific principles has its own language to describe and solve the problems and it is crucial to introduce some initial terms in regards to using throughout the system. Basically, the study of the dynamics can be divided in to main categories, free vibration or forced vibration. In the free vibration analysis, " the system is set in motion by some initial disturbance from its static equilibrium, and is then allowed to move free from any further external forces" [19]. Furthermore, the following motion is a function of the structural properties, in particular, the mass and stiffness.

On the other hand, the forced vibration is happening due to the time deviation external force. Under the condition that the loading frequency is close to the natural frequency of the system, due to the resonance a large motion can turn up. So, during the study and research about the vibration problems, it can be a very good start to work on the determining characterization by free vibration analysis, and the results can use to compute and calculate the forced vibration response.

Regularly, to model a structure it is convenient to decrease the distributed parameters in the system to one which characterized with the motion of the nodal points. Each motion included in the system consider a degree of freedom, for instance, the system which has one displacement consider as a single degree of freedom (SDOF). The total number of the natural frequencies in an individual structure is equal to the total number of the freedom in that system. Whereas, in a SDOF system a unique natural frequency obtain, for a MDOF system it will be many modes of the vibrations due to diverse natural frequencies. In this research work, it will focus on the linear systems analysis, where materials are considered with their elastic range.

4.1 Dynamic Properties of the Physical

The main properties required for the dynamic analysis of a structures are the dispersion of damping (damping ratio), mass and stiffness. In this section, it is describe the importance of these properties and the effects of them on structural analysis.

4.1.1 Mass and stiffness

The primary principle which is controlling the dynamics is the Newton's second law. For a system with a constant mass, it can be written normally as:

$$F = ma \tag{4.1}$$

where 'F' is the forces which is acting on the body, 'm' is the body mass and 'a' is the acceleration. Equation 4.1 explains the motions can occur based on the lack of equilibrium. The mass has possibility to go through an oscillation motion if it is controlled with a system which has a finite stiffness such as a spring. Indeed, any moton or movement of x away from the origin can generate R force which is a restoring force as represented in Figure 4.2. Generally, R can be any function related to the spring expansion x. If the spring system is a linear system the:

$$R = kx \tag{4.2}$$

where k is the constant value of the stiffness with the units of N/m. Consider that R is always tending to bring back the mass to the origin place.

Figure 4.1: Displacements and forces in a simple mass-spring system [19].

4.1.2 Damping

An ideal mass-spring system as it starts in motion, will go on to oscillate endlessly, however, in reality the system will mitigate by passing the time except that there are some forces to keep the motion on. The reason that this mitigation happens in the system is because of the presence of an internal mechanism, which cause the energy took out of the system. This dissipation of the energy in system is called 'Damping'. There are several possible forms for damp a system, such as:

- Dry damping occurs when the energy is mitigating through the friction within sliding surface. It is also known as Coulomb damping.
- Viscous damping occurs when the energy mitigate in fluid lubrication or during fluid flows over as orifice.

- Structural damping occurs during the random vibration of the crystal mesh especially, when it is repeating the cycle of deformation. It is also called as Hysteric damping.
- Radiation damping occurs when the energy is transferred, for instance, from a building to the ground.
- Aerodynamic damping occurs based on the friction between air and a vibrating system.
- hydrodynamic damping occurs due to the movement of a vibrating body to the fluid like an oil rig leg through seawater.

In any mechanical or physical system, the energy dissipation happens due to a combination of the mentioned damping forms. An appropriate selection can be the models that has more available parameters and the experimental validity can check. Indeed, model the damping system is difficult and it requires complex mathematical analysis. Hence, it is convenient to explain the damping by a viscous dashpot, in a way that the piston forces a viscous fluid like oil over an orifice. This system is not always valid for example when there is a strong friction force, however, it is very simple formulate it and have a logical approximation for the diverse damping mechanism.

The dashpot system is shown in Figure 4.2 and it produces a deceleration force proportional to the velocity v across it, that is shown mathematically as:

$$F_D = cv \tag{4.3}$$

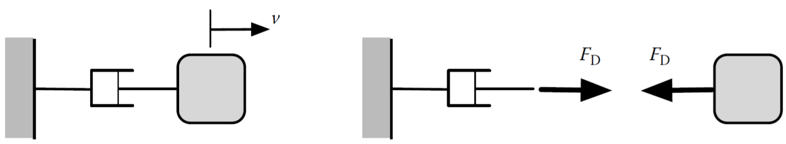

Figure 4.2: Velocity and forces in a simple mass-dashpot system [19].

where, force unit is N and the damping coefficient c unit is Ns/m. The mass force in the dashpot system is always in the opposite side of the velocity direction. The result of the plotting damping force versus velocity will be a simple straight line of the damping coefficient gradient. Moreover, more appealing graph will be the one with force in comparison with deflection. Regarding to the harmonic vibration there are:

$$x = X \sin \omega t \tag{4.4}$$

$$\dot{x} = \omega X \cos \omega t \tag{4.5}$$

Using Equations 4.3 and 4.6, the damping force will be:

$$F_D = c\dot{x} = c\omega X \cos \omega t \tag{4.6}$$

With substitution of the widely known trigonometry relation:

$$\sin^2 \omega t + \cos^2 \omega t = 1 \tag{4.7}$$

Finally, it gives an equation of ellipse that is:

$$(\frac{x}{X})^2 + (\frac{F_D}{c\omega X})^2 = 1 \tag{4.8}$$

The Equation 4.9 is the ellipse equation which is plotted in Figure 4.3 comprising one harmonic cycle. The enclosed area in the plot can compute by the integral of the force respect to the distance moved and it represents the work by the damper force through the cycle, which is indeed, the energy dissipation [19].

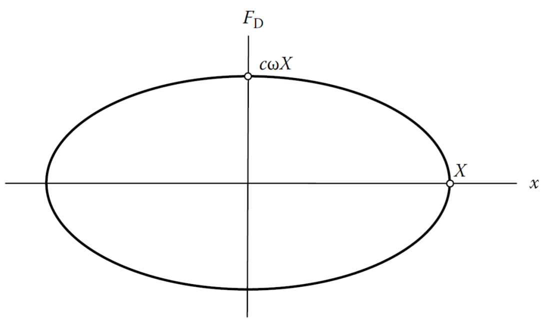

Figure 4.3: Force-displacement loop for a viscous damper undergoing a single vibration cycle of amplitude X.

Considering that the ellipse area is π times the axis intercept products, the work can define as:

$$W_D = \pi c \omega X^2 \tag{4.9}$$

Or, if there is the capability to measure the dissipation energy for each cycle of vibration, to estimate the damping coefficient the equation could rewrite as:

$$c = \frac{W_D}{\pi \omega X^2} \tag{4.10}$$

Regularly, the real damping is not viscous purely, so, the mentioned relations are not a perfect ellipse and may differ from the ellipse shape. Nevertheless, by using the Equation 4.10, it is feasible to compute an identical damping coefficient to obtain the same absorption energy for the similar displacement. This is a simple method to mathematically approximate the real damping in a suitable approach, however, as it is an approximate in most of the cases, to obtain a sufficient result is quite difficult. Contrary to stiffness and mass, the damping values cannot derived easily by analytical method from the physical properties of a consider system, and the experimental data requires using Equation 4.10 which is usually unapproachable.

Consequently, the convenient way is to use a dimensionless parameter, which is known as the damping ratio ζ

$$\zeta = \frac{c}{2\sqrt{km}} \tag{4.11}$$

The damping ratio is beneficial as it takes the same value for a structure with the same material and type, so, it is possible to assume an approximate value for the different analysis. For instance, in structural engineering systems, the approximate value for ζ is usually in the range of 0.02 to 0.05, however, always the higher and lower values can obtain [19].

4.1.3 Vibration Damping in ANSYS software

The damping matrix in ANSYS can be use in different analysis such as harmonic, modal, and transient together with some substructure generation [21]. The most general form of damping matrix can represent as:

$$[C] = \alpha[M] + \beta[K] + \sum_{j=1}^{N_{mat}} \beta_j[K_j] + \beta_c[K] + [C_\zeta] + \sum_{k=1}^{N_{ele}}[C_k] \tag{4.12}$$

where:
α: The constant mass matrix (ALPHAD command).

β: The constant stiffness matrix (BETAD command).

β_j: The constant stiffness metrix (DAMP command) by considering the material dependent damping. It should be noted there are different damping parameters for the different class of analysis while using this type of damping.

β_c: Variable stiffness matrix as it is usable for the harmonic analysis.

$$\beta_c = \frac{\zeta}{\pi f} = \frac{2\zeta}{\omega} = \frac{2\eta}{\omega} \tag{4.13}$$

f: The frequency between the initial (f_a) and terminal (f_b) frequency.

ζ: The damping ratio (DMPRAT command). Regarding to the Equation 4.13 the damping ratio is equal to $\frac{\eta}{2}$ whet η is the loss factor.

$[C_\zeta]$: The frequency-dependent damping matrix. This matrix can compute from $_r$ which is damping ratio for specified mode shape r (MDAMP command).

[C] may be calculated from the specified r (damping ratio for mode shape r) and is never explicitly computed $[C_k]$: the element damping matrix

Chapter 5

Finite Element Modeling

This chapter represents the background of the finite element method, the modeling of metallic foams and structural dynamic analysis related to the metallic (steel) foam structures. In this chapter, the fundamental purpose is to provide a simple and reliable description of structural dynamic analysis and define a relevant constitutive model for metallic foams. In structural mechanics, Finite Element Method is an essential technique to find out estimated solutions for numerical problems. There are different FE methods with their individual advantages.

Finite Element Methods are a remarkably beneficial tool for engineers and scientists in operating tests which are not feasible by experimental methods. Metal foams are quite highly engineered materials and by using the FEM it is possible to examine their behavior and modify their material properties with an economical and efficient technique in order to understand how these materials behave. Relative density is an important property of these materials and in spite of the fact that there have been some mathematical models that endeavored to describe and explain this parameter effects on the material behavior, experimental tests indicate that the material behaviors are more complex than the mathematical models.

5.1 Homogenized Model for Metallic Foam

Over the last few years, metal foams particularly, low-cost aluminum foams have been produced for a wide area of industrial applications such as automotive and aerospace parts. One of the main aims is to produce and develop lightweight structures with high stiffness and capability to absorb a huge amount of energy. Furthermore, improving of the design method based on the constitutive laws is the main demand for having a successful implementation of metallic foams.

The investigation of mechanical properties of metallic foams is still a necessary subject. The first model performing the mechanical properties of the metallic foam are the ones formulated by Gibson and Ashby as represented in Table 5.1 which gives the scaling relations for foam properties [8]. The primary dependent variable of metallic foam property is presented by the relative density, and describing either if it has open-cell or close-cell. "All other properties are lumped into a multiplicative coefficient with typical ranges provided in Table 5.1".

The appropriate coefficient preference should be in accordance with care and resulting expressions are manufactured dependent and are just accurate and valid for relative densities which have small range. Converging solid steel values with high relative density is not inherent to the resulting expressions.

Table 5.1: Equations for mechanical properties of metal foams as set by Gibson and Ashby [2].

Property	Open-Cell Foam	Closed-Cell
Elastic modulus	$\frac{E}{E_s} = (0.1-4).(\frac{\rho}{\rho_s})^2$	$\frac{E}{E_s} = (0.1-1.0).(0.5).(\frac{\rho}{\rho_s})^2 + (0.3).(\frac{\rho}{\rho_s})]$
Compressive yield strength	$\frac{\sigma}{\sigma_{c,s}} = (0.1-1.0).(\frac{\rho}{\rho_s})^{\frac{3}{2}}$	$\frac{\sigma}{\sigma_{c,s}} = (0.1-1.0).[0.5.(\frac{\rho}{\rho_s})^{\frac{2}{3}} + 0.3.\frac{\rho}{\rho_s}]$
Tensile strength	$\sigma_t = (1.1-1.4).\sigma_c$	$\sigma_t = (1.1-1.4).\sigma_c$
Shear modulus	$G = \frac{3}{8}.E$	$G = \frac{3}{8}.E$
Densification Strain	$\epsilon_D = (0.9-1.0).[(1-1.4).(\frac{\rho}{\rho_s}) + (0.4).(\frac{\rho}{\rho_s})^3]$	$\epsilon_D = (0.9-1.0).[(1-1.4).(\frac{\rho}{\rho_s}) + (0.4).(\frac{\rho}{\rho_s})^3]$

B.H. Smith et al. presents comparison of the resulting expression of table 5.1 by considering experimental accessible data for Young's modulus and yield stress which is provided in Figure 5.1. "Data outside the "bounds" of the Gibson and Ashby expressions include steel foams with unusual anisotropy, special heat treatments, and unusually thin-walled hollow spheres" [8]. The Gibson and Ashby resulting expressions (Table 5.1) reveal a sufficient starting point, however, there are other models demand examination.

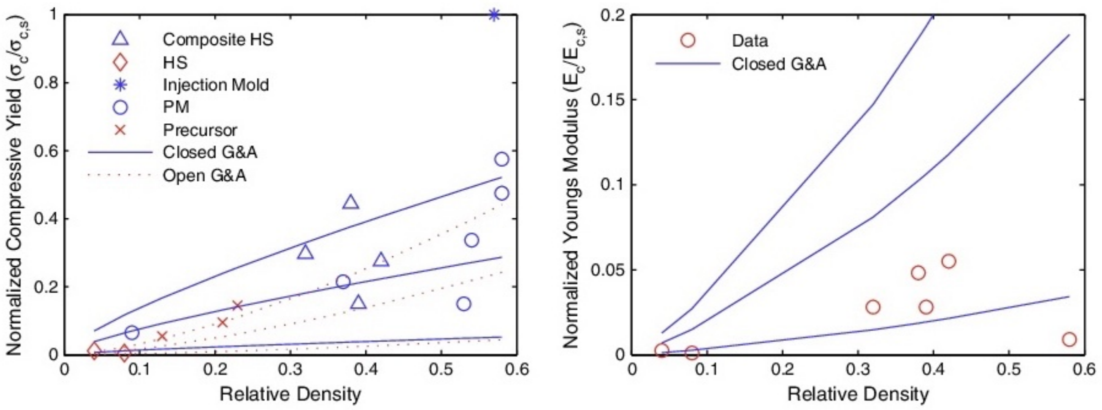

Figure 5.1: Comparison of available experimental data with Gibson and Ashby expressions. Blue lines indicate Gibson Ashby expressions with leading coefficients equal to minimum, maximum, and middle value [8].

Comparison of the new developed application experimental research based on the Gibson and Ashby expressions indicate that they remain with the determined bound of the Gibson and Ashby.

5.2 Structural Dynamic Analysis

5.2.1 Definition

Structural engineering theory is an essential science and extensively used in various field of engineering. Moreover, it uses different mathematical techniques and formulated with adequate perfections.

In finite element methods the most usual application is most likely structural analysis. The term of structure or structural is not only refer to the civil engineering like building and bridges but also take into account other structures suchlike aeronautical and mechanical structures as for instance aircraft bodies, and even machine housing, together with some mechanical compartments like machine parts and pistons, and other gigantic structures like what exist in offshore industries.

Structural dynamic analysis unlike classical static analysis consider the which are differ with time and, accordingly, the structural response. Some examples where structural dynamic analysis are demanded:

- Skyscrapers vortex shedding response.
- Primitive structures where required to resist earthquake motions.
- Floor system response in a vibration-sensitive facility to pedestrian traffic.
- Min. mass of a TMD required to achieve the desirable mitigation.
- Transmitting the vibration through the building with especial mechanical system.

5.2.2 Types of Structural Analysis

There are seven different types of dynamic analysis for structures which available in the ANSYS [1] family products. The initial unknowns that are computed in the structural dynamic analysis are displacements. Other quantities (for instance stresses, strains and reaction forces) can derive from the nodal displacement.

The structural dynamic analysis types which can perform in ANSYS are listed below:

- **Static Analysis:**
  Used to find out displacements, stresses, etc. under the static loading state.
- **Modal Analysis:**
  Used to determine the vibration characteristics (the mode shape and also natural frequencies) of a certain structure. There are different extractions mode methods are usable.
- **Harmonic Analysis:**
  Used to ascertain the structural response to harmonically time-varying load.
- **Transient Dynamic Analysis:**
  Used to figure out the structural analysis to arbitrarily time-varying loads.
- **Spectrum Analysis:**
  As an extensions of the modal analysis, used to determine stresses and strains as a result of a response spectrum or a PSD in put (random vibrations).
- **Buckling Analysis:**
  Used to find out the buckling loads and the buckling mode shape.
- **Explicit Dynamics Analysis:**
  Used to compute fast solutions for the complex contact problems and deformation dynamics.

In this section based on the research project, Modal Analysis and Harmonic Analysis are discussed by details.

Modal Analysis

Modal analysis associate data acquisition and in the industrial application it is also referred as modal testing or experimental modal analysis (EMA), caused a major change by implementing the FFT (Fast Fourier Transform) in computer based analysis in the middle of 1970s which was mainly with analog tools.

As mentioned before modal analysis is used to figure out the vibration characteristics in machinery or a (linear) structure. Indeed, the vibration mode is determined by three peculiar parameters which are mode shape, modal damping and modal frequency (also called resonance frequencies or eigenfrequencies). Using modal parameters estimation is the way to determine these parameters from the experimental

[1] ANSYS is an American global leader simulation software.

data. This analysis can be a starting evaluation for other analysis, more precise, dynamic analysis such as the Harmonic Analysis, the Transient Analysis, or the Spectrum Analysis [59].

The Modal analysis can also apply to prestressed structures [2], for instance, turbine blades, TV towers, underground structures, offshore facilities. There is a further advantageous for this analysis which is modal cyclic symmetry which permits to examines the mode shapes of symmetric structures by modeling only a section of it.

Modal Equations for Undamped Systems The Equation 5.1 expresses the equation of motion for an undamped linear MDF systems.

$$m\ddot{u} + ku = p(t) \tag{5.1}$$

where:

u: The lateral displacement

$\ddot{u}$: The mass acceleration

p(t): the external dynamic force

The displacement vector u for a multidegree of freedom system can be extended with respect to modal contributions. Therefore, the dynamic response of a system can express by Equation 5.2

$$u(t) = \sum_{r=1}^{N} \phi_r q_r(t) = \Phi q(t) \tag{5.2}$$

Φ: Is the modal matrix consisting of all n mode shapes of ϕ, which contain all the information of modal shape.

Modal Equations for Damped Systems The equation of motion for the multidegree of freedom (MDF) damped system subjected to external dynamic forces can be represent as:

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = p(t) \tag{5.3}$$

where m, c, and k are representing, mass, damping and stiffness matrix respectively. p(t) and u(t) are, respectively, the dynamic force and displacement [15].

Estimation of the Modal Parameters A modal analysis provides a set of modal parameters that characterize the dynamic behavior of a structure. These modal parameters form the modal model.

[2]an engineering structural section where stresses in the best possible way are disturbing among the components during fabrication.

If there a possibility to measure an existence structure, therefore, it can suppose that a parametric model will define which can describe that data. Predominantly, frequency response function (FRF) is the starting point for measuring the data or in some cases time domain equivalent, or impulse response (IR) can be used [89]. The relation between modal parameters and the measurement in case o IRs is expressed in Equation 5.4.

$$h_{i,j}(t) = \sum_{k=1}^{N} (r_{ijk}.e^{\lambda_k t} + r_{ijk}.e^{\lambda_k t}) \tag{5.4}$$

For FRFs the corresponding elation is present in Equation 5.5.

$$h_{ij}(j\omega) = \sum_{k=1}^{N} (\frac{r_{ijk}}{(j\omega + \lambda_k)} + \frac{{r_{ijk}}^*}{(j\omega + {\lambda_k}^*)}) \tag{5.5}$$

where:

$h_{ij}(t)$: Impulse Response between the output degree of freedom i and the input degree of freedom j

$h_{ij}(j\omega)$: Frequency Response Function between the response degree of freedom i and reference degree of freedom j

N: number of the vibration modes which provides to the structural dynamic response within the frequency range under consideration

r_{ijk}: residue value for mode k

λ_k: pole value for mode k

* designates complex conjugate

Equation 5.6 indicates that the residue value depends on the three terms.

$$r_{ijk} = a_k v_{ik} v_{jk} \tag{5.6}$$

where:

a_k: a complex scaling constant, the value is computed by the scaling of the mode shapes

v_{ik}: the mode shape coefficient at degree of freedom i of the mode k

v_{jk}: the mode shape coefficient at degree of freedom j of the mode k

if there is a real mode shape, the scaling constant a_k can represent as Equation 5.7

$$a_k = \frac{1}{2jm_k\omega_{dk}} \tag{5.7}$$

where:

m_k: the modal mass of mode k

The pole value is defined in Equations 5.8 and 5.9.

$$\lambda_k = \sigma_k + j\omega_{dk} \tag{5.8}$$

where:

σ_k: the damped natural frequency of mode k

$j\omega_{dk}$: the damping factor of mode k

or by considering undamped natural frequency

$$\lambda_k = -\zeta_k\omega_{nk} + j\omega_{nk}\sqrt{1-\zeta_k{}^2} \tag{5.9}$$

where:

ω_{nk}: the undamped natural frequency of mode k

ζ_k: damping ratio of mode k

Harmonic Analysis

Harmonic analyses are using to find out the response of a steady-state linear structure to the apply loads which can vary harmonically (sinusoidally) along with time. Furthermore, in this analysis there is the capability to verify whether or not the system design overcome the resonance frequency, structural fatigue, and other damaging effects of the forced vibrations. This technique is using to compute the steady-state, forced vibration of a defined structure. At the beginning of the excitation transient vibration analyses occur, however, don't take into account for the harmonic analysis.

In this analysis all other loads along with the structure's response diverge sinusoidally with same frequency. Regularly, the harmonic analysis is computing the structural response by considering a cyclic load over a specified frequency range (like sine sweep) and then obtain a graph including some response values (generally displacement) versus the frequency. Besides, "Peak" responses are obtained from the mentioned graph and stresses can then analyzed at that particular peak frequencies.

To comprehend better the harmonic analysis, the general equation of motion is represent here again:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \tag{5.10}$$

The same as equation of motion which defined in modal analysis, m, c, and k are respectively mass, damping and stiffness matrix, F(t) and u(t) are, respectively, the dynamic force and displacement.

As discussed before, all the existence points in the structures are shifting with the identical known frequency, however, not mainly in phase. Beside that, as it is known the damping make a phase shifts. Therefore, the displacement may be described as:

$$u = (u_{max} e^{i\phi}) e^{i\omega t} \tag{5.11}$$

where:

u_{max}: maximum displacement

i: $\sqrt{-1}$, imaginary term

ϕ: displacement phase shift [rad]

ω: the frequency at which the loading occurs

t: Time

It should be noted that u_{max} and ϕ could have different values for the different DOF. Equation 5.11 can be written as:

$$u = u_{max}(\cos\phi + i\sin\phi) e^{i\omega t} \tag{5.12}$$

or

$$u = u_{max}(u_1 + iu_2) e^{i\omega t} \tag{5.13}$$

where:

u_1=$u_{max}\cos\phi$: real displacement vector

u_1=$u_{max}\sin\phi$: imaginary displacement vector

Following this, the dynamic force can represent in accordance with the displacement as below:

$$\begin{aligned} F &= (F_{max} e^{i\psi}) e^{i\omega t}, \\ F &= F_{max}(\cos\psi + i\sin\psi) e^{i\omega t}, \\ F &= F_{max}(F_1 + iF_2) e^{i\omega t} \end{aligned} \tag{5.14}$$

where:

F_{max}: maximum force amplitude

ϕ: force phase shift [rad]

$F_1 = F_{max} \cos\psi$: real force vector

$F_1 = F_{max} \sin\psi$: imaginary force vector

By substituting the Equation 5.14 into Equation 5.10 there will be:

$$(-\omega M + i\omega C + K)(u_1 + iu_2)e^{i\omega t} = (F_1 + iF_2)e^{i\omega t} \tag{5.15}$$

and by removing the time dependency on both side of the equation there will be:

$$(-\omega M + i\omega C + K)(u_1 + iu_2) = (F_1 + iF_2) \tag{5.16}$$

the solutions for this equation will discussed further by considering different methods.

5.3 Finite Element Simulation

Finite element simulation is commonly used in the development of new products, structures, and machines. Once the finite model approved, it is usable for different simulations, computing stresses, and strains, and to investigate the structural effect modifications on the vibration characteristics of a structure. Modal parameters are used for comparing the analytical and experimental results as finite element and experimental modal analysis bring in a set of modes for a peculiar structure [16].

Since metal foams are highly engineered materials, using finite element methods to modify their material properties and observe their behavior is an efficient and economical technique and to understand further how the material behaves. One of the most important property of this material is that of relative density and even though there have been mathematical models that attempt to explain how the modification of this property affects the overall behavior of the material, experimental tests suggest that the material behavior is more complex than these mathematical models [8].

For the purpose of replicating the damping behavior of metal foam in FEM analysis, an APDL ANSYS V19.1 model is built. This model comprises the geometry of an ordinary sandwich specimen with core structure and of the clamping section with the length of 30 mm the face-sheet thickness considered negligible and with the side length of 80 mm, the finite element model is shown in Figure **??** which is related to the specimen 500D. The constraint in the middle was fixed the degrees of freedom on the top and bottom of the clamping section as it presented in the experimental setup description.

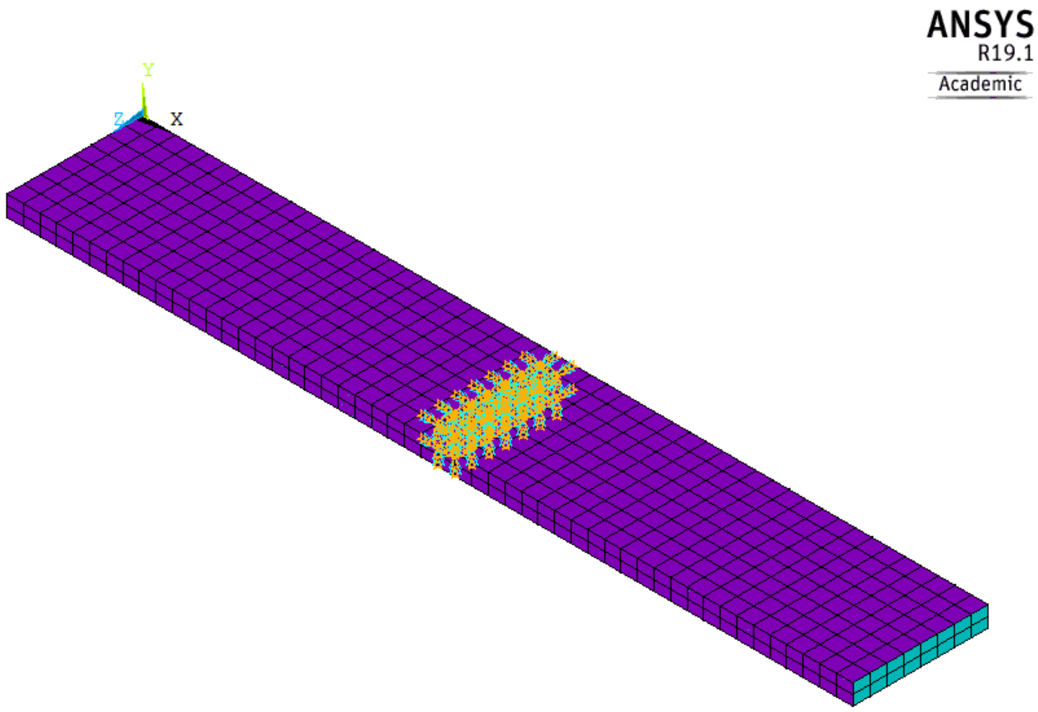

Figure 5.2: Finite Element Model of the Sandwich Specimen (500D).

The finite element analysis by ANSYS has accomplished with two important analysis steps: a first frequency extraction by using modal dynamic time-dependent analysis. In the former, the harmonic analysis employed by considering the random noise and sweep sine test [17]. Modal analysis in ANSYS family considered a linear analysis. Any nonlinearities like plasticity are neglected even when they are defined.

The mechanical material properties of the defined specimen which are applied to the model by Young's modulus consideration and a Poisson's ratio are presented in Table 5.2. For the modal analysis there is an undamped model consideration, however, for the harmonic analysis, material damping with 5% for each mode is applied to adjust with experimental values. The mesh of the specimen is composed of 1900 Elements (1020 Elements for the specimen 290D) and 1404 nodes (756 nodes for the specimen 290D)in order to have an appropriate deformation control.

Table 5.2: Specimen Material Properties Data

Specimen Unit	Density	Young's Modulus	Poisson's Ratio
Solid Shell	7800 kg/m^3	210GPa	0.3
Core	450 kg/m^3	560MPa	0.1

5.3.1 Overview of Steps in a Modal Analysis

In the numerical modal analysis, each dynamic responses such as displacement, velocity, acceleration and etc. can be selected. Further, there is the possibility to have obtained much more data from the numerical analysis as every finial element nodes can make a dynamic responses' time history. Once the time domain responses determined from the excited dynamic structure, the Fast Fourier Transform can be used in order to convert the data from time domain to frequency domain data.

There are four leading steps for a modal analysis:

1. Build the model
2. Employ the load and obtain the needed solution
3. Extend the modes
4. Review and examine the results

You can choose from several mode extraction methods: subspace, Block Lanczos, PowerDynamics, reduced, unsymmetrical, and damped. The damped method allows you to include damping in the structure. Details about mode extraction methods are covered later in this section.

Build the Model

After defining the jobname and title for the analysis, PREP7 [3] was used in order to indicate the element constants, element types, geometry of the model, and the material properties. Certainly, these tasks are the general part for the most analysis.

A very significant point in modal analysis is, just linear behavior is valid and suitable. If there is any nonlinear elements, they will be considered as linear. For instance, if the contact elements take into account, their stiffness will be calculated on the basis of their primary and initial condition and never vary or change.

Material properties in modal analysis can be linear, isotropic or orthotropic, and temperature can be constant, conditional or dependent. For making the model, Young's modulus (EX) or stiffness in some form, density (DENS) or mass in some condition should be defined. Any nonlinear properties or nonlinearities are neglected.

[3] These PREP7 commands are functioned to indicate model data into the database, list out the database, and regulate the numbering of entities in the database.

Employ the Load and Obtain the Needed Solution

From this side, the analysis type and options, apply load, load step options specifications, and the finite element solutions for the natural frequencies are defined. After initial solution employed, the mode shape expansion will apply for review. Expansion the mode shape will explain in the next subsection.

ANSYS proposes different options to define analysis type and option for a modal analysis. The optioned have used in this project are described below.

- **ANTYPE:**
  Identifies the analysis type and restart status. Note that in the modal analysis the restart is not valid. There are different types of analysis such as
  - **STATIC**:
    Perform for a static analysis and efficient for all degrees of freedom.
  - **BUCKLE**:
    Perform for a buckling analysis and it is valid only for structural degrees of freedom.
  - **MODAL**:
    Perform for a modal analysis and it is Valid for both structural and fluid degrees of freedom. This analysis type is interested in this research project together with harmonic analysis.
  - **HARMIC**:
    Perform for a harmonic analysis and it is valid and efficient for structural, fluid, magnetic, and electrical degrees of freedom. As mentioned before, this type of analysis is also interested in this research work.
  - **TRANS**:
    Perform for a transient analysis and it is valid for all degrees of freedom like the static analysis.
  - **SUBSTR**:
    Perform for a substructure analysis and it is valid for all degrees of freedom.
  - **SPECTR**:
    Perform for a spectrum analysis and it is Implied that a previous modal analysis was performed. It is only efficient for structural degrees of freedom like a buckling analysis.
- **MODOPT:**
  It is for mode extraction method and indicates modal analysis options. In case of the non-symmetric and damped method a large number of modes are required. There are different extraction mode methods for the modal analysis which are listed below.
  - **Subspace**:
    This method is used for the large symmetric eigenvalue problems. For applying modal analysis with high number of constraints equations, it is very efficient to use the subspace method, or the Block Lanczos.

- **Block Lanczos**:
  This method is employed for the same problems types (large symmetric eigenvalue problems) which used in subspace method, however, there is a quicker convergence rate for it.
- **PowerDynamics**:
  This method is used for extremely large models such like the ones with more than 100,000 degrees of freedom, and in order to understand the model behavior for the first several modes it is significantly useful. To have the final solution it is sufficient to choose an extraction method like Block Lanczos. Consider that lumped mass approximation will select on automatically in this method (LUMPM, ON).
- **Reduced (Householder)**:
  This method is the same as subspace method, but the computing is faster cause it has reduced system matrices for calculating the solutions. On the other hand, it is less precise than the subspace method as the reduced mass matrix is estimate.
- **Unsymmetric**:
  This method is used for the non-symmetric matrices, suchlike fluid-structure interaction problems.
- **Damped**:
  This method is used where damping should consider and it is not possible to neglect it, like bearing problems.

• **MXPAND:**
Specifies the number of modes in order to expand and write for a modal or buckling analysis. This command is only efficient for the reduced, non-symmetric, and damped methods, however, if there is a need for the element results, the option of "calculate elem result" should turn on. If there is the single point response spectrum (SPOPT, SPRS) and also dynamic analysis method (SPOPT, DDAM), after the spectrum analysis it is possible to use and perform the modal expansion by considering the SIGNIF factor on this command.

Extend the Modes

Extend or expand the modes means developing and increasing the existence reduced solution to the full degrees of freedom set. In the modal analysis extending the modes are performing to write the mode shapes to the result files. This term is not only apply for the reducing mode shape from the reduced mode extraction method, but also for the full mode shapes.

Review and Examine the Results

The results what obtained from modal analysis can be written to the structural results file which is called Jobname.RST. Generally, the result compromising of:

- Natural frequencies
- Expanded mode shapes
- Relative stress and force distributions (if requested).

The output of the modal analysis examination is presented below:

Table 5.3: Index of Data Sets on Results File (500D)

Set	Time/Freq.	Load Step	Substep	Cumulative
1	234.24	1	1	1
2	236.25	1	2	2
3	922.17	1	3	3
4	1004.9	1	4	4
5	1150.8	1	5	5
6	1160.6	1	6	6
7	1194.4	1	7	7
8	1197.4	1	8	8

Table 5.4: Index of Data Sets on Results File (290D)

Set	Time/Freq.	Load Step	Substep	Cumulative
1	234.24	1	1	1
2	236.25	1	2	2
3	922.17	1	3	3
4	1004.9	1	4	4

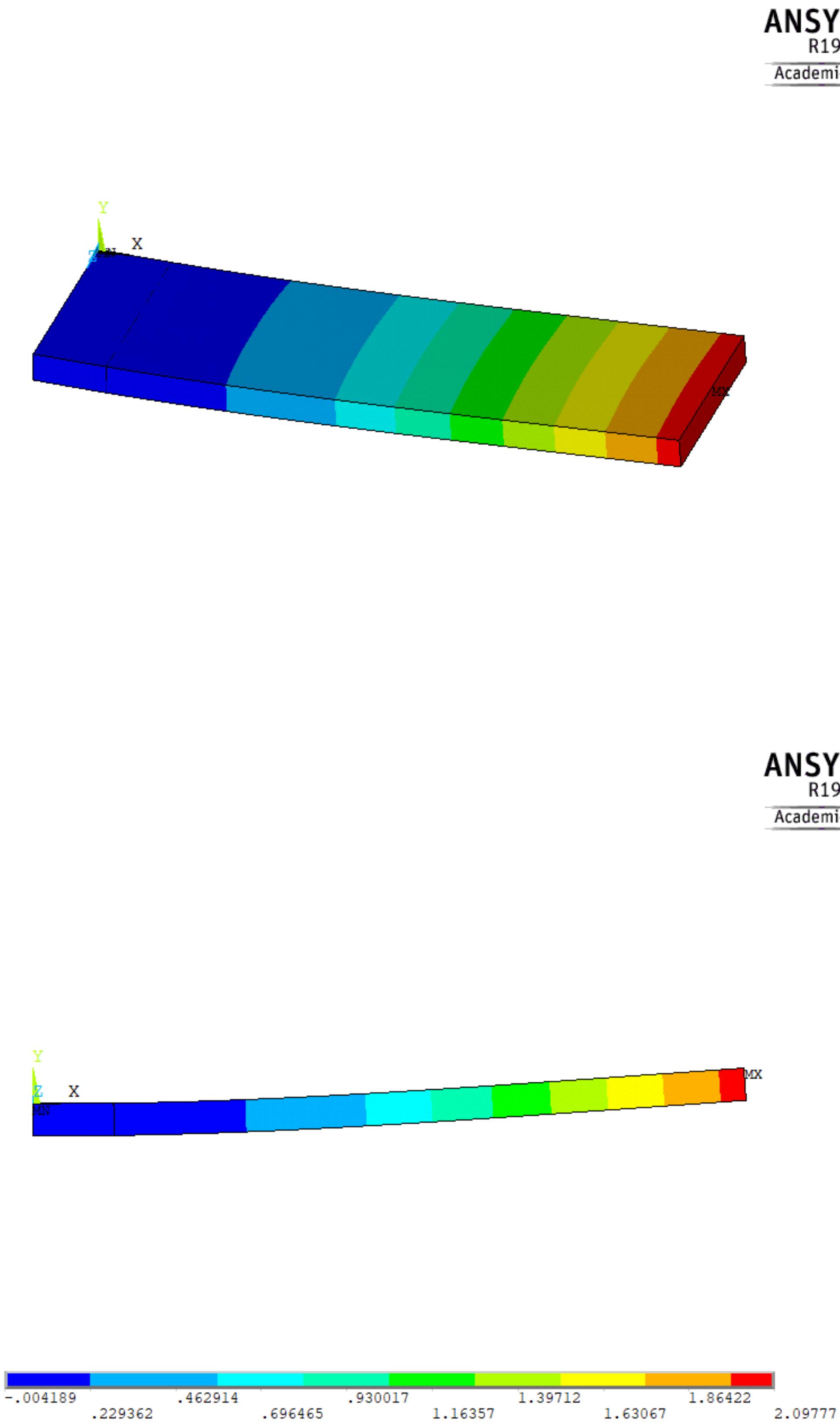

Figure 5.3: First Mode Shape at 234.24Hz (290D)

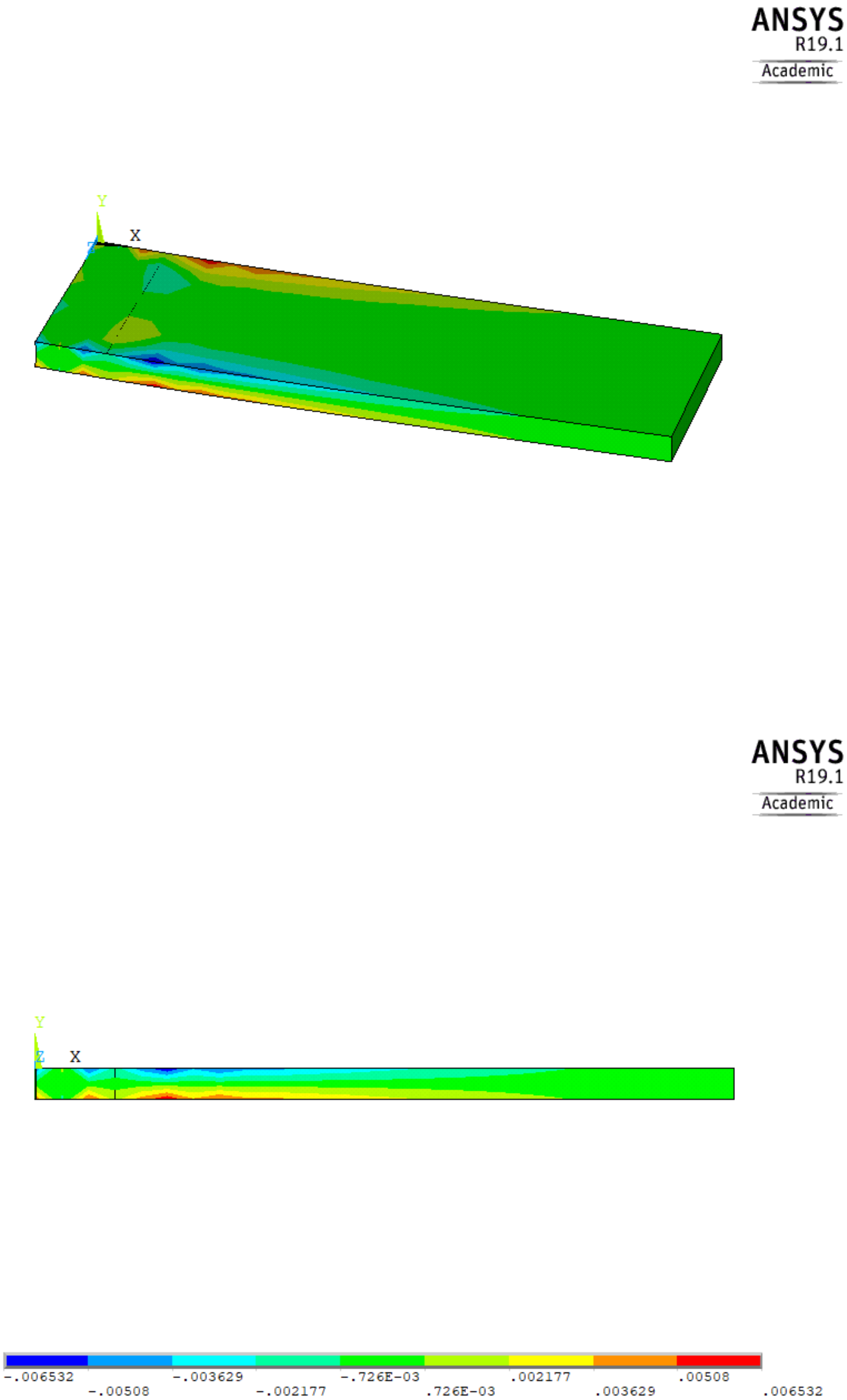

Figure 5.4: Second Mode Shape at 922.17Hz (290D)

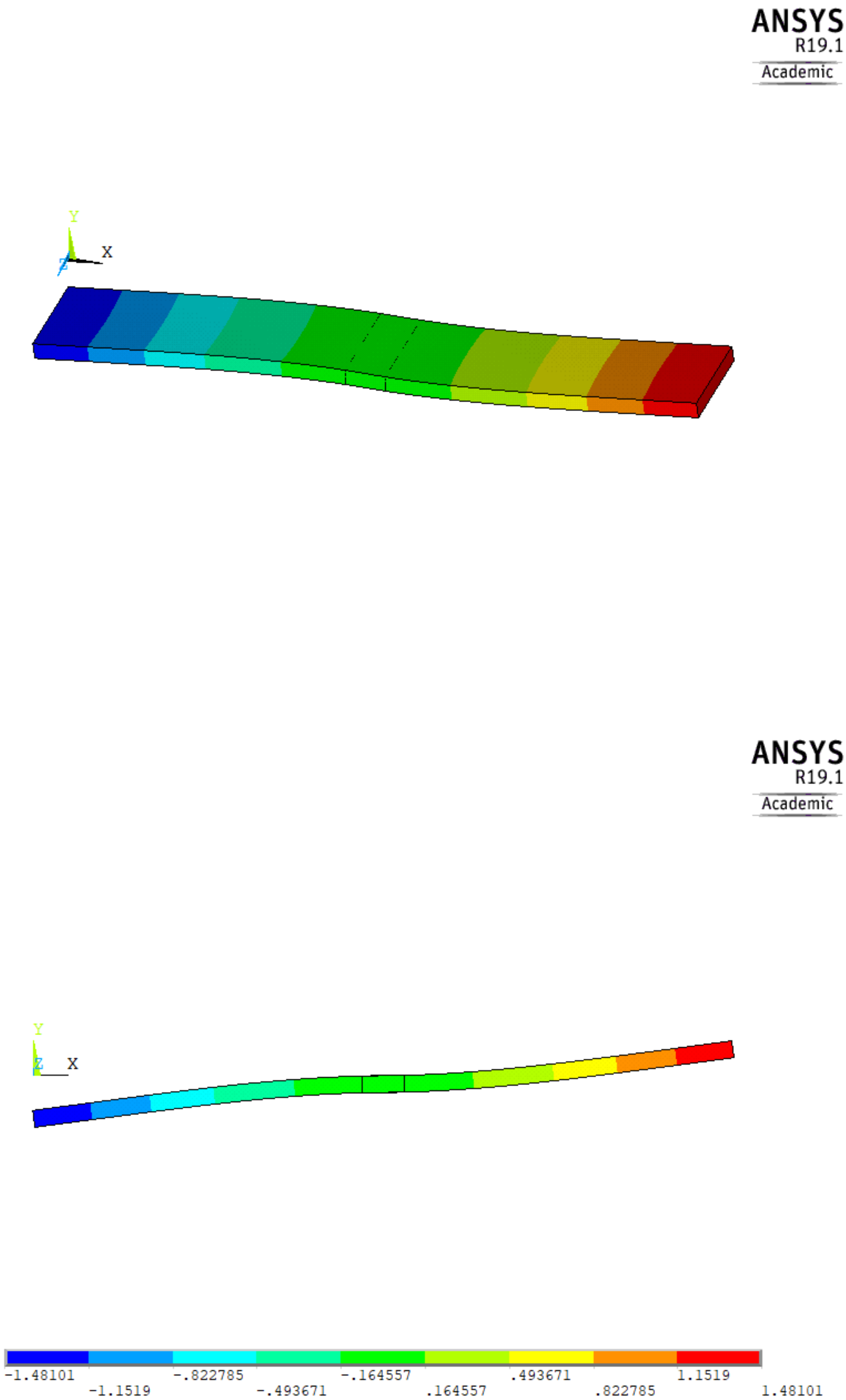

Figure 5.5: First Mode Shape at 234.24Hz (500D)

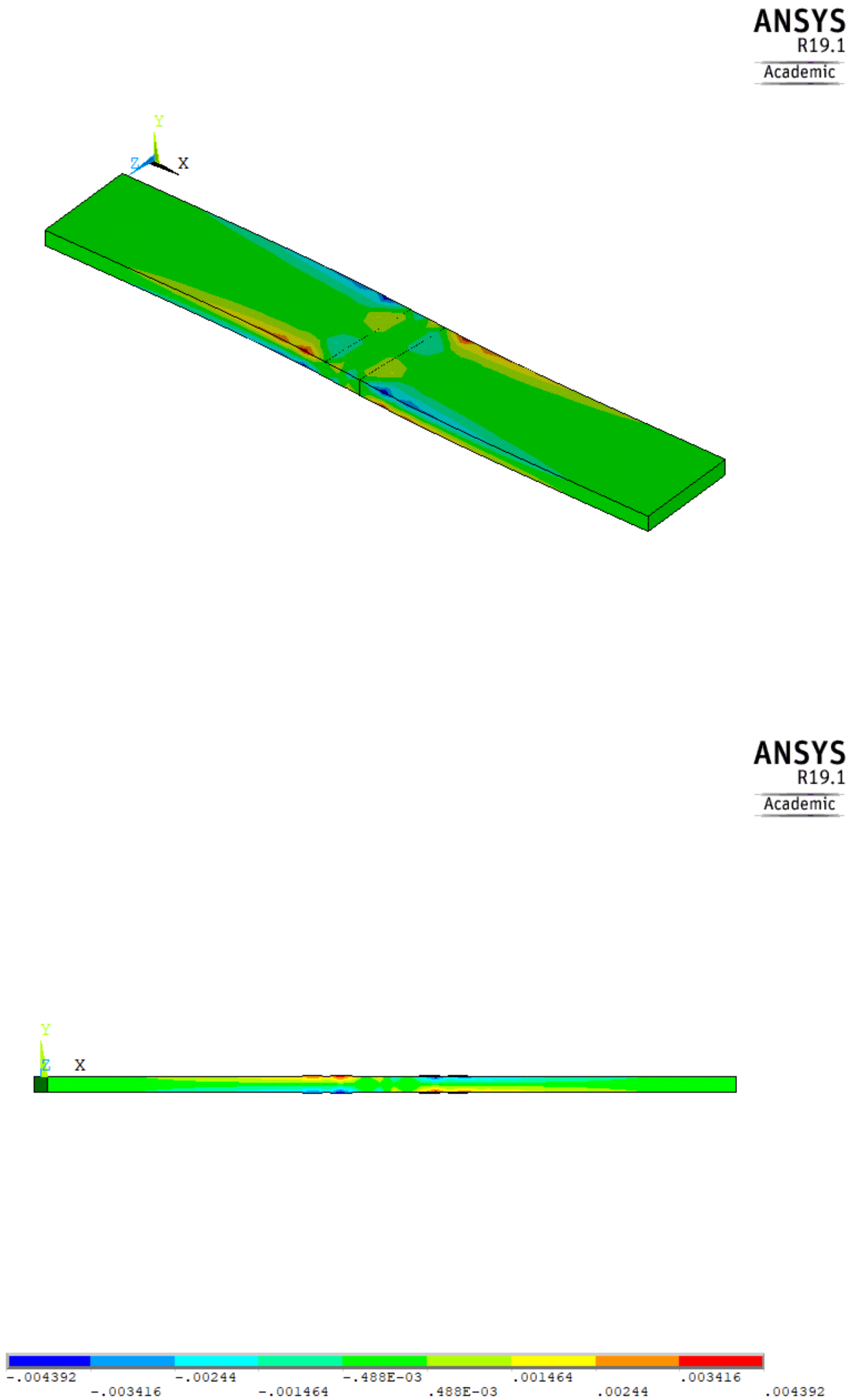

Figure 5.6: Second Mode Shape at 922.17Hz (500D)

5.3.2 Overview of Steps in a Harmonic Analysis

To perform a harmonic (response) analysis the same set of command has been used similarly to other types of FEA like modal analysis. There are three fundamental methods available which are: the full method, the reduced method, and the mode superposition method. Each method briefly explained below before going through the principal steps of modeling.

The Full Method

Indeed, the full method is the easiest among the other three methods and it is using all system matrices with no reduction to compute the harmonic response. These matrices can be either symmetric or non-symmetric. Some advantages of this method are:

- As there is no need to choose mode shapes or master DOF, it is easier respect to the other methods to use.
- No matrix estimation is concerned because full matrices consider in this method.
- Non-symmetric matrices can define by this method, which are common for some applications such as bearing and acoustics problems.
- All stresses and displacements can consider in a single pass.
- All loads type such as nodal forces, elements loads (temperatures and pressures), and imposed displacements are defined and acceptable.

However, there is also some disadvantage for this method, for instance, there is no activate prestressed mode, or in case of using the frontal solver[4] this method is more expensive than others. Despite that, it is very efficient when JCG or ICCG solver is using.

The Reduced Method

Generally, the reduce method is using to shorten the problem size by considering a master DOF and reduced matrices. Some advantages of this method are:

- Compare to the full method, it is faster especially when using the frontal solver.
- It considers the prestressed effects.

In addition, there is some disadvantage for this method which are:

- The initial solution just compute the displacements.
- Element loads like temperature, pressures, etc. cannot apply.

[4] A frontal solver is a technique for solving sparse linear system that is using widely in FEA. Indeed, it is a Gauss elimination variant that spontaneously neglects the operations which concern zero terms.

The Mode Superposition Method

This method is the one also used for the harmonic response analysis of this research. It sums eigenvectors (mode shapes) from the modal analysis for computing the structural response. The advantages are:

- This method is faster and less expensive than other two methods.
- The elements loads which apply in the modal analysis can consider in harmonic analysis too.
- It enable to be clustered the structural frequencies which allows to have more smoother and accurate results.
- It considers the prestressed effects.
- Modal damping and damping ratio (as a frequency function) can apply.

The only disadvantage for this method is that imposed displacements cannot defined or applied.

The harmonic analysis procedure has three essential steps which are:

1. Build the model
2. Employ the load and obtain the solution
3. Review and examine the results

Build the Model

The procedure for building a model is the same as the one explained before for modal analysis.

Employ the load and obtain the solution

For this step, similar to the modal analysis, the type of the analysis, the loads that applied, and the FE solution defined. In advance of obtaining the solution from harmonic response, the structures natural frequencies defined which computed from modal analysis.

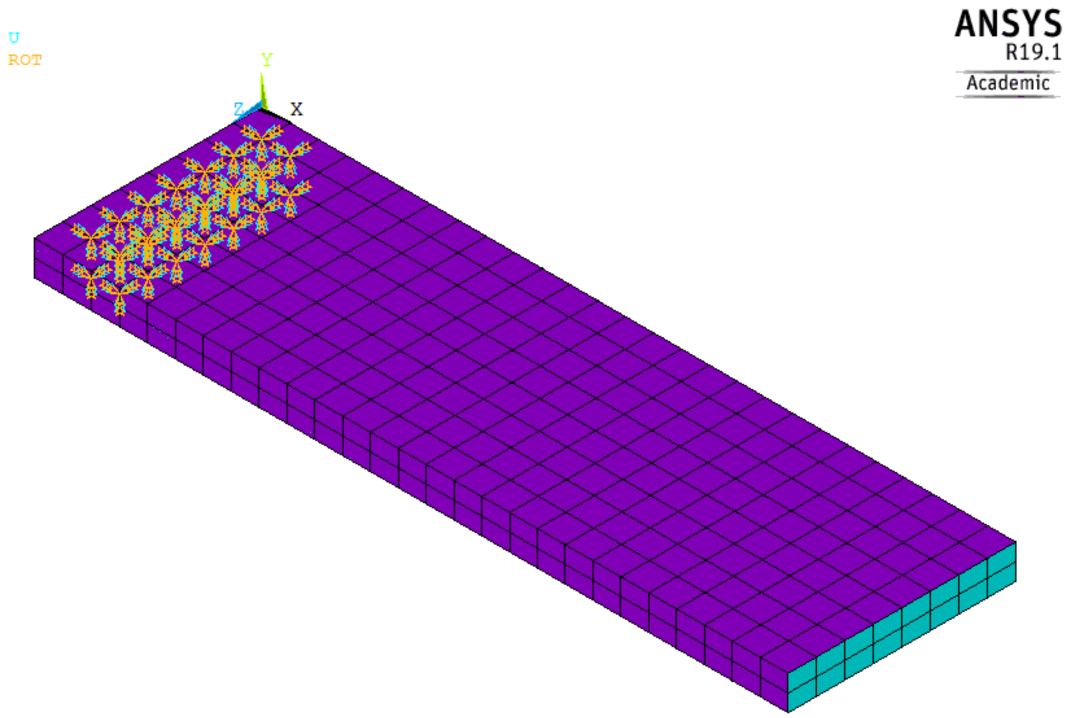

Figure 5.7: Finite Element Model of the Sandwich Specimen (290D).

Review and examine the results

Result from the harmonic response analysis are comprising the data as listed below:

- Primary data:
  Nodal displacement can obtain (UX, UY, UZ, ROTX, ROTY, ROTZ). This data are the one achieved in this research project by applying the harmonic analysis.

- Derived data :
  Nodal and element strains and stresses, Element forces, Nodal reaction forces, and etc. can be obtained.

It should consider that all of the output data are varying harmonically for each individual forcing frequency where the solution was computed. If the damping (damping ratio) define for the structure, the harmonic response will be quite out of the phase. Besides, all the possible results will be saved concerning the real and imaginary terms. To review the results in the harmonic response analysis by using ANSYS, there are two different procedures. The normal procedure is using the POST26 in order to detect the critical forcing frequencies at the maximum displacements, indeed, the POST26 permits a result review around total frequency range and this procedure is the one has been used in this research thesis. Following that, it is convenient to use POST1 to review the results in some specific frequencies.

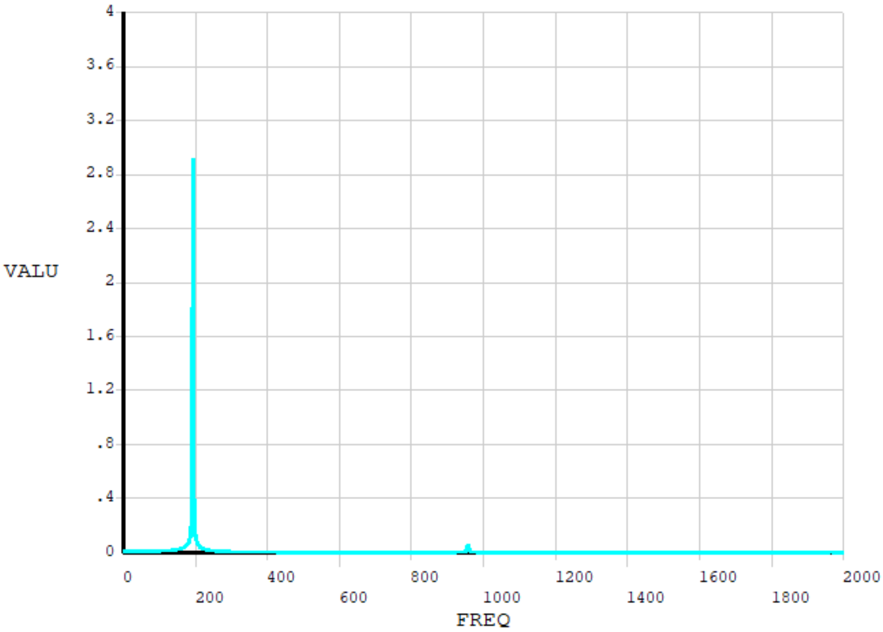

Figure 5.8: Harmonic response analysis for the sandwich specimen (290D-I).

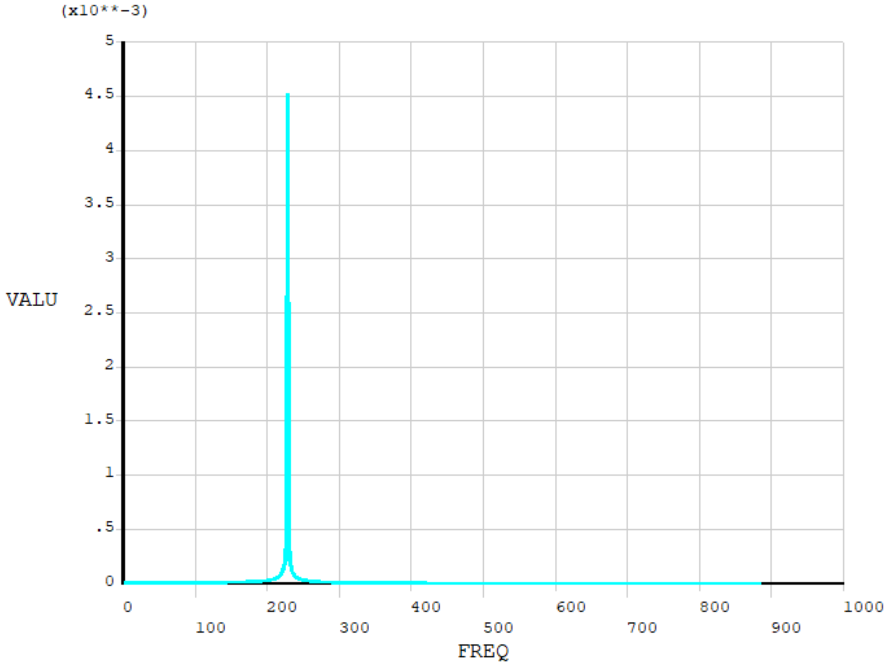

Figure 5.9: Harmonic response analysis for the sandwich specimen (500D-I).

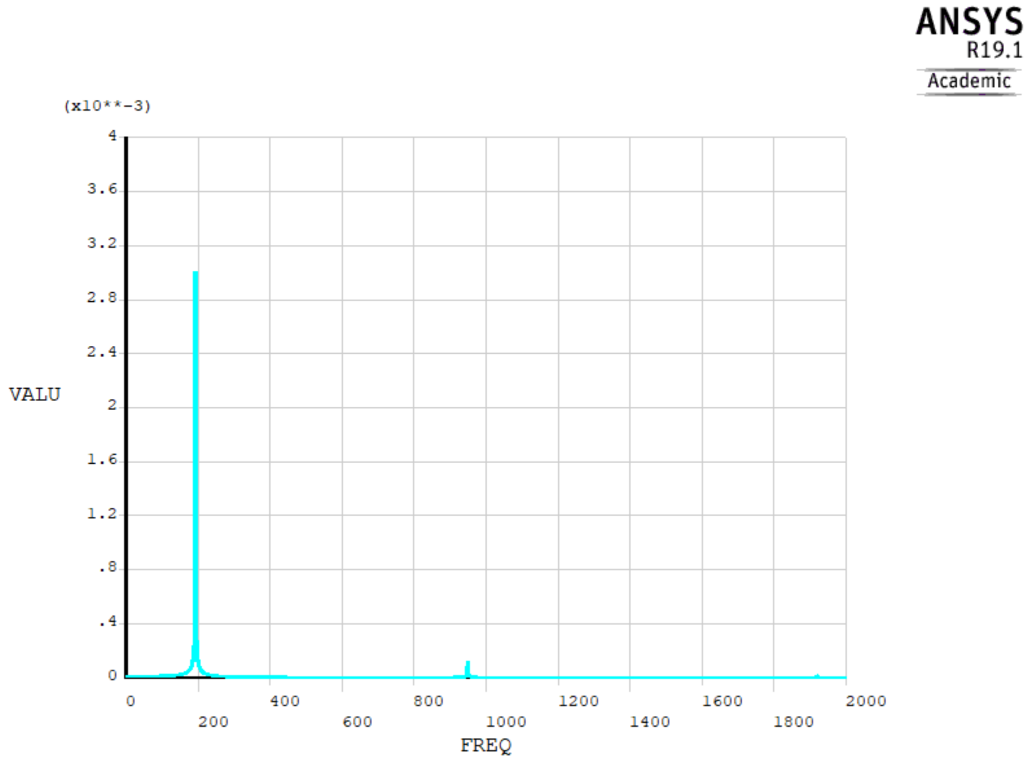

Figure 5.10: Harmonic response analysis for the one-phase sandwich specimen (290D-III).

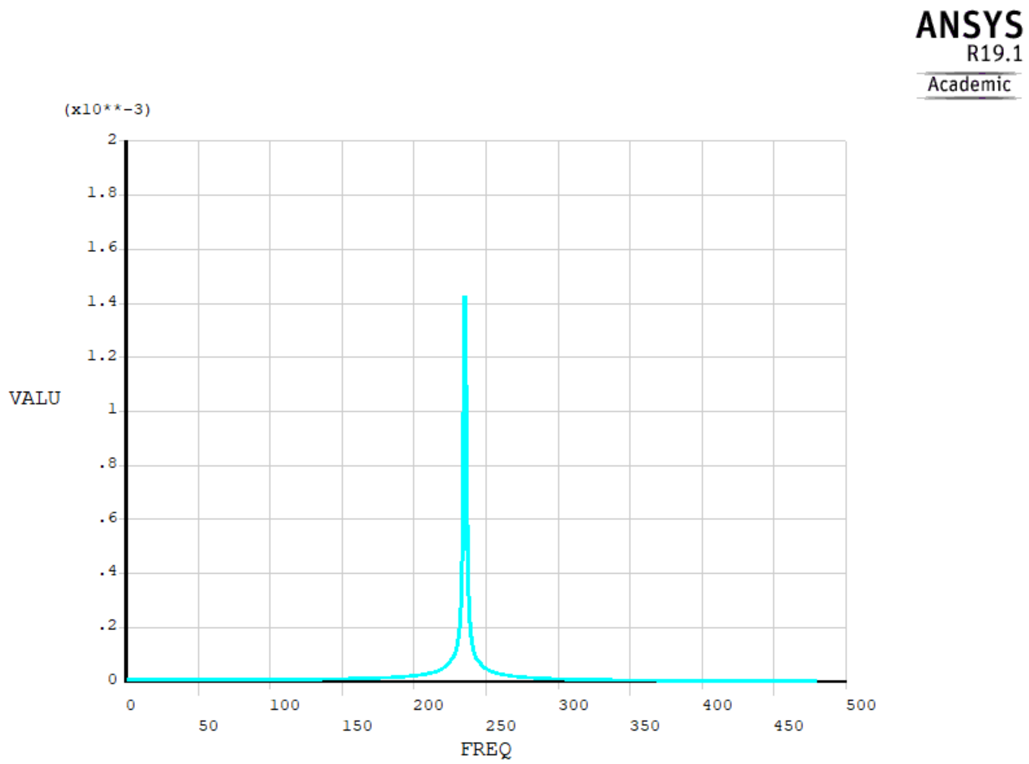

Figure 5.11: Harmonic response analysis for the one-phase sandwich specimen (500D-III).

Chapter 6

Experimental Setup

6.1 Experimental Manufacturing

The specimens which are utilized for this research project comprised of steel foam hollow spheres shown in Figure 6.1, prepared by Hollomet GmbH[1] and coated by thermosetting[2] epoxy Araldite AT1-1[3] which are bonded together to form the core of sandwich configuration surrounded by two mild steel faceplates DC01 [1].

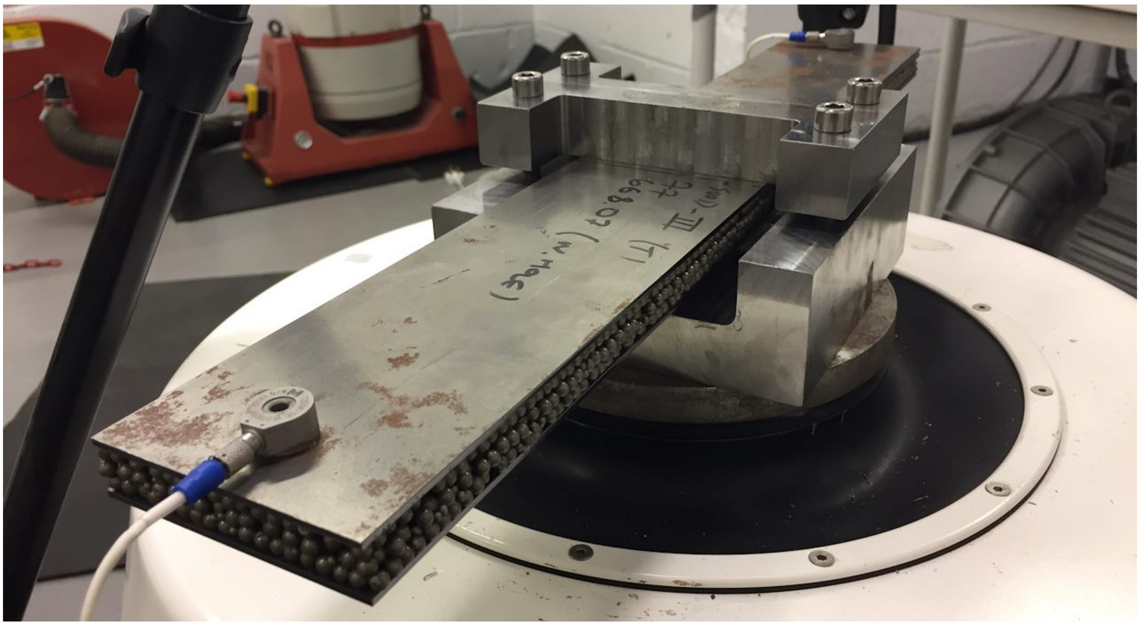

Figure 6.1: Hollomet Specimen

[1]Service Company in Dresden, Germany

[2]The two principal components of a typical composite material are the polymeric resin matrix and the fibrous reinforcement. In the aerospace industry, thermosetting resins are commonly used as one of the major ingredients in a variety of resin matrices.

[3] Araldite AT 1-1 is one component, heat curable, the epoxy adhesive in powder form for use in general industrial applications such as the bonding of abrasive and magnetic powders. Araldite AT 1-1 is solid at room temperature, highly viscous at 70 - 90°C, and a low viscosity liquid at 130 - 140°C. It is cured by prolonged heating at temperatures above 120°C

6.2 Experimental Procedure

On account of increasing the demand of the high-speed operation and utilizing light structures in the modern industries, static analysis and measurement of stress and strain properties are not adequate and sufficient. Furthermore, the vibration testing is required and the dynamic measurements have found extended to use.

In practice, due to the determination of the dynamic properties of the structures vibrational force is more functional than the actual vibration. This concept is found for instance in the determination of the ability to transmit or damp vibrations or In the description of the vibrational modes of a structure at resonances. To generate a vibration and find the dynamic characterization of the samples an electromagnetic vibration exciter (also called a shaker) V400HG/DSA4 of Data-Physics[4] is employed (Figure 6.2).

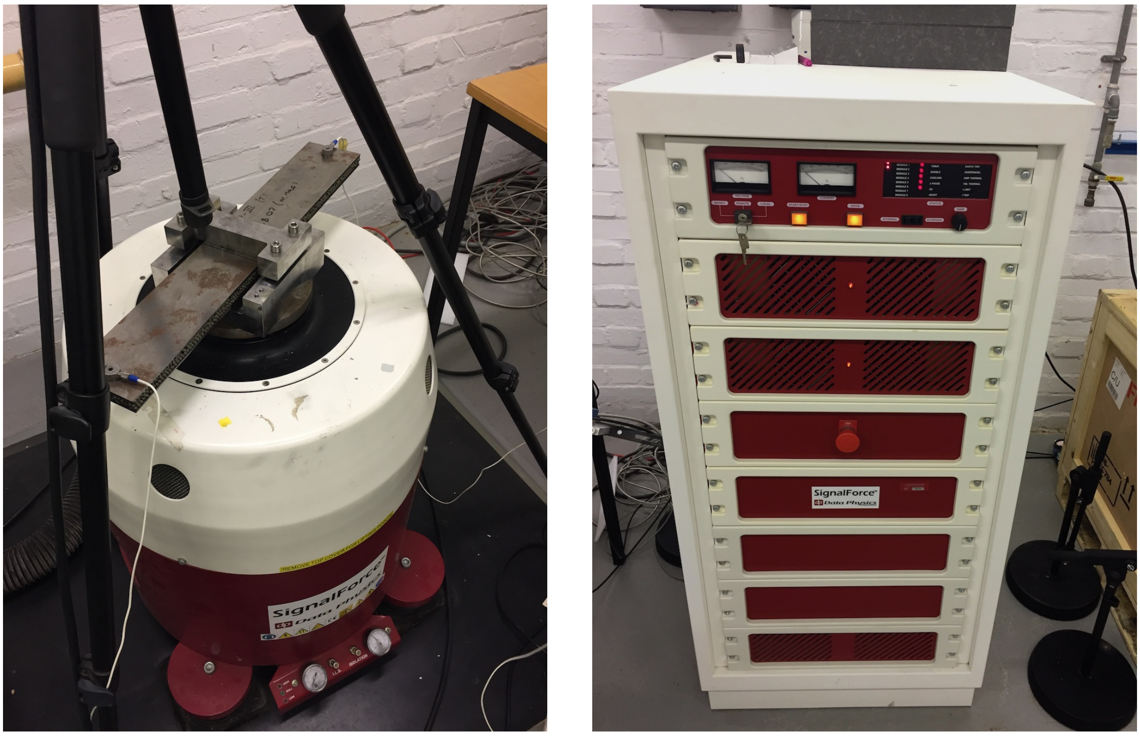

Figure 6.2: Electrodynamics Shaker V400HG/DSA4 of Data-Physics

The closed-loop control of the shaker was provided by a Signal-Star Vibration Controller and the corresponding control software. The signal acquisition has been done using a Polytec OFV-505 laser vibrometer to measure the output on the tip of the specimen and using a PCB piezoelectric accelerometer to measure the shaker feedback signal Figure 6.3. Moreover, the specimen clamped to the shaker table by applying a torque of 20 N.m to hold two blocks and minimize friction damping. The higher stiffness and considerably larger size of the steel blocks with respect to the test specimen minimize structural perturbations [22].

[4]Data Physics is a global supplier of complete vibration test systems including vibration shaker tables, shakers, power amplifiers, slip tables, vibration controllers, and dynamic signal analyzers.

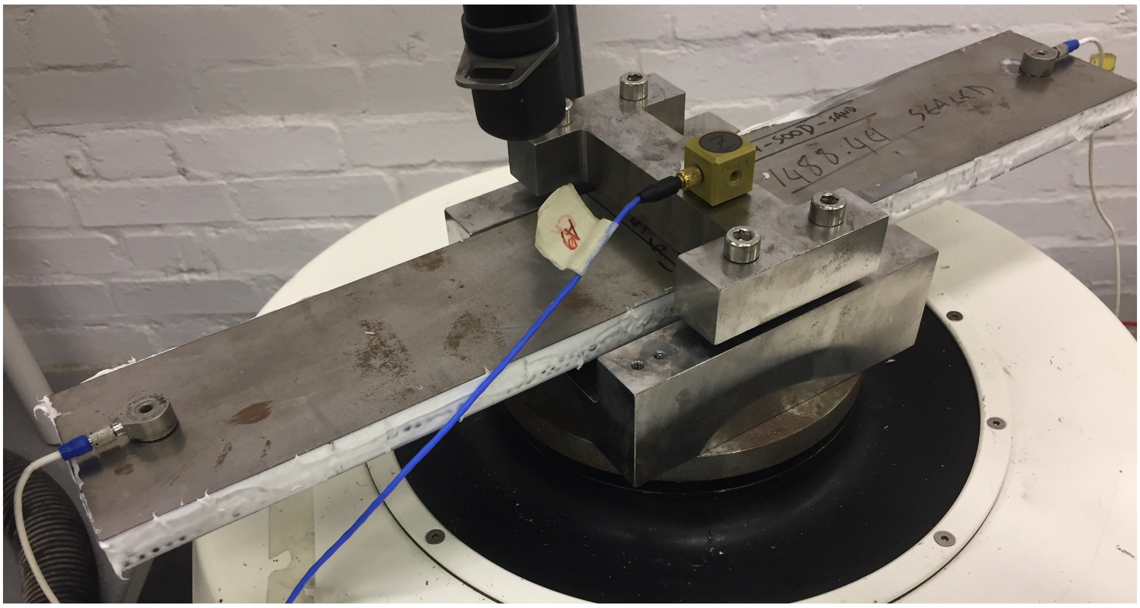

Figure 6.3: The specimen with a PCB piezoelectric accelerometer.

Concerning the type of tests carried out on each specimen, and base on the vibration domain three procedures have been defined using different excitation: a sweep sine, a random noise, and an impact Table6.1. In all the three different tests, it was possible to record both the input and the output signals thus allowing for input-output identification methods. The 500D specimens were in a double cantilever configuration (235mm cantilever span on either side) and the 290D specimens in a single cantilever configuration (240mm cantilever span). The laser vibrometer target was centrally located in the cantilevers.

Understanding the vibration analysis and implementing the right technique is an essential requirement in order to verify the design. The sine sweep vibration test is a kind of the first step for performance verification and particularly, it is using for fatigue analysis and structural dynamics characterization. In the next section the theory of a sine sweep test, test setup, and the experimental result shall be discussed [23].

Table 6.1: Specimen Characterizations and Tests

Specimen code	Length [mm]	Sand Volume [ml]	Sweep sine [Hz]	Random noise [g/Hz]	Impact [g]
SFS4-500D-I	500	N/A	30-500	0.0025	20
SFS4-500D-II	500	N/A	30-500	0.0025	20
SFS4-500D-III	500	0	30-500	0.0025	20
SFS4-500D-IV	500	0	30-500	0.0025	20
SFS4-290D-I	290	N/A	30-500	0.0025	20
SFS4-290D-II	290	0	30-500	0.0025	20
SFS4-290D-III	290	0	30-500	0.0025	20
SFS4-290D-VI	290	N/A	30-500	0.0025	20
SFS4-290D-VII	290	N/A	30-500	0.0025	20

6.2.1 Sine Sweep Testing

Sine Sweep or sinusoidal testing is one of the most common types of vibration test which can apply in the laboratory. Sine sweep testing extends between a low and high range of frequency. The displacement can be constant or even variable and an important note is for a given acceleration the displacement will increase when frequency will decrease. It is possible to determine the resonances with comparing vibration response of the specimens or products to the vibration of the shaker table. Moreover, many different specific tests are applied by using sine sweep vibration testing in order to present the endurance and strength of the samples and products by requiring several sweeps.

The sine sweep analysis usually describes with the amplitude and their frequencies and the test which has been performed in this project has a frequency range between 30 and 500 Hz (frequency range can be between 2 and 10000 Hz). It was not possible to carry out the analysis using the closed-loop[5] feedback strategy due

[5]The two types of control systems, open loop and control loop are entirely different from each other. Open loop is simple and works on the input while the closed loop is complex and works on the output and modifies it.

to the very high response of the specimen. It was thus decided to use an open loop control strategy, setting two acceleration levels at 30 Hz (0.5g and 2g) and then accomplish the test with the constant driving voltage. This modality will create a slight distortion in the output results because the shaker frequency response function is not perfectly flat in the frequency range between 30 and 500 Hz, but measuring the input signal this can be removed by the response.

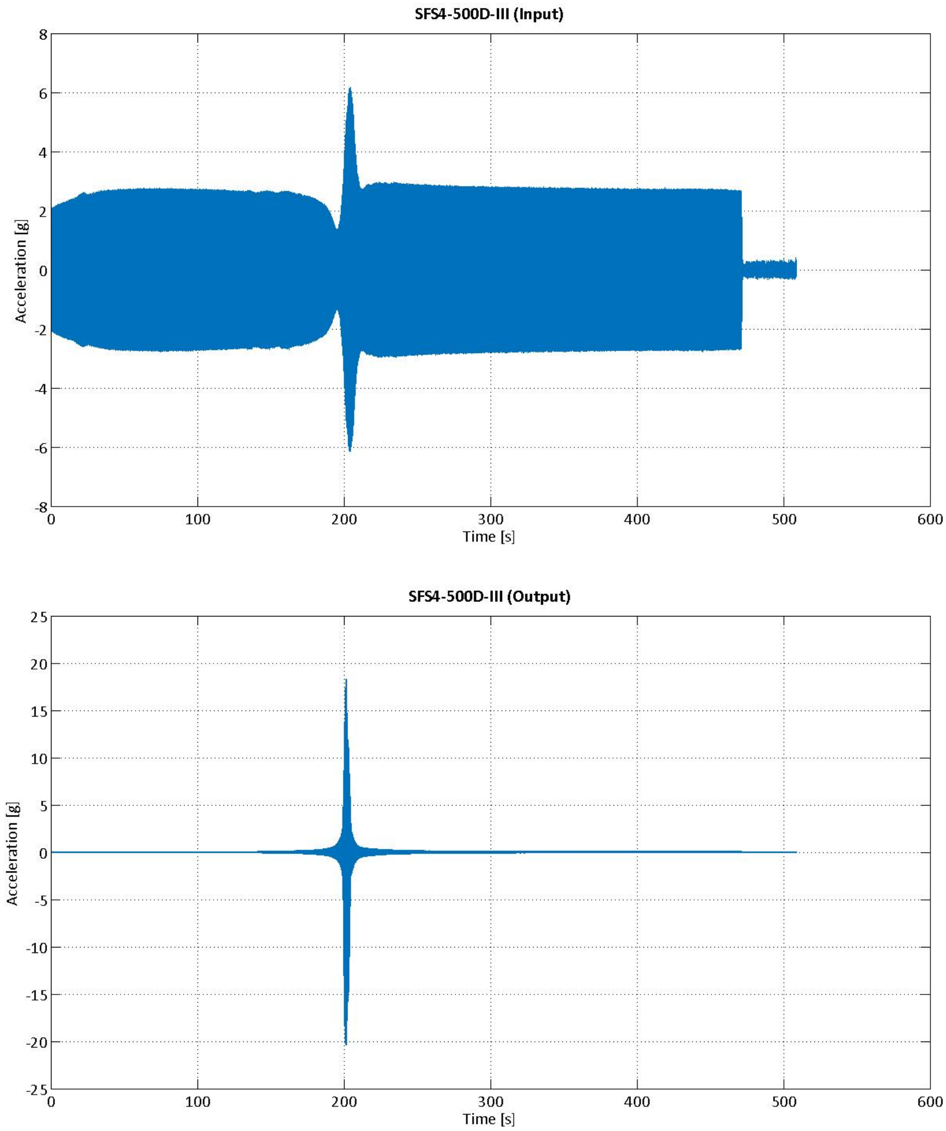

Figure 6.4: Top: the input acceleration, Bottom: time-history signals of the output (Specimen 500D-2g level).

Indeed, sine sweep vibration is applying an individual frequency and optionally excites the structural resonant. In a sweep sine test for a particular rate and time, the sine tone vibration will upraise and down for a specific frequency range. Sine sweep vibration test is an essential and useful way to identify the resonant structures and it is an effective way to understand how the vibrations are propagating throughout the structures. So, it can help engineers to decrease the possibility to have the fatigue with damping or stiffening. This test also has a very significant effect when there are reciprocating structures and they have a substantial sine characteristic.

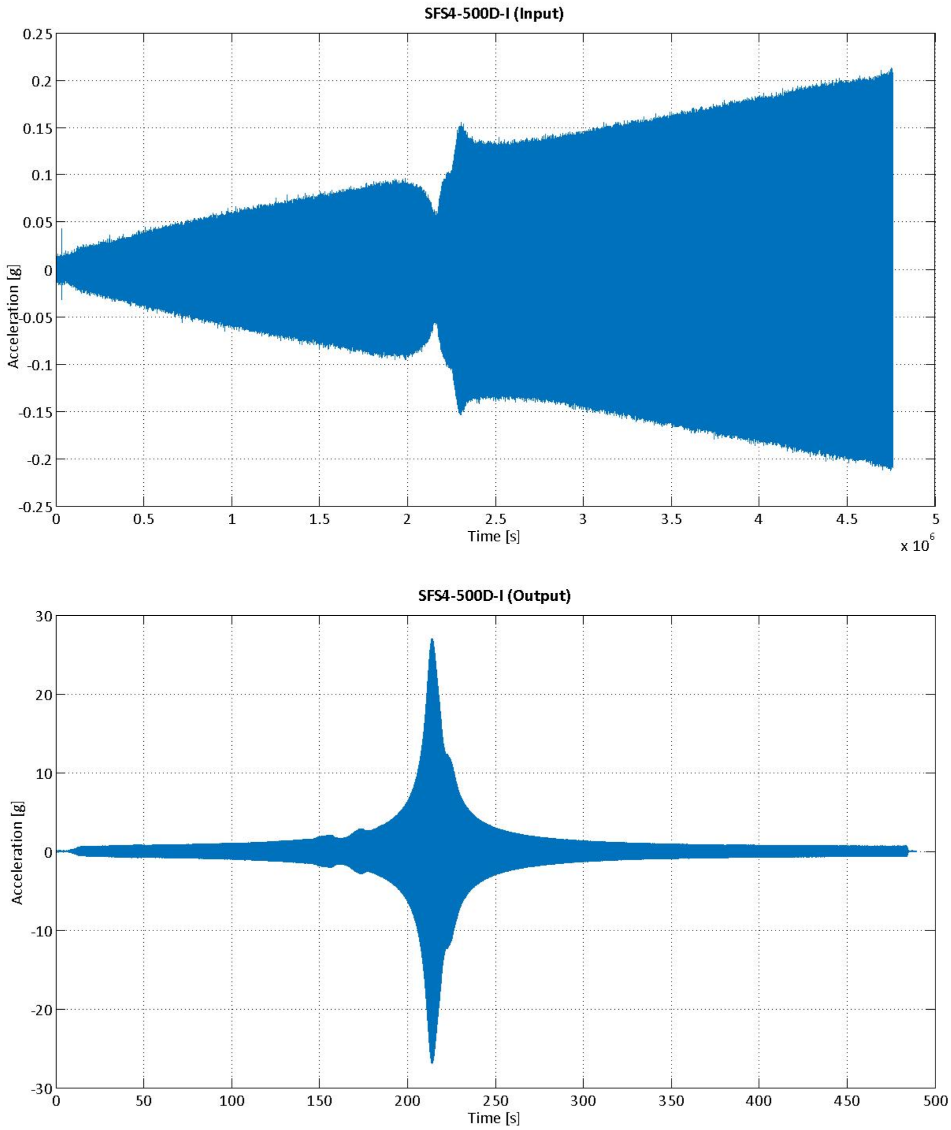

Figure 6.5: Top: the input acceleration, Bottom: time-history signals of the output (Specimen 500D-0.5g level).

6.2.2 Random Noise Testing

Random vibration testing is another common type of vibration test, indeed, vibrations in the real world are random type suchlike vibrations from aircraft, rockets, and automobiles. Random vibration contains all frequencies and all resonances' product will be excited coincidentally On the contrary, in sine sweep test they propose individually. The vibrational frequencies of a specific component which comprise the input signal in order to have a random test integrate in phase and amplitude in order to originate a time waveform that shows on an oscilloscope as the random noise.

Whereas sinusoidal vibration occurs at distinct frequencies, random vibration contains all frequencies simultaneously. Also, phase changes occur over time with random vibration. Sine sweep and random noise vibration testing cannot be equated. According to the Gaussian distribution, random noise signals has a continuous spectrum with varied amplitude. Ordinarily, in a vibration test, it is required to consider the peak-values of the random noise signal three times of the RMS value.

The random noise spectrum is mainly described with its PSD (Power Spectral Density) or ASD (Acceleration Spectral Density) with the unit equal to $(m/s^2)^2/Hz$. To control and shape the spectrum the vibration signals must be analyzed by a narrow band analyzer and also compressor loops must be employed to the individual bandwidth. Digital techniques based on Fourier transforms are normally used and the control is achieved using a computer, a process called equalization.

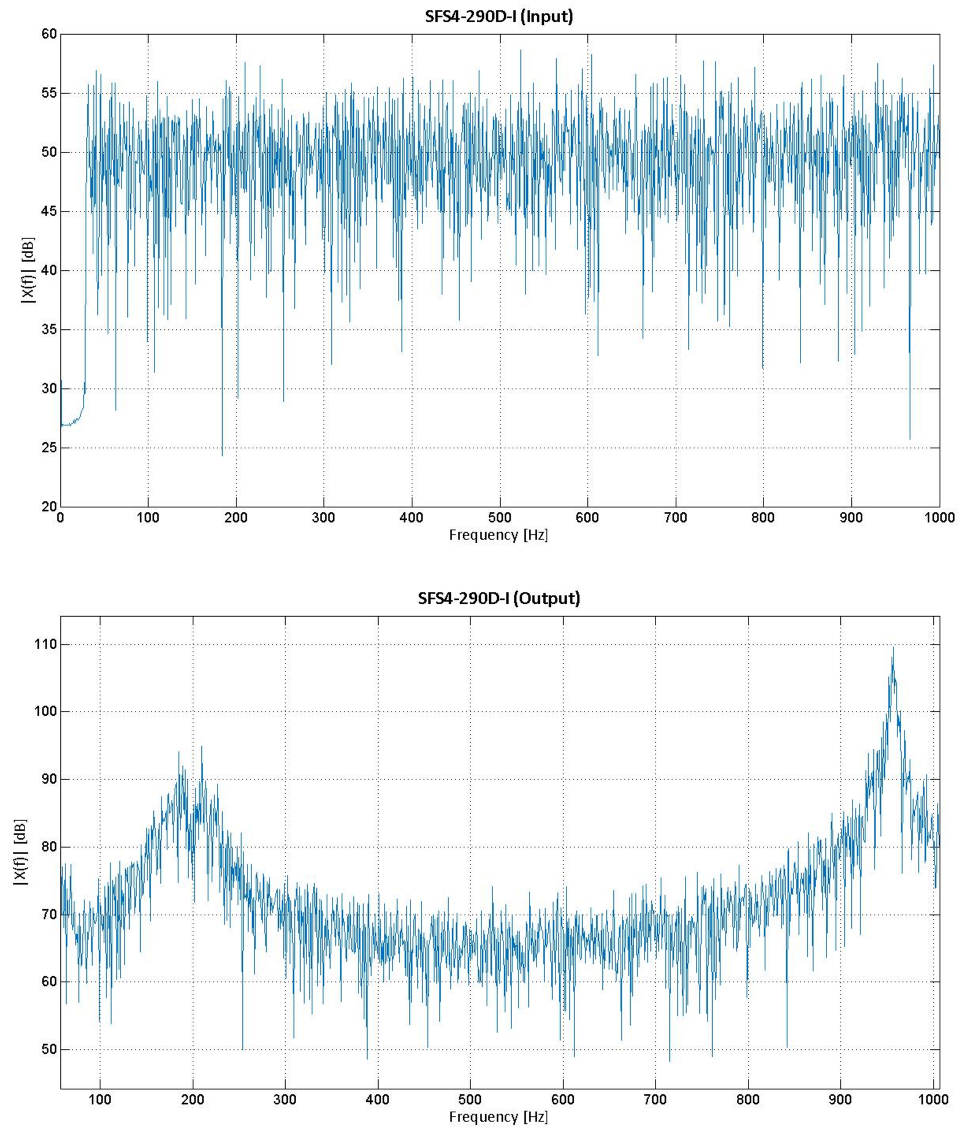

Figure 6.6: Top: Random noise spectrum measured at the feedback accelerometer., Bottom: FFT of the response at the tip of the cantilever beam in dB (Specimen 290D).

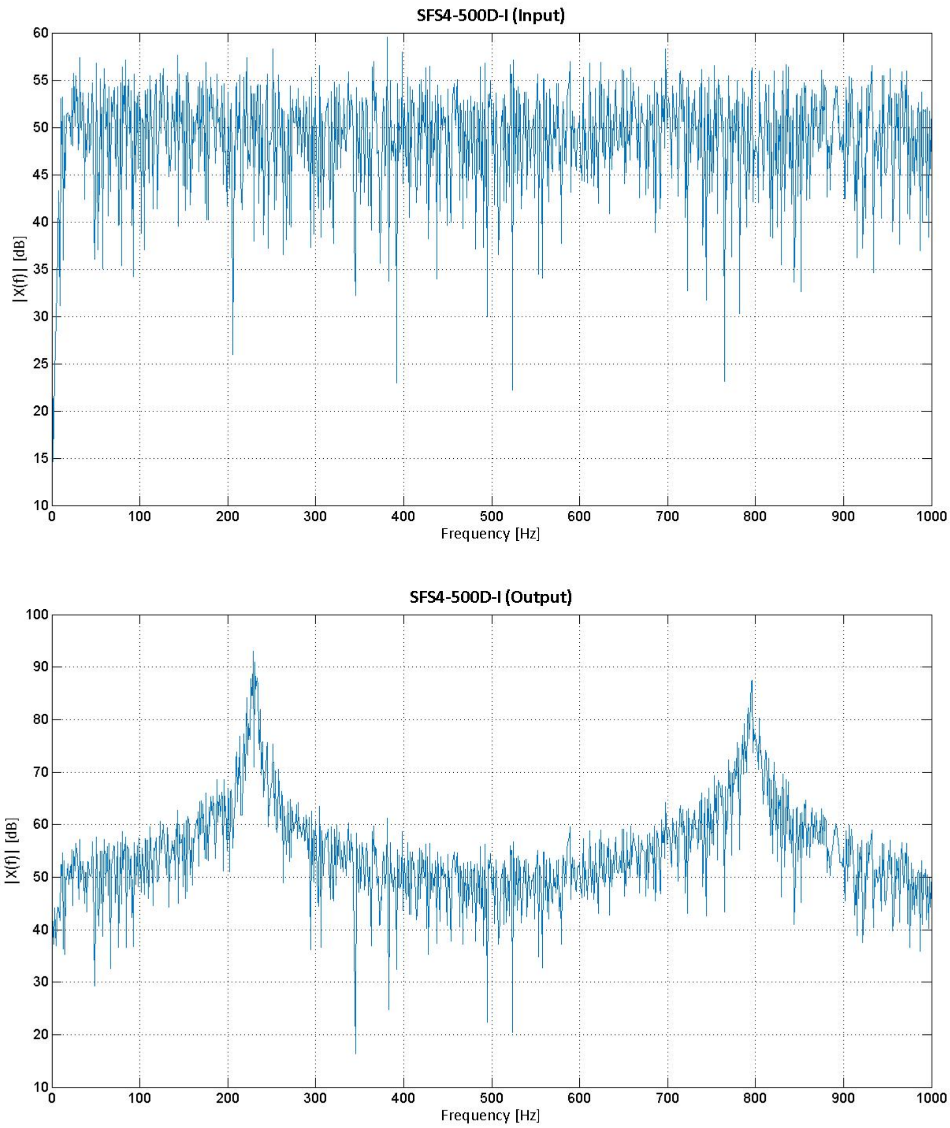

Figure 6.7: Top: Random noise spectrum measured at the feedback accelerometer., Bottom: FFT of the response at the tip of the cantilever beam in dB (Specimen 500D).

The random capacity of an exciter is specified as the maximum acceleration spectral density at different loads of a spectrum, shaped according to the International Standard, ISO 5344.

For what concerns the random noise testing a bandwidth from 30 to 2000 Hz has been selected for the 500 mm samples and of 30 to 2500 Hz for the 290 mm samples. It was chosen to eliminate very low frequencies from the input (below 30 Hz) to minimize the shaker displacements. No relevant modes are present at those low frequencies, so it was an appropriate assumption. The root means square amplitude of the random noise was set to 0.0025 g/$\sqrt{\text{Hz}}$.

6.2.3 Shaker Impact Testing

The shaker impact procedure was defined with a trial and error approach. The final parameters selected were a half-sine impact profile, with a time length of 3 ms and a peak-amplitude of 20g. The laser vibrometer thus recorded a free-decay response of the specimen to this impact. The feedback accelerometer recorded the input signal.

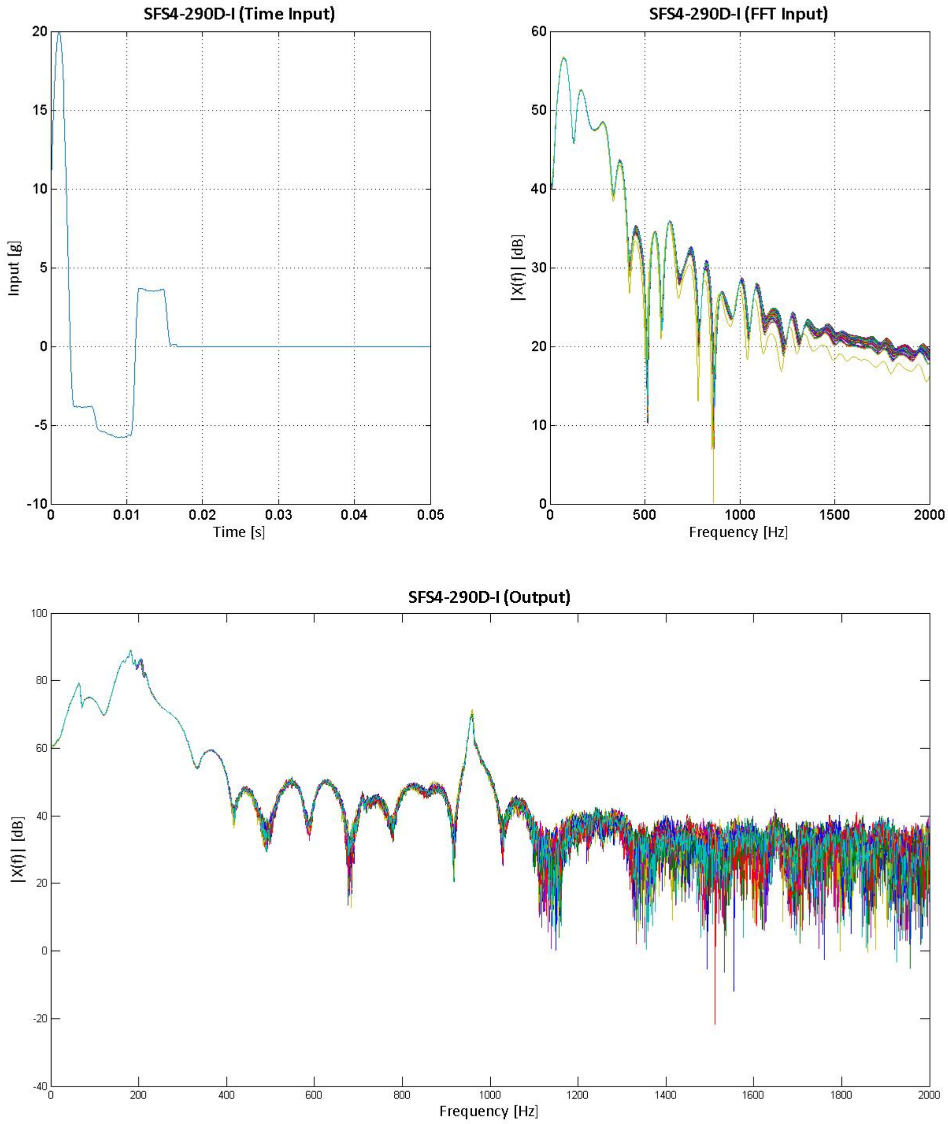

Figure 6.8: Top: Random noise spectrum measured at the feedback accelerometer., Bottom: FFT of the response at the tip of the cantilever beam.

6.2.4 Data Acquisition and Processing

The acquisition set up for all the different test has been applied the same. For this processing, a National Instrument data acquisition NI-9234[6] has been considered. The signals were recorded using a specific software LabView[7] which was set at the sampling frequency of 10240 Hz.

[6]The NI 9234 is a four-channel dynamic signal acquisition module for making high-accuracy measurements from IEPE sensors. The NI 9234 delivers 102 dB of dynamic range and incorporates integrated Electronics Piezoelectric (IEPE) signal conditioning at 2 mA constant current for accelerometers and microphones. The four input channels simultaneously acquire at rates up to 51.2 KS/s. In addition, the module includes built-in anti-aliasing filters that automatically adjust to your sampling rate.

[7]Laboratory Virtual Instrument Engineering Workbench is a system design platform and development environment which offers a graphical programming approach that helps to visualize every aspect of the various application, comprising hardware configuration, measurement data, and debugging.

Chapter 7

Results

FRF fitting model has been considered for two different samples along with the different range of frequencies, in the range 0-2000Hz for the specimen 500D and 0-2500Hz for the specimen 290D. Since the results achieved by finite element model optimization, damping ratio has been obtained (Table 7.1) with experimental results comparison from random noise test.

The experimental results for the cantilever specimen (290D) presents a superb correlation with the finite element (analytical) results with 2-3% difference for the first and second mode shapes in random noise test (Figure **??**), whereas, the double cantilever specimen (500D) indicates a sufficient results by representing 3-5% difference for the first mode shape and with 10-15% difference for both mode shapes based on the identical test (Figure **??**).

The results based on the final damping ratio for each samples are listed in the table 7.1.

Table 7.1: Random Noise Results

	Frequency [Hz]	Damping [%]	Frequency [Hz]	Damping [%]
SFS4-500D-I	227.70	0.249	793.90	0.150
SFS4-500D-II	243.60	0.267	871.90	0.150
SFS4-500D-III	231.80	0.220	808.50	0.120
SFS4-500D-IV	248.70	0.150	838.60	0.067
SFS4-290D-I	190.60	0.100	956.10	0.020
SFS4-290D-II	250.90	0.015	1039.10	0.002
SFS4-290D-III	193.40	0.015	955.20	0.002
SFS4-290D-VI	193.70	0.055	870.40	0.021
SFS4-290D-VII	156.20	0.070	902.00	0.020

On average, the damping ratio of the first natural frequency for the single-phase specimen is 0.015% and 0.17% respectively for the specimen 290D and 500D. Regarding to the two-phase sandwich core the average damping ratio increased to 0.07% for the specimen 290D and 0.26% for the specimen 500D.

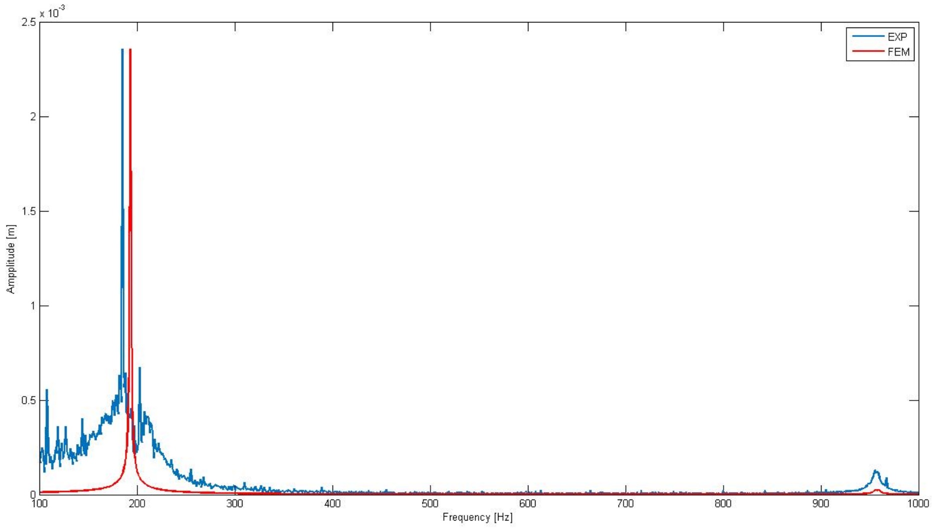

Figure 7.1: FEm vs. EXP results (Specimen 290D).

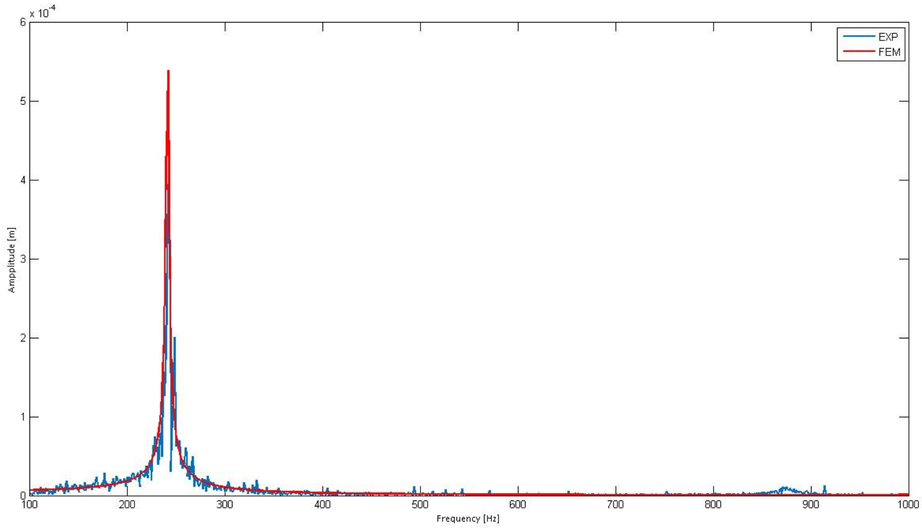

Figure 7.2: FEm vs. EXP results (Specimen 500D).

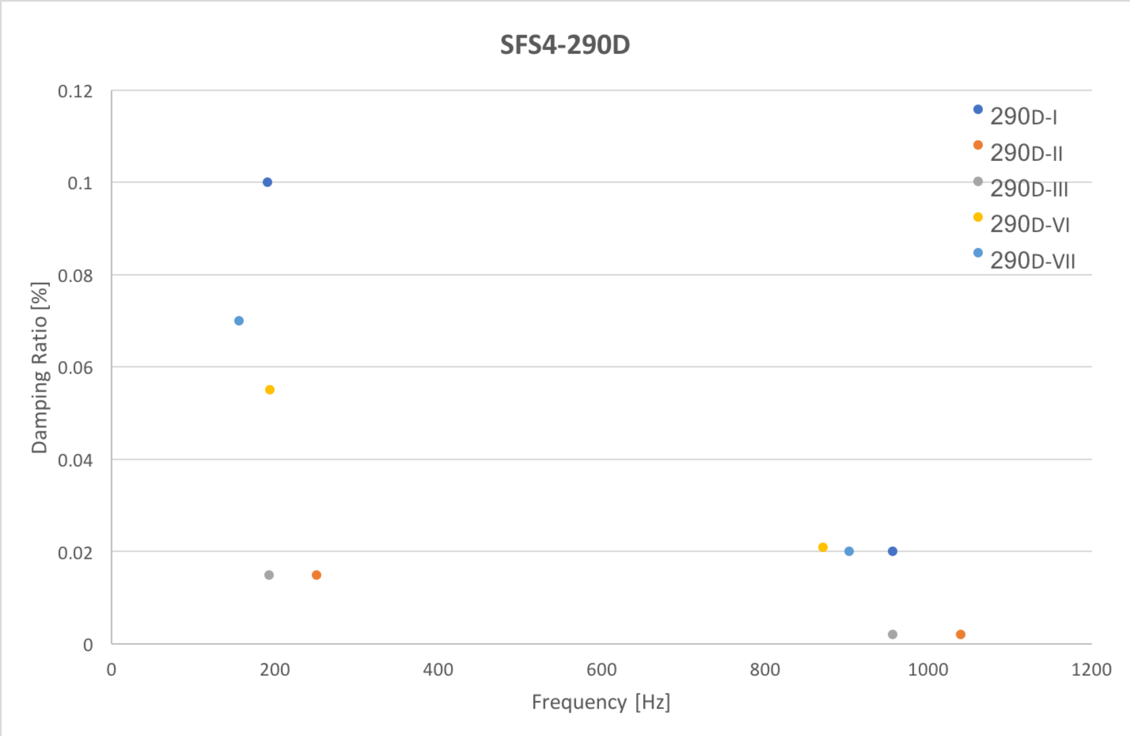

Figure 7.3: Damping ratio [%] vs. Frequency [Hz] for all 290D samples.

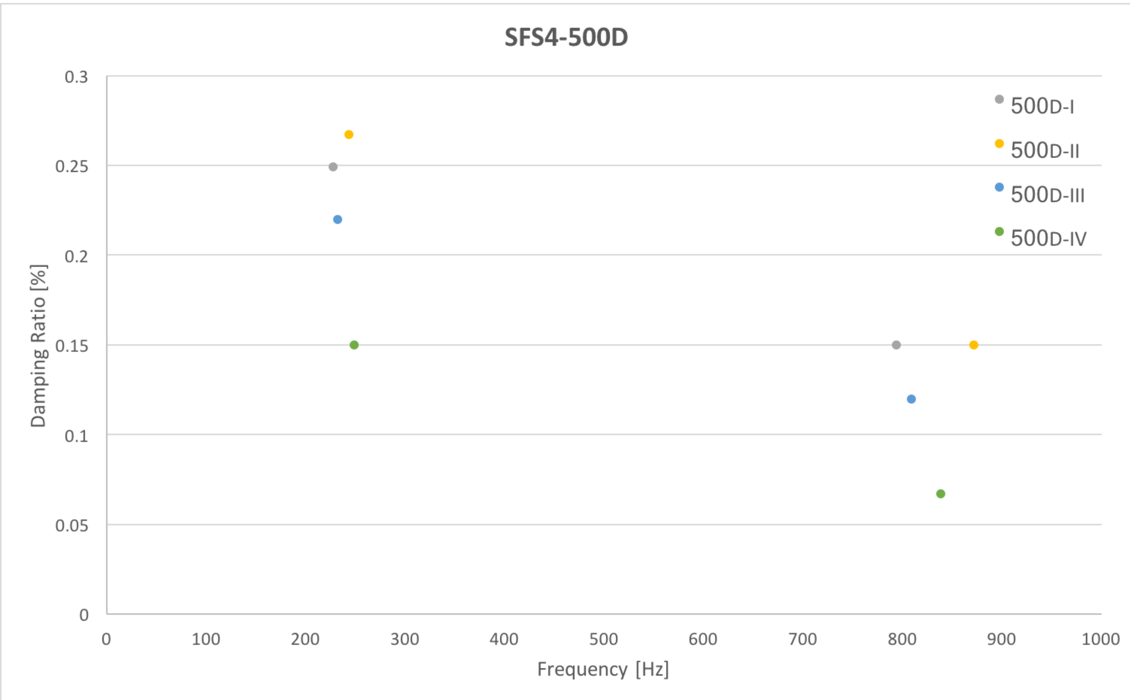

Figure 7.4: Damping ratio [%] vs. Frequency [Hz] for all 500D samples.

Chapter 8

Conclusion

This research thesis was an experimental examination for the purpose of evaluating the light metallic (steel) foam sandwich structure to behave as a passive damping. In order to achieve that, three different experimental test were used to analyze the particular steel foam structure in a single-phase core along with a double-phase core. Moreover, the output frequency result of 'Random Noise Test' compared with the analytical model which made by ANSYS. In the final part, the damping ratios for different specimen has been computed and for the first resonant frequency the ratio is increasing regarding to have two-phase sandwich core for both 290D and 500D samples.

On average, the damping ratio of the first natural frequency for the single-phase specimen is 0.015% and 0.17% respectively for the specimen 290D and 500D. Regarding to the two-phase sandwich core the average damping ratio increased to 0.07% for the specimen 290D and 0.26% for the specimen 500D.

Chapter 9

Future Work

In this chapter, the possible future researches either in the laboratory or industrial scale provided. Apparently, researches about composite materials in different sectors are growing surprisingly. This high demand occurs on account of new challenges.

Advanced composite materials based on the current research work or thousands of others have the capability to substitute by expensive existence steel components and materials. Recently, the main composite material usage in marine structures are in the pipeline repairs or fabrications. However, there are new research area which is going to target offshore facilities and structures is the Auxetic composite material that commands a negative Poisson's ratio based on its complex structure and rare deformation behavior and mechanism [30].

To predict the future request for composites, oil and gas leading company Aramco has signed a contract with TWI Ltd[1] and National Structural Research Center to build a new non-metallic innovation center in order to develop new technologies and applications.

Further research work is in the unique aerospace industry. In fact, the primary work and development for multi-functional structure technologies was based on the U.S. military and fabulous NASA (National Aeronautics and Space Admin) together. The first multi-functional structure was made on NASA especial program for Deep Space 1 Spacecraft. The multi-functional electronic structure in this project caused 50-80 percent reduction in mass and volume and this step was the reason of high demand of the multi-functional structures in all industrial areas.

[1] research and technology organization located in Cambridge

Bibliography

[1] S. Yiatros, I. Petrunin, L. Zanotti Fragonara F.P. Brennan. Experimental investigation of vibration damping in steel foam sandwich structures, Institution of Structural Engineers Research Fund, 2017

[2] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson and H.N.G. Wadley. Metal Foams: A Design Guide, 2000.

[3] Qiang Zhang, Yingfei Lin, Haitao Chi, Jing Chang, Gaohui Wu. Quasi-static and dynamic compression behavior of glass cenospheres, Composite Structures, 2017.

[4] J.L. Yu , J.R. Li, S.S. Hu. Strain-rate effect and micro-structural optimization of cellular metals, Mechanics of Materials, 2005.

[5] Lin Jing, Fei Yang, Longmao Zhao. Perforation resistance of sandwich panels with layered gradient metallic foam cores, Composite Structures, 2017.

[6] Francisco García-Moreno. Commercial Applications of Metal Foams: Their Properties and Production, Materials, 2016.

[7] Andrzej Katunin. Vibration-based spatial damage identification in honeycomb-core sandwich composite structures using wavelet analysis, Composite Structures, 2014.

[8] B.H. Smith, S. Szyniszewski, J.F. Hajjar, B.W. Schafer, S.R. Arwade. Steel foam for structures: A review of applications, manufacturing and material properties, Constructional steel research, 2011.

[9] J. Muriel, A. Sánchez Roa, W. Barona Mercado1 and H. Sánchez Sthepa. Steel and gray iron foam by powder metallurgical synthesis, 2009.

[10] Kenneth Kremer, Anthony Liszkiewicz, James Adkins. Development of Steel Foam Materials and Structures, 2004.

[11] A. Rabiei, L.J. Vendra. A comparison of composite metal foam's properties and other comparable metal foams, Materials Letters, 2008.

[12] W.S. Sanders, L.J. Gibson. Mechanics of hollow sphere foams, Materials Science and Engineering, 2002.

[13] Di Miao, Afsaneh Rabiei. Introduction of a new type of metal foam, Procedia Materials Science, 2014.

[14] Louis-Philippe Lefebvre, John Banhart, David C. Dunand. Porous Metals and Metallic Foams: Current Status and Recent Developments, Advanced Engineering Materials, 2008.

[15] Weiwei Xiao, Li Li, Sheng Lei. Accurate modal superposition method for harmonic frequency response sensitivity of non-classically damped systems with lower-higher modal truncation, Mechanical System and Signal Processing, 2016.

[16] Mark Richardson, Brian Schwarz. Modal Parameter Estimation from Operating Data, Sound and Vibration, 2013.

[17] Massimo Goletti, Valerio Mussi, Andrea Rossi, Michele Monnob. Procedures for damping properties determination in metal foams to improve FEM modeling, Procedia Materials Science, 2013.

[18] Jerry G. Williams. Composite Material Offshore Corrosion Solutions, International Workshop on Corrosion Control of Marine Structures and Pipelines, 1999.

[19] Martin Williams. Structural Analysis, Oxford University, United Kingdom, 2016, CRC Press Taylor Francis Group.

[20] A. Treviso, B. Van Genechten, D. Mundo, M. Tournour. Damping in composite materials: Properties and models, Composites Part B, 2015.

[21] C. Cai, H. Zheng, M. S. Khan and K. C. Hung. Modeling of Material Damping Properties in ANSYS, Defense Systems Division, Institute of High Performance Computing, 2002.

[22] Emanuele Lamanna, Nikhil Gupta, Paolo Cappa, Oliver M. Strbik, Kyu Cho. Evaluation of the dynamic properties of an aluminum syntactic foam core sandwich, Journal of Alloys and Compounds, 2016.

[23] Eric Sauther. Sine Sweep Vibration Testing for Modal Response Primer, Department of Optical Sciences, University of Arizona, 2016.

[24] John Banhart. Manufacture, characterisation and application of cellular metals and metal foams, Progress in Materials Science, 2001.

[25] Cheon-Hong Min, Sup Hong, Soo-Yong Park, Dong-Cheon Park. Sensitivity-based finite element model updating with natural frequencies and zero frequencies for damped beam structures, International Journal of Naval Architecture and Ocean Engineering, 2014.

[26] V. Rizov, A. Shipsha, D. Zenkert. Indentation study of foam core sandwich composite panels, Composite Structures, 2005.

[27] John Banhart. Metal Foams—from Fundamental Research to Applications, Frontiers in the Design of Materials, 2007.

[28] John Banhart. Metal Foams—from Fundamental Research to Applications, Frontiers in the Design of Materials, 2007.

[29] J. Banhart, J. Baurneister, M. Weber. Damping properties of aluminium foams, Materials Science and Engineering, 1995.

[30] Naveen Ravirala, Paul Jukes. Advanced Composite Structures for Subsea Pipeline Design Development, International Society of Offshore and Polar Engineers, 2017.

[31] Monica Carfagni, Edoardo Lenzi and Marco Pierini. THE Loss factor as a Measure of Mechanical Damping, University of Florance, 2007.

[32] Jean-Marie Berthelot, Youssef Sefrani. Damping analysis of unidirectional glass and Kevlar fibre composites, Composites Science and Technology, 2003.