

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**IMPACT ANALYSIS OF THE STEPPED CONCENTRIC CRASH TUBES: THE
EFFECT OF THE NUMBER OF TUBES**

M.Sc. THESIS

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Department of Aeronautical and Astronautical Engineering

Aeronautical and Astronautical Engineering Programme

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**KADEMELİ VE EŞ MERKEZLİ ÇARPIŞMA KUTULARININ ANALİZİ: TÜP
SAYISININ ETKİSİ**

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To Eda Kılınçarslan and my family,

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May 2015

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ABBREVIATIONS

ADINA	: Automatic Dynamic Incremental Nonlinear Analysis
ANSYS	: Analysis System
J	: Joule
kg	: Kilogram
LS DYNA	: Livermore Software Dynamic
m	: Meter
min	: Minute
N	: Newton
s	: Second
SEA	: Specific Energy Absorption
SPC	: Single Point Constraint
t	: Time

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IMPACT ANALYSIS OF THE STEPPED CONCENTRIC CRASH TUBES: THE EFFECT OF THE NUMBER OF TUBES

SUMMARY

In this study, stepped concentric crash tubes with circular AL6063 material are investigated using experimental and numerical methods. Crash tubes are used generally in automotive industry to as a passive safety component. In this study, feasibility of crash tubes in different areas are sought. So, it is designed almost ten times smaller than the conventional car crash tubes.

The purpose of this study is to examine the energy absorption characteristics of stepped concentric crash tubes subjected to an axial impact load. The peak forces, internal energy and the total deflection are the selected parameters for the comparison of various crash tubes. The stepped concentric tubes have different lengths and different diameters, while the total mass and volume are kept constant. The area of the impacting object is taken as greater than the internal tube's cross sectional area to prevent passing the impacting object through the tube hole.

First of all, a comprehensive study about articles on crash tubes presented. Almost 127 scientific articles are reviewed and tabulated information according to solution methods, geometry, material properties, impact velocity and impact mass properties. Table is given in Appendices section.

In the next part, one selected model with AL6063 material is fabricated and tested at dynamic and quasi-static velocities. Dynamic tests are done by using INSTRON 8150 Drop Test Machine and quasi-static test is done by using MTS 647 Hydraulic Test Machine. Then, results of experiments compared and validated with results of analysis by using LS-DYNA, an engineering simulation software program.

In the second part, the effects of the number of the tubes and impact velocity are studied at high dynamic velocities by using LS-DYNA software program. To define optimal mesh quality, results of five different mesh sizes of a sample are investigated and chosen the most proper type of them to use in all analyses. After that, four different models are constituted with 3, 6, 9 and 12 stepped concentric tubes, respectively. All samples are analyzed at three different velocities: 50, 60 and 70 m/s and results are compared with one another.

In the third part, stepped concentric crash tubes are modelled with aluminum foam and analyzed at 50 m/s impact velocity. Results of model with foam filled and empty tubes are compared and studied to demonstrate the advantages and disadvantages of foam material. All graphics are established using GRAPHER software program.

KADEMELİ VE EŞ MERKEZLİ ÇARPIŞMA KUTULARININ ANALİZİ: TÜP SAYISININ ETKİSİ

ÖZET

Dünya Sağlık Örgütü'nün verilerine göre her yıl dünya genelinde bir milyon üzerinde insan trafik kazalarında hayatını kaybetmektedir. 2010 yılına ait verilerde 1.24 milyon insanın hayatını kaybettiği ve 20-30 milyon insanın ölümcül olmayan yaralanmalara maruz kaldığı belirtilmiştir. Bu nedenle yolcu ve sürücülerin güvenliğinin sağlanması ve araçta oluşan hasarın en aza indirilmesi için çok sayıda bilimsel çalışma yapılmıştır. Bu amaçla geliştirilen donanımlardan birisi de otomobillerde tampon ve şase arasına yerleştirilen ezilme kutularıdır.

Ezilme kutuları üzerine yapılan çalışmalarda iki önemli parametre ön plana çıkmaktadır. Bunlar tüplerin enerji emme kapasitesi ve pik kuvvetidir. Ezilme kutuları, çarpışma anında şekil değiştirerek ortaya çıkan kinetik enerjinin bir bölümünün yolcuya ve diğer donanımlara iletilmeden soğurulmasını sağlar. Ayrıca kaza anında oluşan kuvvetlerin ilk anda oluşan kuvvet değeri, diğer kuvvet değerlerinden daha yüksektir. Çarpma anında ortaya çıkan en yüksek kuvvet değeri pik kuvveti olarak adlandırılır. Pik kuvveti ile diğer kuvvetler verileri arasındaki farktan dolayı ivmelenme oluşur ve bu ivmelenme yolcu ile sürücülere zarar verebilmektedir. Zararlı etkinin azaltılması için bu farkın azaltılması gerekir. Ezilme kutularının temel amacı maksimum seviyede enerji emilmesinin yanı sıra pik kuvveti değerlerinin düşürülmesidir.

Enerji emme kapasitesinin yükseltilmesi ve pik kuvvetinin düşürülmesi birbirini olumsuz etkileyen iki prosestir. Yani bir tüpün bir yandan enerji emme kapasitesi artırılmak istenirken, diğer taraftan pik kuvvetleri istenmeyen şekilde artırılabilir. Bu nedenle en ideal ezilme kutularının tasarımı için farklı kesit geometrilerinde, et kalınlıklarda, boylarda ve farklı malzemelerde çok sayıda model geliştirilmiştir. Araştırmalar deneysel, analitik ve sayısal yöntemler kullanılarak yapılmaktadır.

Bu çalışmanın ilk bölümünde ezilme tüpleri ile ilgili kapsamlı bir literatür araştırması yapılmıştır. Ezilme kutuları üzerine yazılan 127 adet bilimsel makaleye ait bilgiler tablolaştırılarak sunulmuştur. Bu çalışmanın amacı ezilme kutuları hakkında çalışma yapmak isteyen araştırmacılara, daha önce yapılmış çalışmaların verilerinin daha kolay incelenebileceği bir kaynak sağlamaktır. Tablonun ilk bölümünde yapılan çalışmalarda kullanılan yöntemler analitik, sayısal ve deneysel olarak sınıflandırılmıştır. İkinci bölümde çarpan kütleinin büyüklüğü ve çarpma hızı bilgileri yer almaktadır. Sonraki bölümde geometri ile ilgili bilgiler yer almaktadır. Kesit geometrileri, et kalınlıkları ve boylarına ait bilgiler tabloda sunulmuştur. Malzeme bilgileri ise bu bölümden sonra gelmektedir. Genellikle alüminyum, çelik ve kompozit malzemeler üzerine yapılan çalışmalar olduğu için bu üç başlıkta sınıflandırma yapılmıştır. Son bölümde ise ezilme tüplerinin konfigürasyon türleri sınıflandırma yapılmıştır. Konfigürasyon tipleri içi boş, köpük dolgulu, tek gözlü ve çok gözlü tüpler olarak sınıflandırılmıştır.

Bu tezin ana konusu kademeli ve eş merkezli iç içe ezilme tüplerinin deneysel ve sayısal yöntemler kullanılarak incelenmesidir. Çalışmanın amacı eksenel darbe yüklerine maruz kalan kademeli eş merkezli ezilme tüplerinin enerji emme karakteristiklerinin değerlendirilmesidir. Pik kuvvetleri, iç enerjiler ve ezilme miktarları incelenen ve çeşitli tüp modelleri için karşılaştırmalarda kullanılan karakteristik özelliklerdir. Testler ve doğrulama analizleri için dairesel kesitli ve AL6063 malzemeli tüpler kullanılmıştır. Diğer analiz çalışmalarında tüpler ve köpük malzeme için alüminyum alaşımı tercih edilmiştir. Numunelerin boyutları otomobillerde kullanılan ezilme tüplerine göre oldukça küçük modellerdir. Bunun nedeni boyutları yeterince küçük ezilme tüplerinin dar bölgelere çok sayıda yerleştirilmeye uygun olması ve uçak ve uzay araçları için de kullanılabilmesi için bir araştırma önerisi olarak ileri sürülmesidir.

Farklı çaplarda ve boylarda iç içe tüpler dıştan içe doğru artan uzunluklarda yerleştirilmiştir. Yerleştirme yapılırken her bir model için en dıştaki tüpün çapı ve en içteki tüpün boyu sabit tutularak farklı tüp sayılarında çeşitli modeller denenmiştir. Numunelerin toplam ağırlıklarının da aynı kalması için kesit kalınlıkları koşulu sağlayacak şekilde her bir model için değiştirilmiştir. Yani farklı numuneler karşılaştırılırken toplam dış hacim ve ağırlıklarının yaklaşık olarak aynı olmasına dikkat edilmiştir.

İlk olarak deneysel çalışmalar ile bu deneysel çalışmaların sayısal yöntemlerle doğrulanması yer almaktadır. Bu çalışma için kademeli eş merkezli iç içe üçlü tüplerden üç adet üretilerek dinamik ve sanki statik hızlarda testleri gerçekleştirilmiştir. Dinamik testler için TÜBİTAK Malzeme Enstitüsü bünyesinde bulunan Instron 8150 Darbe Test Cihazı kullanılmıştır. İki adet numunenin farklı hızlarda dinamik testleri gerçekleştirilmiştir. Üçüncü numune ise İTÜ Uçak ve Uzay Bilimleri Fakültesi Kompozit Yapı Laboratuvarı'nda bulunan MTS 647 Hidrolik Test Cihazı kullanılarak 2 mm/dak basma testine tabi tutulmuştur. Deney sonuçları ile numunelerin ezilme öncesi ve sonrası görselleri karşılaştırmalı olarak sunulmuştur. Yapılan testlerin sayısal yöntemlerle doğrulanması için LS-DYNA'da açık zamanlı çözücü ile dinamik analizler ve kapalı zamanlı çözücü ile de sanki statik analizler yapılarak deney sonuçları ile karşılaştırılmıştır. Deneysel ve sayısal yöntemlerin sonuçları birbiriyle uyumlu olduğu gözlemlenmiş ve sonuçlar karşılaştırmalı olarak sunulmuştur.

İkinci bölümde ise LS DYNA yazılımı kullanılarak farklı tüp sayılarında ve farklı hızlarda dinamik analizler yapılmıştır. İlk olarak ideal mesh kalitesinin belirlenmesi amacıyla farklı mesh kalitelerinde beş farklı model tasarlanarak aynı hızlarda ve darbe yüklerinde analizleri yapılmıştır. Mesh boyutları 0.3x0.3, 0.4x0.4, 0.5x0.5, 0.6x0.6 ve 0.7x0.7 mm olarak belirlenmiştir. Mesh boyutları küçültüldükçe sonuçların birbiriyle uyumlu olduğu ancak analizin gerçekleşme süresinin uzadığı tespit edilmiştir. Sonuçları birbirine benzer olan en küçük iki mesh boyutundan analiz süresi daha kısa olanı seçilmiş ve sonraki tüm analizler buna göre yapılmıştır.

Bu bölümde kademeli eş merkezli ve iç içe üçlü, altılı, dokuzlu ve on ikili dört farklı model incelenmiştir. Her model için en geniş tüpün çapı 20 mm ve en uzun tüpün boyu ise 30 mm olarak belirlenmiştir. Et kalınlıkları üçlü tüplerde 1 mm, altılı tüplerde 0.5 mm, dokuzlu tüplerde 0.3 mm ve on ikili tüplerde 0.25 mm olarak belirlenmiştir. Farklı tüp sayılarında tasarımı yapılan dört farklı modelin 50 m/s hız ve 100 gr çarpma yükü etkisinde analiz sonuçları karşılaştırılarak tüp sayısının enerji

emme karakteristikleri üzerindeki etkileri incelenmiştir. Tüp sayısı artırıldıkça analizin ezilme süresi uzamakta olduğu ve pik kuvvetleri arasındaki farkların azaldığı gözlemlenmiştir.

Dört model için daha sonra farklı hızlarda dinamik analizler yapılarak bu sefer çarpma hızın enerji emme karakteristiklerine etkileri incelenmiştir. 50, 60 ve 70 m/s hızlarda 12 adet analiz yapılarak sonuçlar karşılaştırılmıştır. Dört model için ayrı ayrı farklı hızlara ait “kuvvet–zaman” ve “iç enerji-zaman” grafikleri GRAPHER programı kullanılarak çizdirilmiştir.

Son bölümde ise, kademeli eş merkezli iç içe tüplerin en iç kısmındaki boşluk, alüminyum köpük malzeme ile doldurularak her bir modelin 50 m/s çarpma hızında analizleri yapılmıştır. Tüpler kabuk olarak modellenirken, köpük malzeme katı model olarak tasarlanmıştır. Her bir modelin kuvvet ve iç enerji değerlerinin zamanla değişimleri aynı grafikler üzerinde çizdirilip karşılaştırılarak köpük dolgulu ezilme tüplerinin içi boş tüplere göre farkları incelenmiştir.

Yapılan deneysel ve sayısal çalışmalar ile tablolama çalışmasına ait sonuçlar tezin sonuçlar bölümünde aktarılmıştır. Bu konuda yapılması öngörülen çalışmalar sonuçlar bölümünün ardından listelenmiştir.

1. INTRODUCTION

Impact phenomenon can be encountered in many field such as automobile accident, debris impact on spacecraft vehicle, impact on a protection shield, etc. Because of having various types of this phenomenon, researchers have tried several ways to take precaution and reduce its harmful effects on drivers, passengers and vehicles.

In space, vehicles might be subjected to impact of meteoroids and debris particles or the loads acting during landing. Design of spacecraft shield gains more importance for protection of spacecraft's structural integrity and crews' health. Researchers generally focus on hypervelocity impact phenomenon due to being more common encountered problem.

Over one million people are killed and 20-50 million people are injured during traffic accidents per a year. According to WHO, 1.24 million people are killed in 2010 [1]. For this reason, raising safety level of a car is an important scientific research subject. Crash tubes are used to reduce the harm of the accidents on passengers and equipped generally in front of the cars. They have an important role to reduce harmful effects of accidents. Numerous studies have been done to enhance the crashworthiness characteristics of crash tubes at dynamic and quasi-static velocities.

The main targets of crash tube design are peak load should be lower and amount of energy absorption should be higher at the same time despite being adverse processes. Researchers aim to obtain its better crashworthiness characteristic.

1.1 Literature Review

There are several studies based on experiences of different geometrical parameters such as thickness and cross section of the crash box. Yamashita et al. [2] investigated the different types of polygonal crash boxes and the effects of wall thickness and plastic hardening rate of material on the crush behavior. As long as the number of corners of cross-sections increases, the crush strength of tube increases. It is observed apparently at smaller initial wall thicknesses. In addition, strength of

circular cross section is higher than square cross section tubes. Palanivelu et al. [3] searched crashworthiness characteristics of different geometrical shapes (cylindrical, square, hexagonal, conical, and hourglass) and different thicknesses (1 and 2 mm) of composite tubes under quasi-static loading conditions. Conical circular tubes gives higher SEA and P_{peak} values than the other standard geometrical profiles. Abramowicz and Jones [4,5] investigated the circular and square steel crash tubes under dynamic and static loading. Salehghaffari et al. [6] showed that wall thickness, ring spacing and ring thickness width have important effects on the reinforced cylindrical crash box and demonstrates externally stiffened circular tubes are more efficient than prismatic circular tubes. Karagiozova and Jones [7] searched dynamics effects of cylindrical shells testing numerically different types of materials to show the influence of the material properties, shell geometry, boundary conditions and loading techniques on buckling and energy absorption. It is shown that the fold length increases with increase of the shell thickness.

Experimental tests and numerical solutions are also important ways of study on crush boxes. There are several studies about comparison of numerical and experimental results. Jensen et al. [8] investigated the transition from progressive to global buckling by investigating AA6060-T6 crash boxes using ABAQUS software program. The impact velocity has important role on the collapse mode. Fyllingen et al. [9] studied the influence of the element type and formulation for modeling aluminum profiles under axial loading using LS-DYNA and ABAQUS software program. According to Kazancı and Bathe [10], the results of numerical analysis using ADINA (based on implicit time integration method) and LS DYNA (based on explicit time integration method) are in agreement with the experimental results at quasi static crush speeds which means that ADINA can be a good alternative because of having shorter solution time. Besides, changing velocity of impact mass affects the crashworthiness characteristics of crash boxes. They are tested many times at various dynamic and quasi-static speeds. Karagiozova et al. [11] studied the inertial effects in axissymmetrical cylinders and showed shell elements absorbed higher energy while crash speed is increased and impact mass is reduced.

Steel, aluminum and composite materials are the most common used materials for crash boxes. Ince et al. [12] investigate the energy absorption characteristics of hybrid crash tubes saving of %17.5 for total weight. Mamalis et al. [13] analyzed

theoretically failure mechanism of thin walled fiberglass composite circular crash boxes based on experimental results. Langthseth et al. [14] validated the experimental results of Al6060-T4 and T6 alloy crash box by analyzing them at dynamic and static speeds. Kim [15] analyzed the new types of multi-cell profiles with square elements at the corner over conventional square box column to improve energy absorption and weight efficiency. Aktay and Kroplin [16] investigated the quasi-static axial crushing behavior of empty and foam-filled single, bitubular and multi-tube-packed made experimentally and numerically. Foam filling changes the failure mechanism of crash box, but it has lower SAE over the single empty tubes. In addition, squared and hexagonal multicellular tubes increased SAE values over single empty tubes. Olabi et al. [17] analyzed numerically and experimentally the quasi-static lateral compression of nested systems that is different from multi cell profiles.

1.2 Review of Articles on Crash Tubes

In this section, 127 articles on crash tubes are reviewed. These articles are listed in Reference section [2-11,13-15,19 and 21-131]. They are listed according to their published year and important informations are tabulated, shown in Table A1 in the Appendix section. This study can be used by researchers as a source including some general informations and datas of these articles. Table is divided into mainly six parts.

In the first section, software programs: LS-DYNA, ABAQUS, ADINA, PAM-CRASH and ANSYS and solution methods: implicit or explicit are placed. Besides, analytical and experimental studies are figured out afterwards. Second part of table includes datas of impact mass and impact velocity.

In the third section geometrical information like cross section types, thickness and length measurements are listed in the next section. Cross section types are classified as circular, square, rectangular, hexagonal and a generalized row for the other types of cross section.

Then material information are given. In the literature, it can be observed that there there main material types of crash tubes which are aluminum, aluminum alloys, steel, and composite materials. Table presents a row for each material types.

Finally, configuration types are indicated for all articles. They are listed according to empty, foam-filled, multi-cell and singular types.

1.3 Purpose of Thesis

The purpose of this study is to examine the energy absorption characteristics of stepped concentric crash tubes experimentally and numerically subjected to an axial impact load. The stepped concentric tubes considered here have different tube numbers and thickness, but external volume and total mass are kept constant. Effects of the tubes numbers, velocity and foam filled are investigation parameters in this thesis. Also, a comprehensive literature research is presented as a tabulating study at the end.

2. EXPERIMENTAL STUDIES

2.1 Model Specifications

In this study, three stepped and concentric circular crash tubes are tested at dynamic and quasi-static speeds. Tube lengths are 30, 25 and 20 mm, diameters are 12, 16, 20 mm from the inside out and wall thickness of all of them is 1 mm. After cutting process, three samples are located in grooves on a plate and fastened with gluing method, shown in Fig. 2.1.

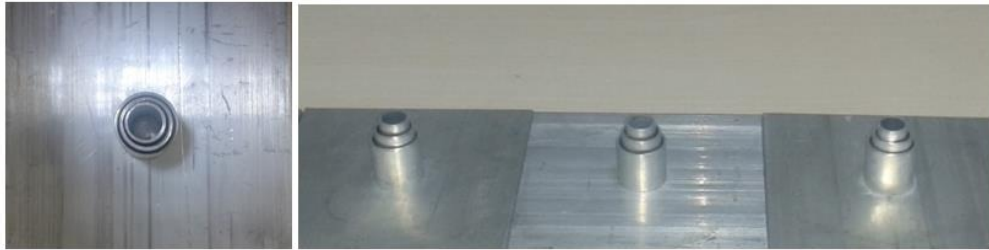


Figure 2.1 : Test specimens.

2.1.1 Material properties

All specimens are made of same material. The material is selected as AA6063, which is a strain rate insensitive material. Young modulus, E is equal to 68.7 GPa and density, ρ is equal to 2700 kg/m³. Stress-strain curve of AL6063 is shown in Fig. 2.2.

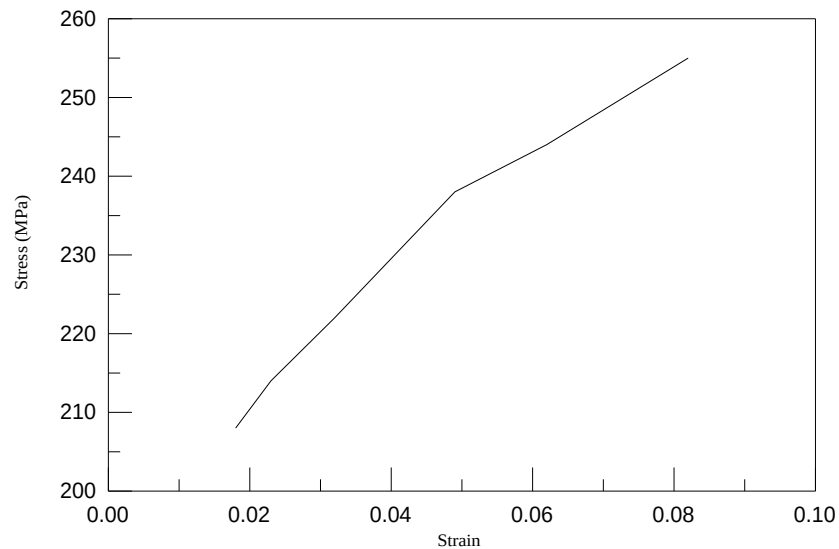


Figure 2.2 : Stress-strain curve of AL6063.

2.2 Quasi Static Test

Static test is done with MTS 647 Hydraulic Test Machine in Composite Structure Laboratory in ITU shown in Fig. 2.3. This machine is used for tension, compression and fatigue tests. Maximum load capacity is 100 kN. For this study, compression test is applied at 2 mm/min speed constantly.

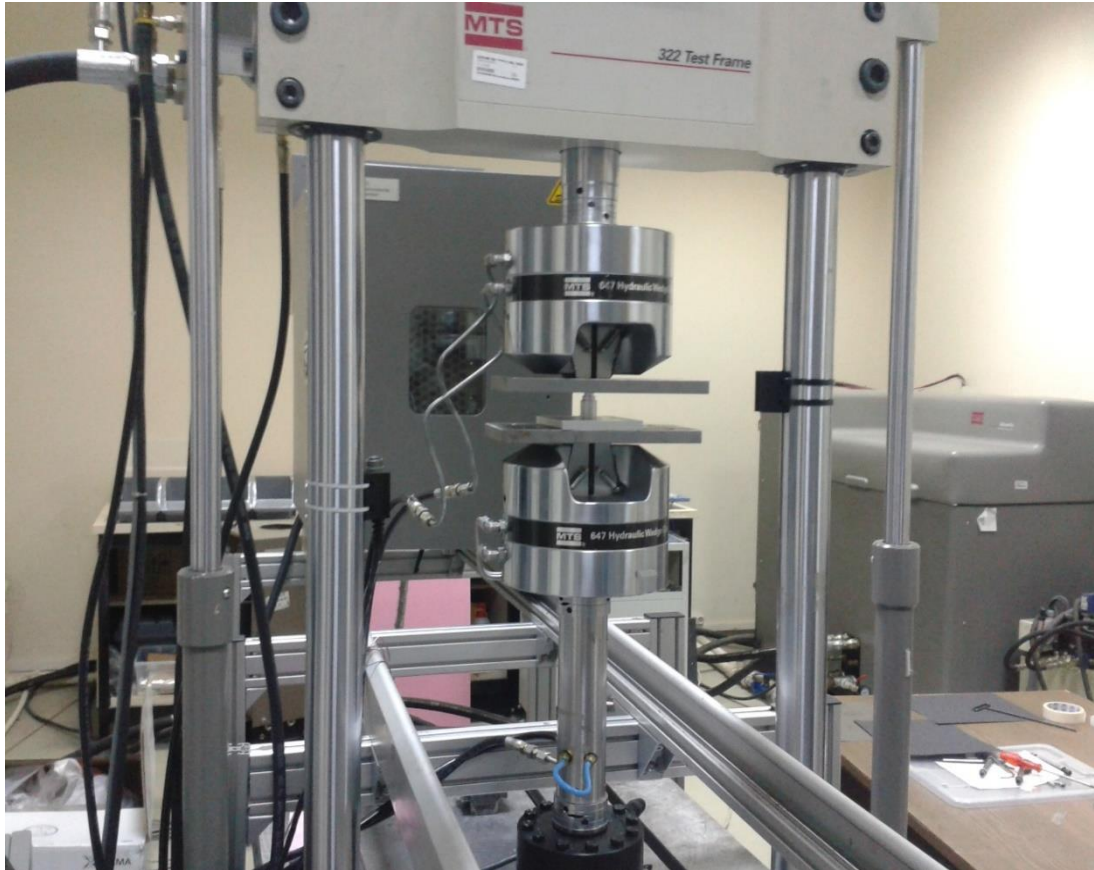


Figure 2.3 : MTS 647 Hydraulic Test Machine.

Appearances of the crushing sample are shown in various time for static test in Fig. 2.4a-h. Tubes fold progressively and interactions come out between tubes that are side by side. Force versus time curve is plotted according to experimental results, in Fig 2.5. The peak forces of all tubes can be viewed on this curve. Quasi-static test takes about 500 second.

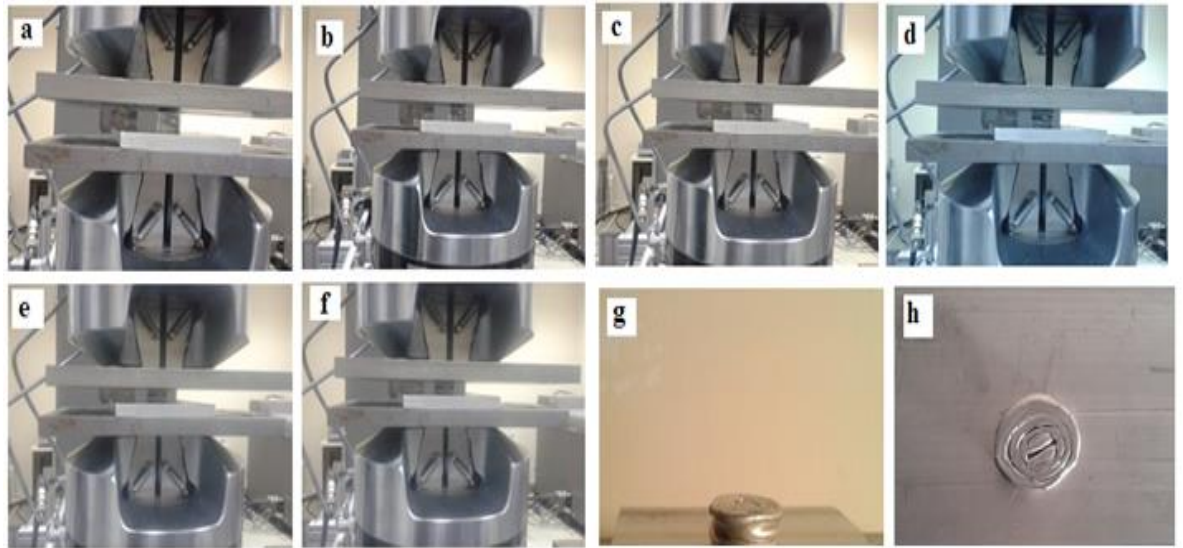


Figure 2.4 : Results of static test.

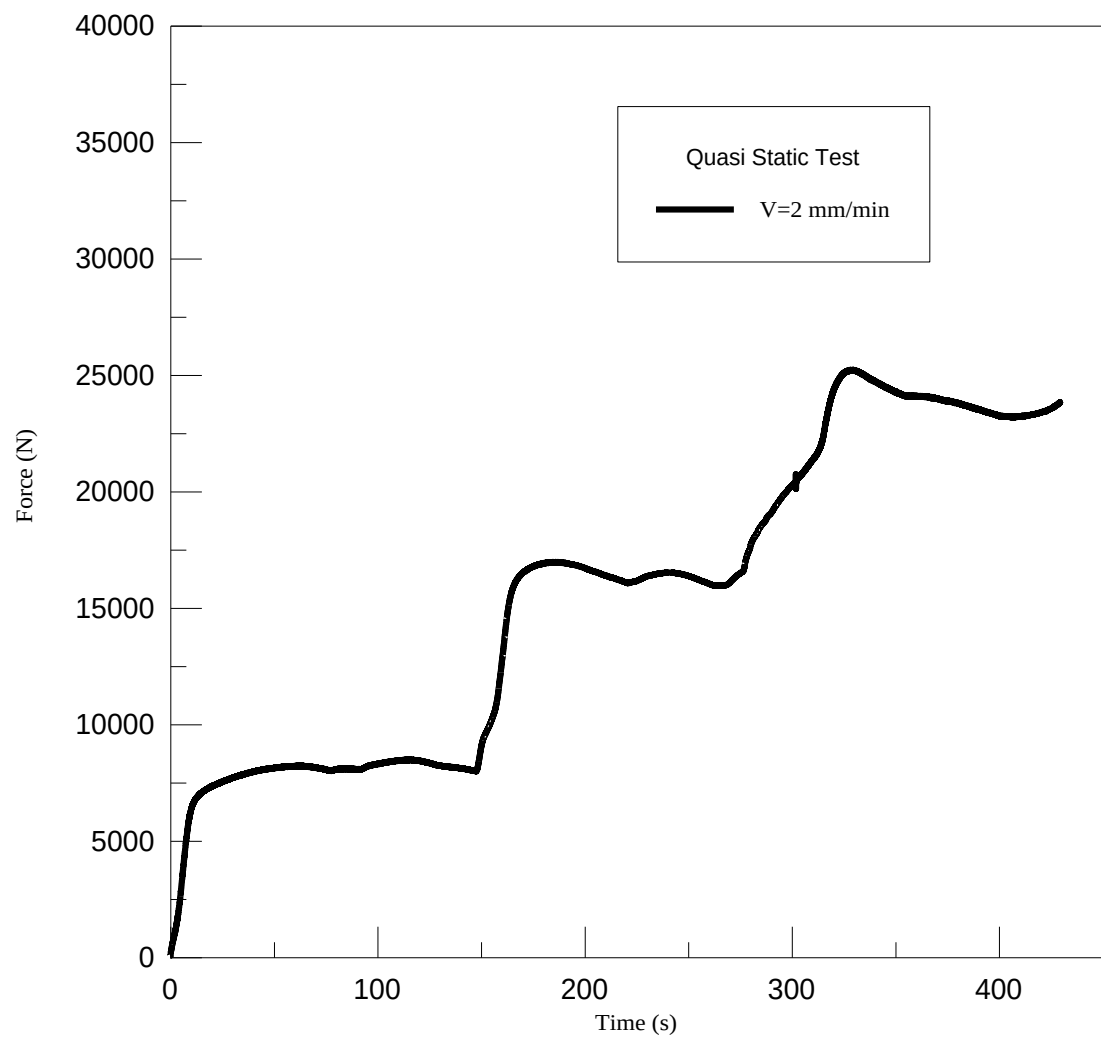


Figure 2.5 : Force vs time for static test.

2.3 Dynamic Tests

Dynamic tests are done by using INSTRON 8150 Impact Test Machine at TUBITAK Marmara Research Center (MAM), in Fig. 2.6. Impact mass capacity of this machine is 1132 kg. Its working principle is based on free fall motion. It can be reached 7 m/s impact velocity with this machine. However, dimensions of test specimens are too low and can be deformed with low energy. Also, the amount of impact mass can not be changed. Therefore, it is dropped too lower height.



Figure 2.6 : INSTRON 8150 Drop Test Machine [18].

2.3.1 Test of specimen A

In Fig. 2.7.a and 2.7.b, front and top view of sample A are demonstrated. The appearance of sample after test is demonstrated in Fig. 2.7.c and 2.7.d. From the figures, it can be observed that tubes folded progressively and interactions come out between tubes which are side by side like static test.

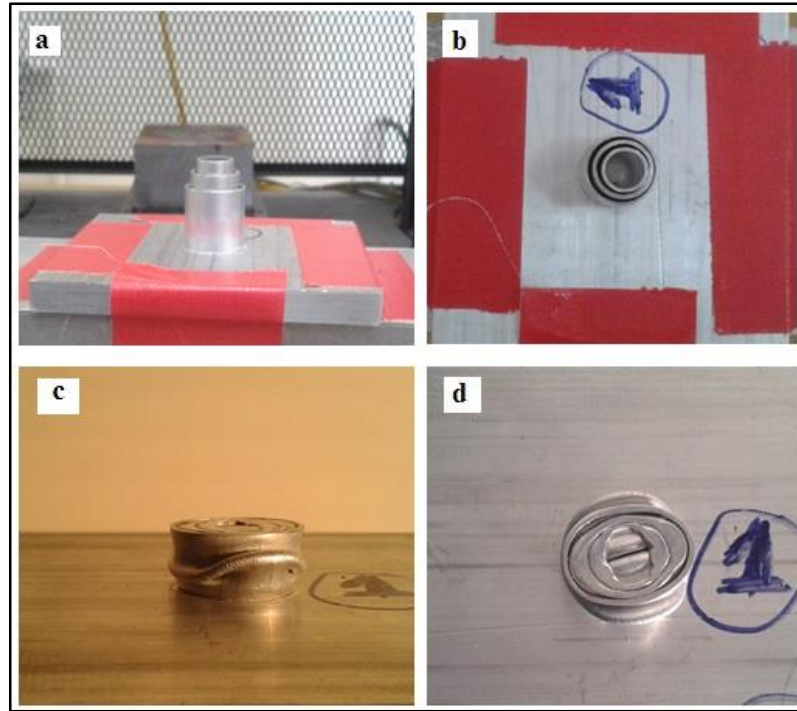


Figure 2.7 : Dynamic test of sample A.

2.3.2 Test of specimen B

In Fig. 2.8a and 2.8b front and top view of sample B is shown. The appearance of sample after test is demonstrated in Fig. 2.8c and 2.8d. Folding mechanism of sample B is similar with specimen A.

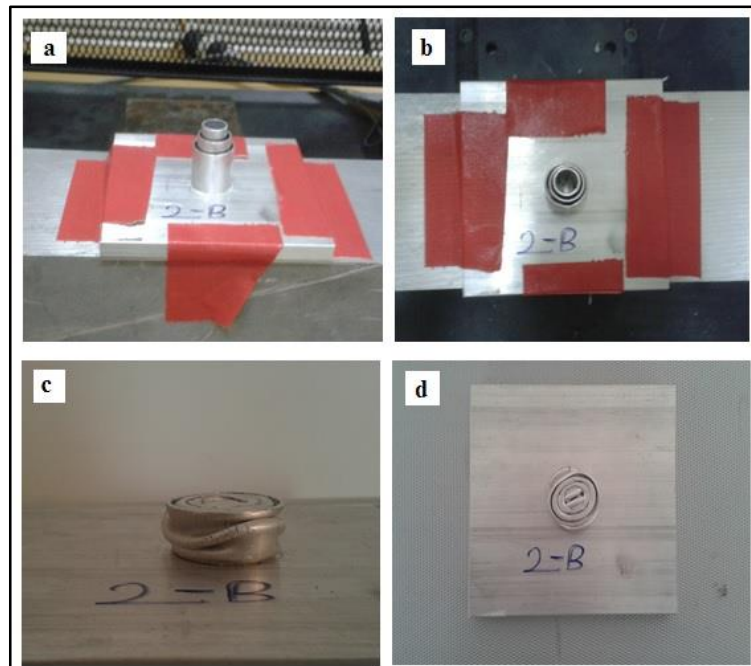


Figure 2.8 : Dynamic test of sample B.

2.3.3 Comparison of dynamic tests

“Force vs. Time” graphic is plotted in Grapher software program for two dynamic tests, in Fig. 2.9. Their peak forces and internal energy change are close each other due to having low difference between impact velocities.

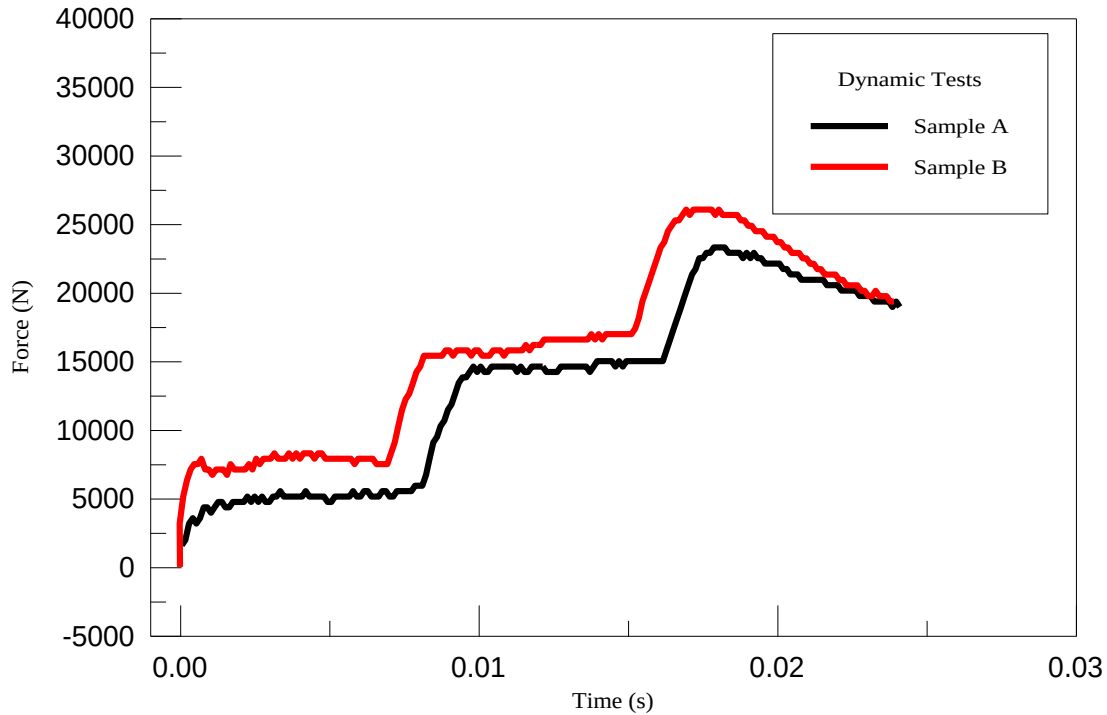


Figure 2.9 : Force versus time for dynamic tests.

2.4 Validation of Dynamic and Static Tests by Using LS DYNA

It is preferred to use mostly the explicit solver of the nonlinear finite element code LS-DYNA. Therefore, dynamic tests are validated by using LS-DYNA software program that is generally selected as an explicit time integration method to study nonlinear dynamic problems. In the next parts, modelling of specimen in LS-DYNA is explained and compared numerical and experimental results.

2.4.1 Finite element modelling

Three concentric circles are drawn under CURVE toolbar in XY plane, then circles are extruded in Z direction by using “extrude” under SURFACE toolbar. Thickness of cross section is defined as 1 mm by using SHELL under SECTION toolbar. The bottom of all tubes is clamped with SPC NODE and a rigid wall is defined 1 mm far from the top of the longest tube.

All tubes are modeled by using Belytschko-Tsay shell elements. After comparing the analysis of triple concentric tubes at different mesh qualities, optimum element size is defined as 0.4x0.4 mm. Element number of tubes is 22712. Defining optimum mesh sizing is explained in Section 3.1.

AUTOMATIC SINGLE SURFACE contacts are identified for each sample, because they have possibility of lapping after deformation. Also, AUTOMATIC SURFACE TO SURFACE contacts are defined between surfaces of tubes. The static and dynamic friction coefficients are chosen as 0.2 and 0.3 respectively for each contact definition [19].

2.4.2 Explicit analysis in LS DYNA

To model dynamic analysis, RIGIDWALL-PLANAR MOVING FORCES is used as an impactor in LS DYNA. An example schematic view for sample 1 and rigid wall is plotted together in Fig. 2.10. Tubes are crashed with an initial velocity in the axial direction. Mass of rigid wall is 1132 kg, and its initial velocity is 0.65 and 0.70 m/s.

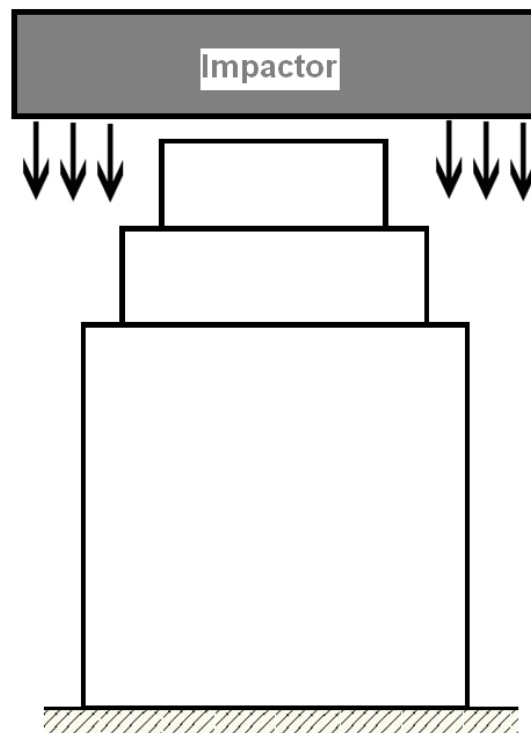


Figure 2.10 : Schematic of geometry with an example model and rigid wall.

2.4.2.1 Comparison of dynamic test results with analysis results

To validate experimental results with numerical solution, “Force vs. Time” curve is drawn in LS-DYNA by selecting SPCFORC under DATABASE toolbar. This module gives reaction forces at boundaries which are defined SPC NODES under BOUNDARY toolbar. “Force vs. Time” curves of experimental and numerical results are plotted in same graphic for each velocity, in Fig 2.11 and Fig 2.12.

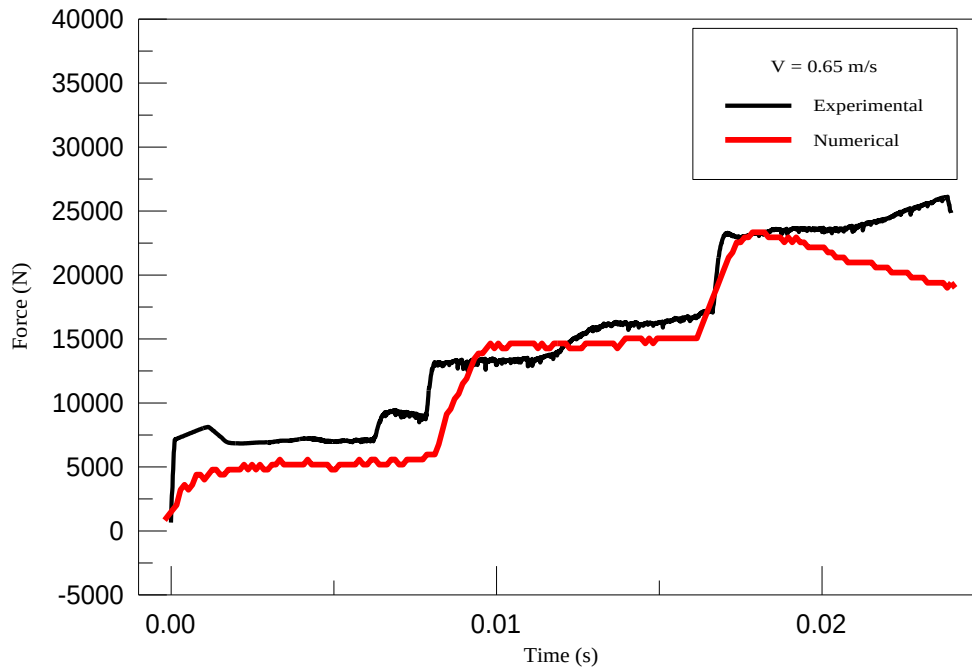


Figure 2.11 : “Force vs. Time” curves of sample A.

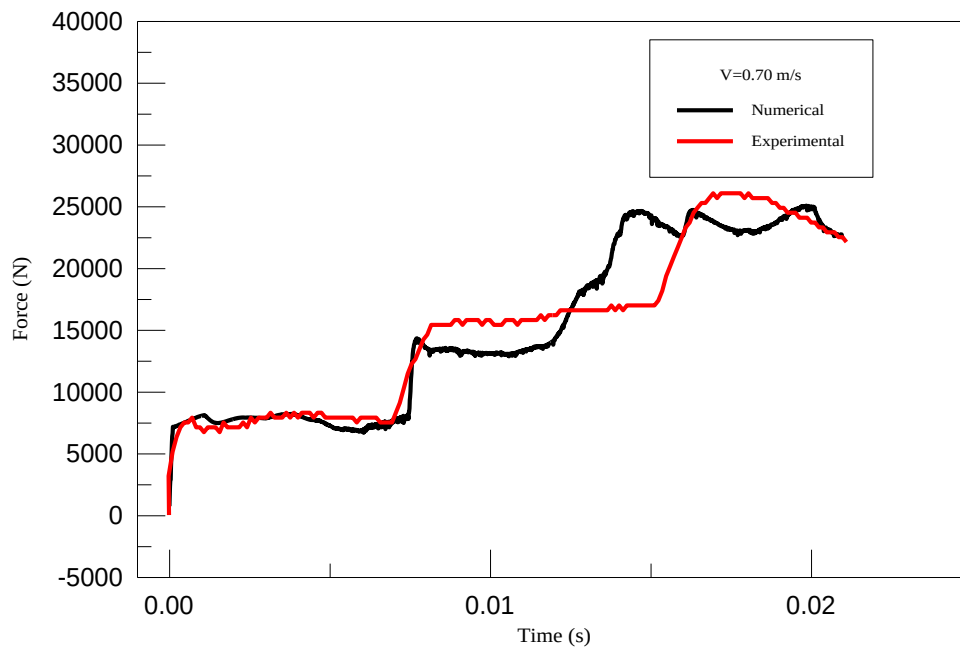


Figure 2.12 : “Force vs Time” curves of sample B.

It can be understood from the figures results of analyses and experiments are compatible each other. In addition, the values of three peak forces and their percentage error are listed in Table 2.1.

Table 2.1 : List of peak forces for dynamic cases

	1 st peak force (kN)	Error (%)	2 nd peak force (kN)	Error (%)	3 rd peak force (kN)	Error (%)
Dynamic Test A	8.69	7	16.18	17	25.60	8
Analysis A	8.08		13.43		23.45	
Dynamic Test B	8.68	6	15.78	9	26.04	5
Analysis B	8.15		14.31		24.69	

2.4.3 Quasi static analysis in LS DYNA by using implicit solver

To model static test in LS DYNA, implicit solution method is practical rather than explicit methods. Solution time takes longer by using explicit method contrary to implicit method. A SHELL is modelled in LS DYNA to crush the tubes. It is defined by using PRESCRIBED MOTION RIGID under BOUNDARY toolbar. An example schematic of model for implicit analysis is plotted in Fig. 2.13.

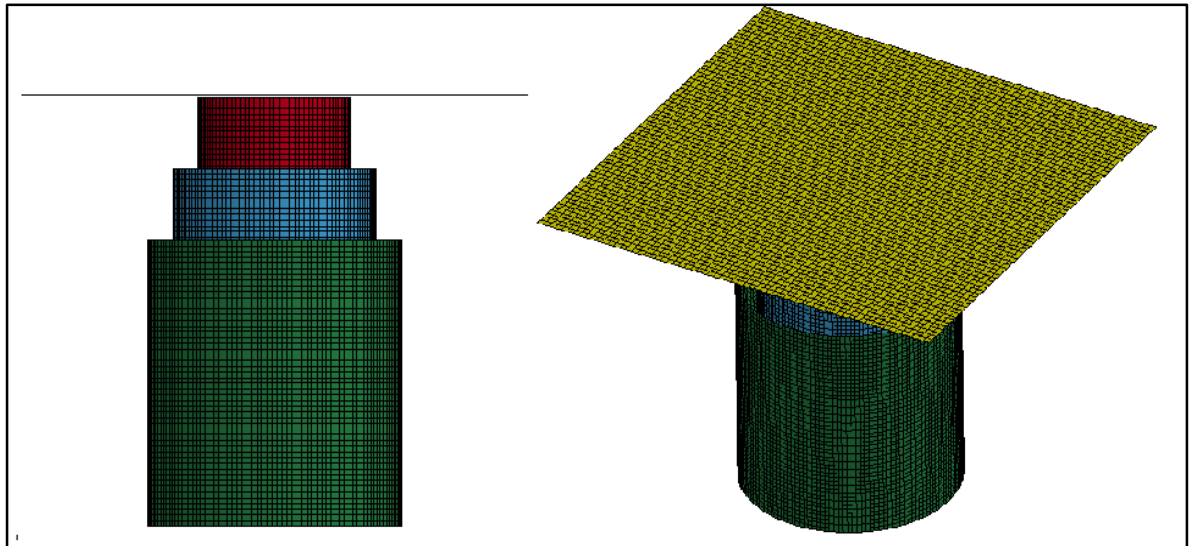


Figure 2.13: FEM for implicit analysis in LS DYNA.

2.4.3.1 Comparison of quasi static test results with analysis results

To validate static test results with numerical solution, “Force vs. Time” curve is drawn in LS-DYNA by selecting SPCFORC under DATABASE toolbar. “Force vs.

Time” curves of experimental and numerical results are plotted in same graphic, in Fig 2.14.

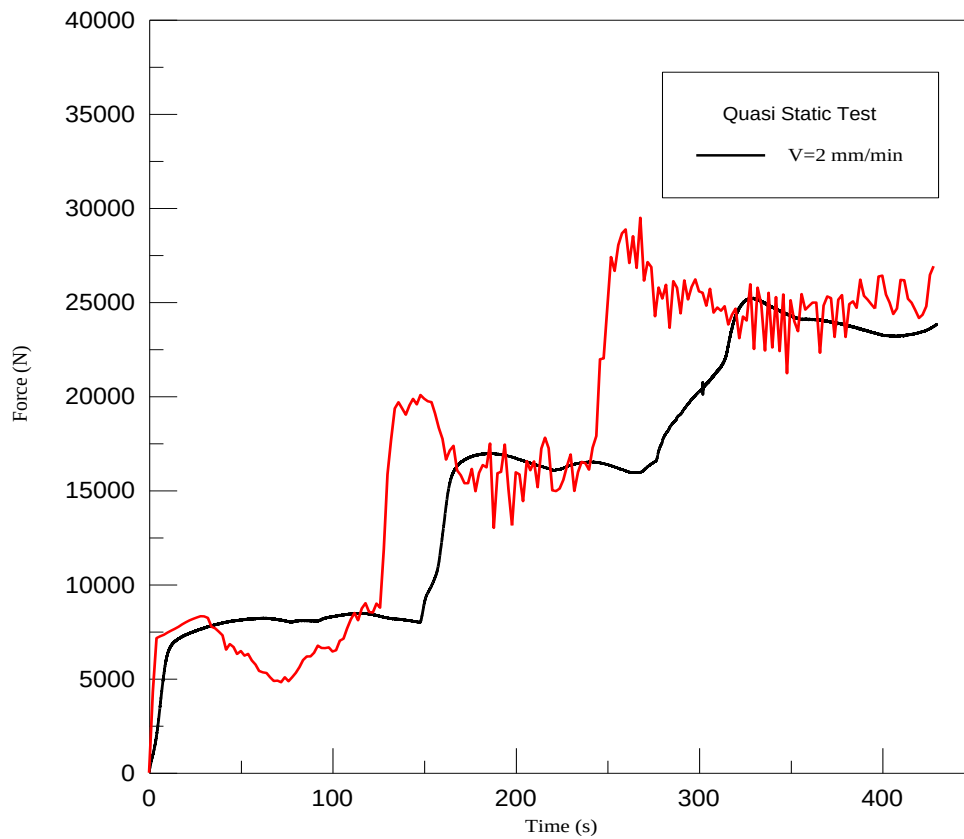


Figure 2.14 : Force vs. time curves of static case.

It can be understood from the Fig. 2.14, results of analyses and experiments are compatible each other despite of a bit differences. The values of three peak forces and their percentage error are listed in Table 2.2 .

Table 2.2 : List of peak forces for static case.

	1 st peak force (kN)	Error (%)	2 nd peak force (kN)	Error (%)	3 rd peak force (kN)	Error (%)
Static Test	8.09	3	16.80	19	25.94	14
Static Analysis	8.30		20.06		29.47	

3. NUMERICAL STUDIES BY USING LS DYNA

3.1 Defining Optimum Mesh Sizing

3.1.1 Material properties

All specimens are made of same material. The material uses here AL alloy, which is a strain rate insensitive material, has young modulus, E is equal to 78 GPa and density, ρ is equal to 2700 kg/m³. Material properties are listed in Table 3.1 and stress-strain curve shown in Fig. 3.1 is used to determine the material properties. Tubes are modelled with MAT024 PIECEWISE LINEAR PLASTICITY material model in LS-DYNA.

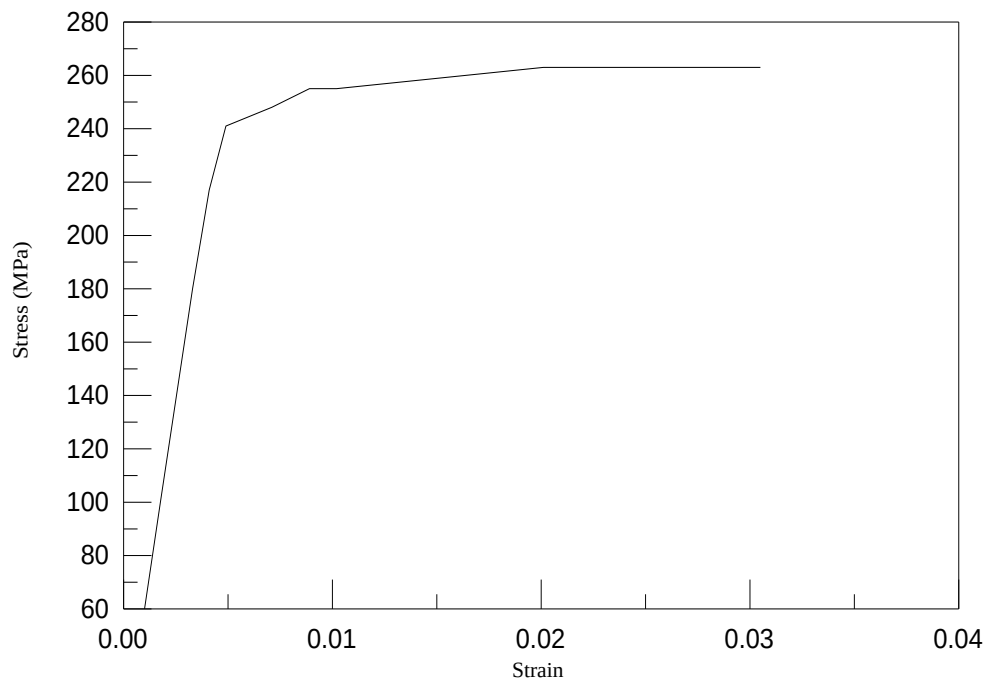


Figure 3.1 : Stress-strain curve of AL6063.

Table 3.1: Material properties.

Density (kg/m ³)	Young Modulus (GPa)	Poison Ratio	Yield stress (MPa)	Ultimate tensile stress (MPa)
2700	78	0.33	241	263

3.1.2 Comparison of results

In this section, stepped concentric three tubes are modelled with 5 different mesh qualities. Mesh sizes are 0.3x0.3, 0.4x0.4, 0.5x0.5, 0.6x0.6 and 0.7x0.7 mm. Impact velocity and mass are defined as 50 m/s and 100 g, respectively. “Force vs. Time” graphics are plotted separately for each analysis result, which are shown in Fig 3.2-3.6. It can be came out that force values in time are so close between two smallest mesh sizes models: 0.3x0.3 and 0.4x0.4 mm.

However, solution time strings out so much that is not suitable to do more analysis. Accordingly, 0.4x0.4 mm mesh size is chosen for all analysis models.

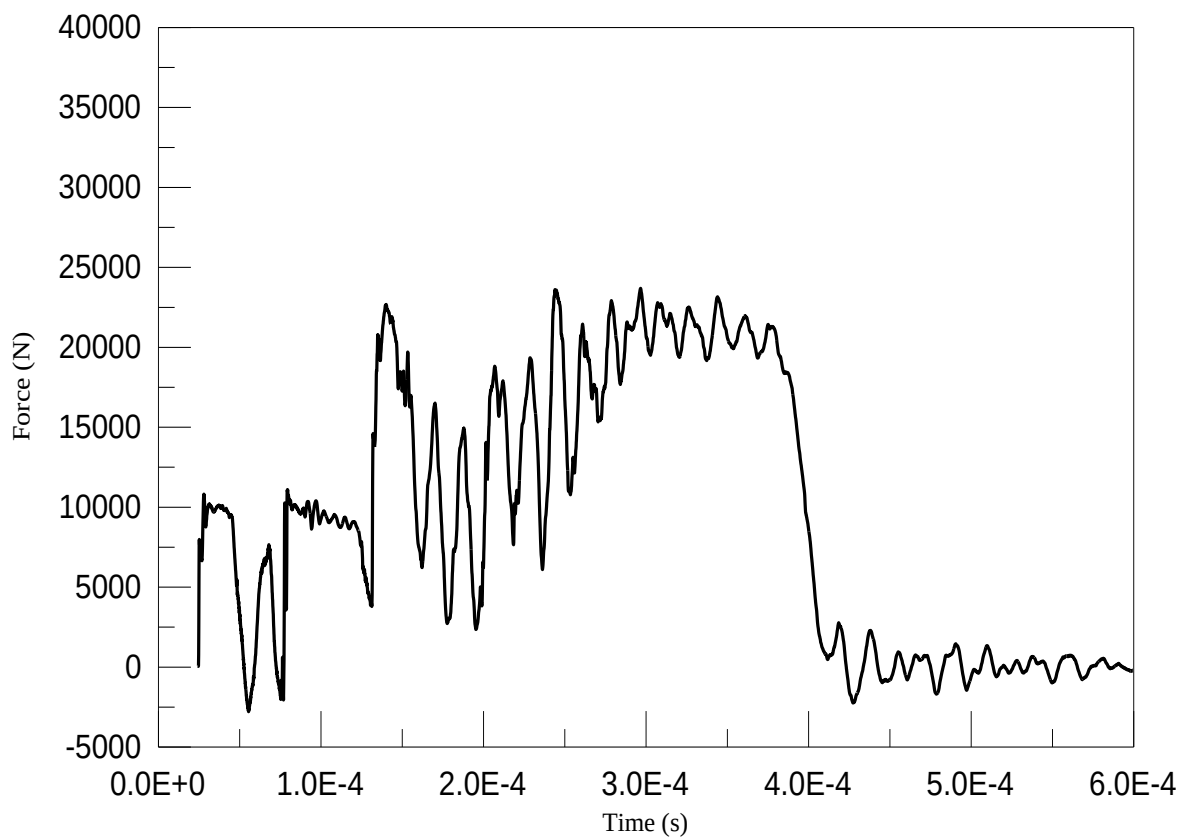


Figure 3.2 : Force versus time of 0.3x0.3 mm mesh sizing.

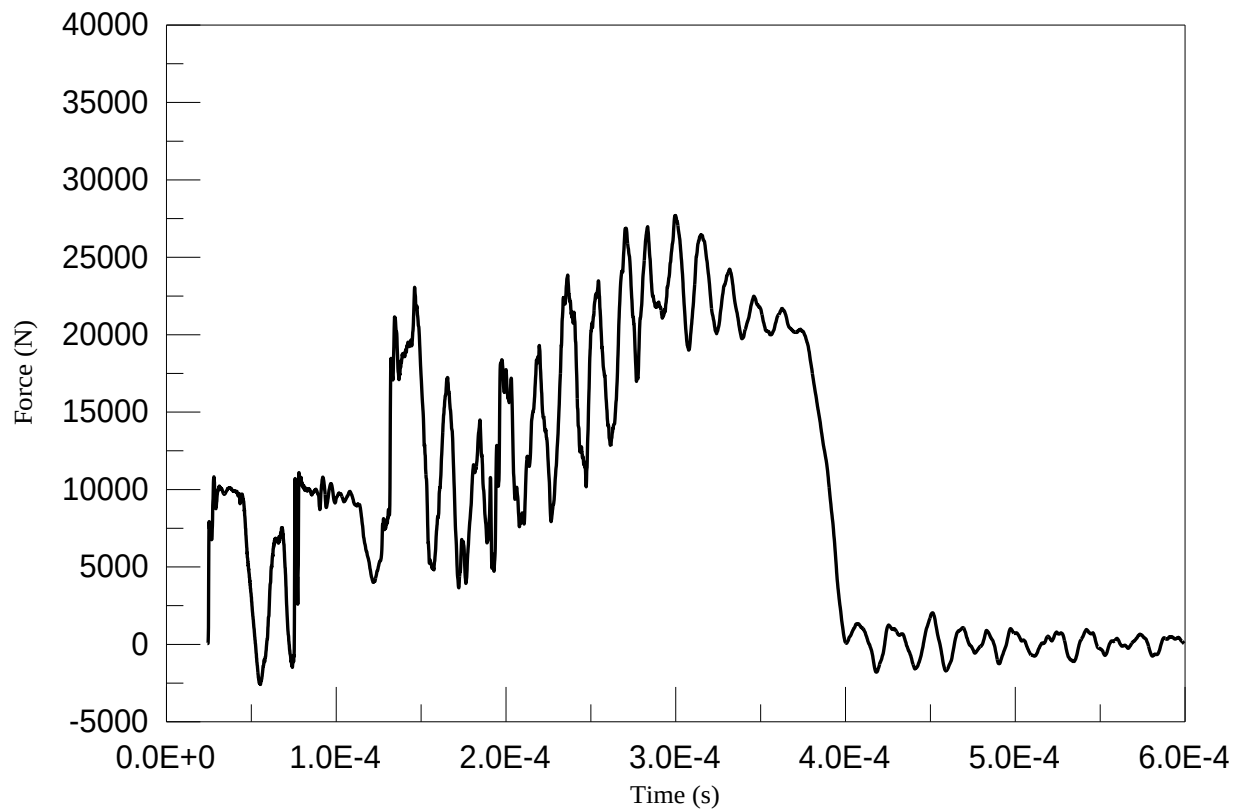


Figure 3.3 : Force versus time of 0.4x0.4 mm mesh sizing.

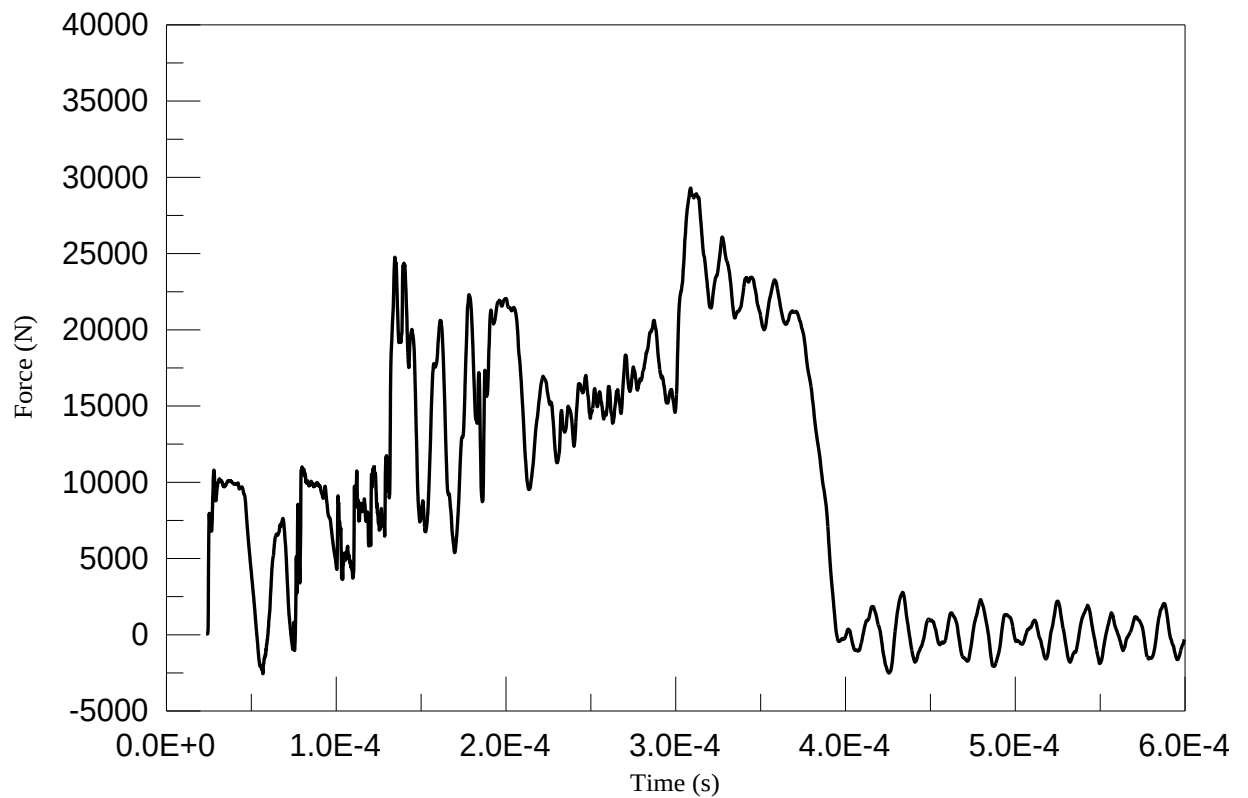


Figure 3.4 : Force versus time for with 0.5x0.5 mm mesh sizing.

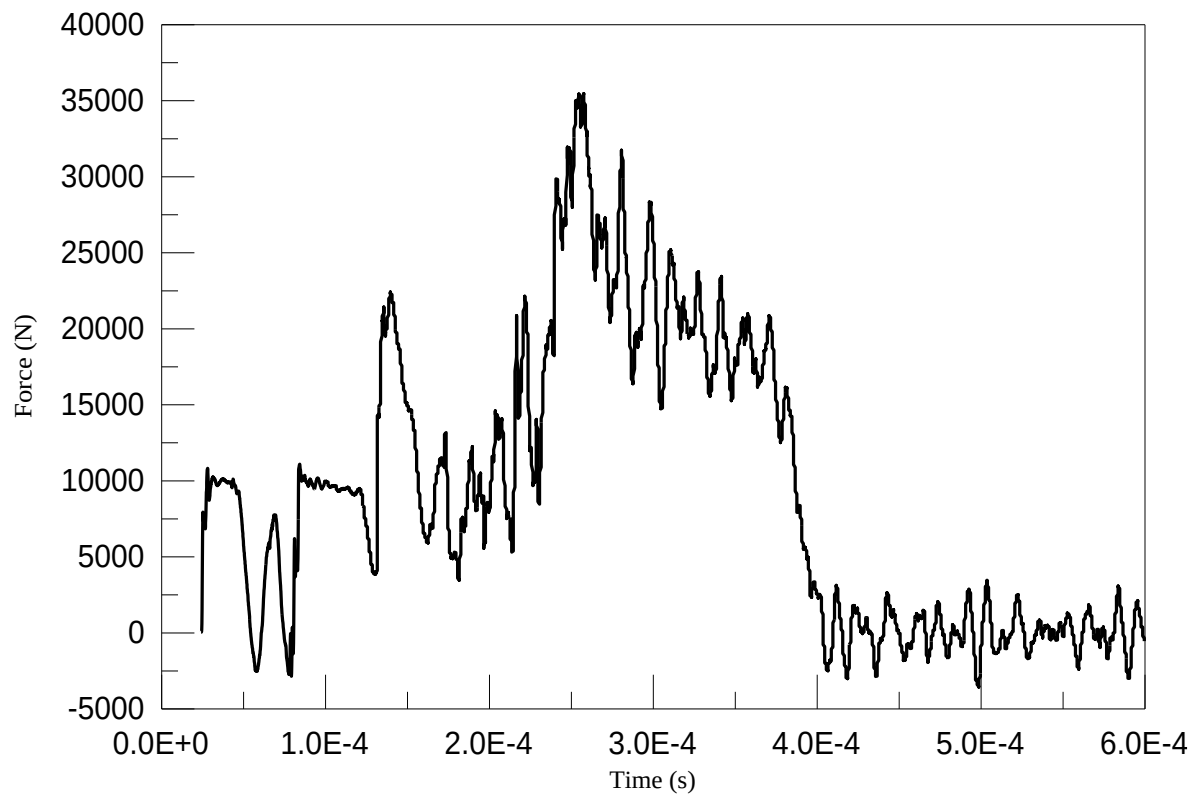


Figure 3.5 : Force versus time of 0.6x0.6 mm mesh sizing.

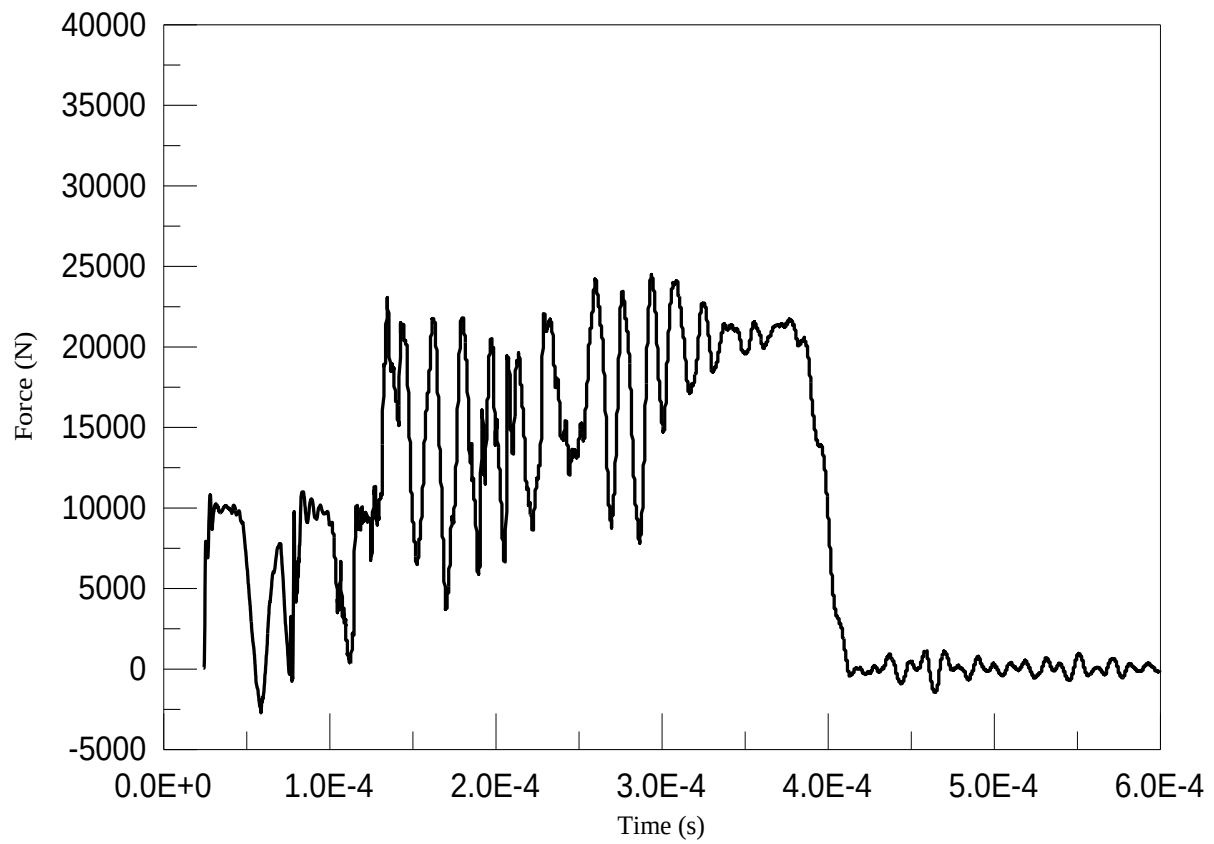


Figure 3.6 : Force versus time of 0.7x0.7 mm mesh sizing.

3.2 Investigation the Effects of Tube Numbers

In this part, the effects of tube numbers are studied at a constant velocity. Four different models are constituted with 3, 6, 9 and 12 stepped concentric tubes and all are named as Sample 1, 2, 3 and 4, respectively.

3.2.1 Specifications of samples

Dimensions of Sample 1 and 2 are listed in Table 3.2, also, Sample 3 and 4 are listed in Table 3.3. Tube no states how many number of tubes are concluded. Mean radius, length and wall thickness are listed for each tube one by one.

Table 3.2 : Dimensions of Sample 1 and 2.

	Sample 1			Sample 2		
Tube no	r_{mean} (mm)	L (mm)	t (mm)	r_{mean} (mm)	L (mm)	t (mm)
1	6	30	1	5	30	0.5
2	8	25	1	6	28	0.5
3	10	20	1	7	27	0.5
4				8	25	0.5
5				9	23	0.5
6				10	21	0.5

Table 3.3 : Dimensions of Sample 3 and 4.

	Sample 3			Sample 4		
Tube no	r_{mean} (mm)	L (mm)	t (mm)	r_{mean} (mm)	L (mm)	t (mm)
1	6.0	30.0	0.3	4.5	30	0.25
2	6.5	28.5	0.3	5.0	29.5	0.25
3	7.0	28.0	0.3	5.5	29	0.25
4	7.5	27.0	0.3	6.0	28.5	0.25
5	8.0	26.0	0.3	6.5	28	0.25
6	8.5	25.0	0.3	7.0	27	0.25
7	9.0	24.0	0.3	7.5	26	0.25
8	9.5	23.0	0.3	8.0	25	0.25
9	10.0	22.5	0.3	8.5	24	0.25
10				9.0	23	0.25
11				9.5	22	0.25
12				10.0	21	0.25

In Fig. 3.7, front and section views of finite element models are shown from LS-DYNA. Maximum tube lengths and diameters are same for all samples. It can be seen that spaces between tubes reduces when the tube number increases.

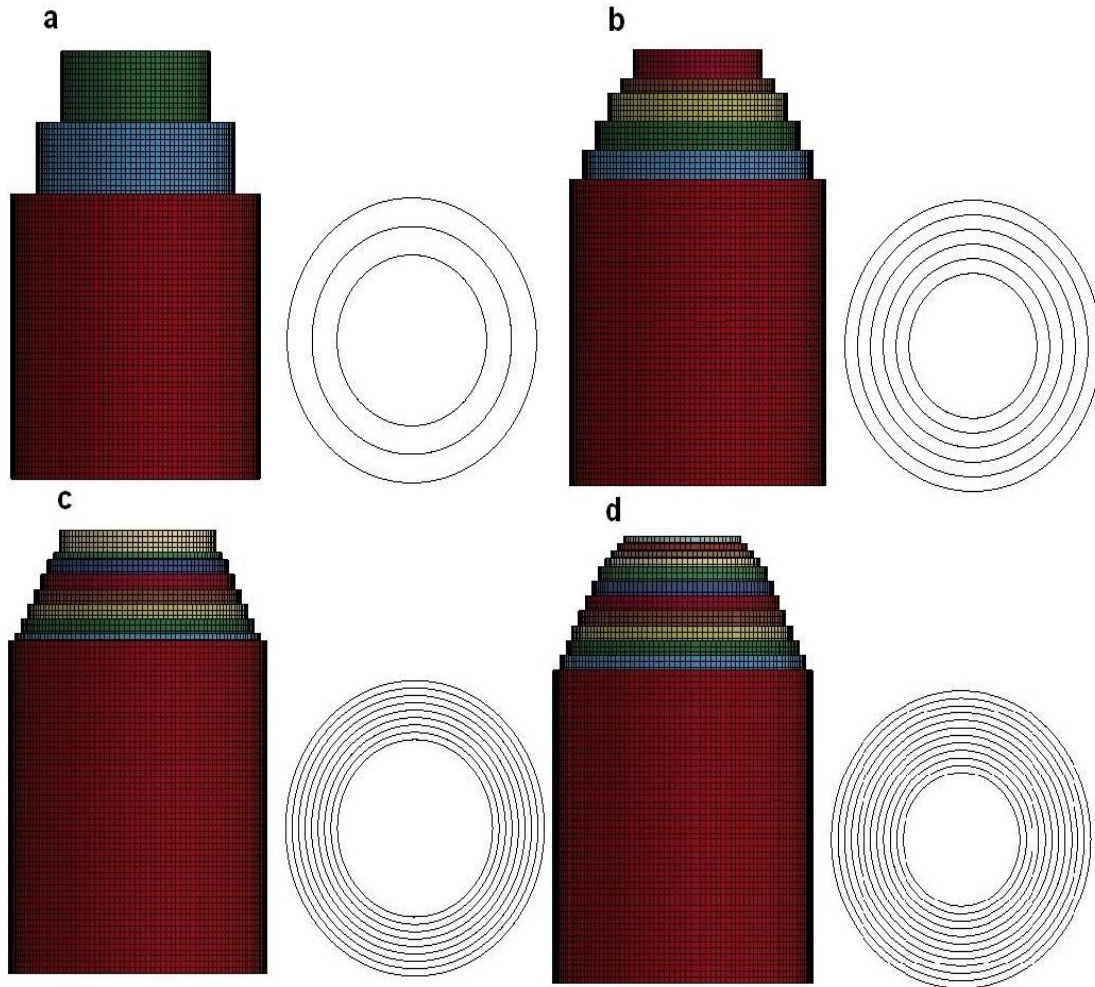


Figure 3.7 : FEM of four samples.

3.2.2 Comparison of results

“Force vs. Time” curve of each sample is plotted separately, in Fig. 3.8-11. Sample 1 has three noticeable peak forces in Fig.3.8. Also, peak forces of Sample 2 can be seen on Fig. 3.9, but difference between two neighbour forces decrease. In addition, number of peak forces are not same with the tube numbers for Sample 3 and 4. This means some of the peak forces disappear with the increase of the number of tubes. It results from reduction of the wall thickness and space between two side by side tubes.

“Internal Energy vs. Time” curve of four sample are plotted in same figure, Fig. 3.12. According to this figure, total internal energy reduces, while the tube numbers are increased.

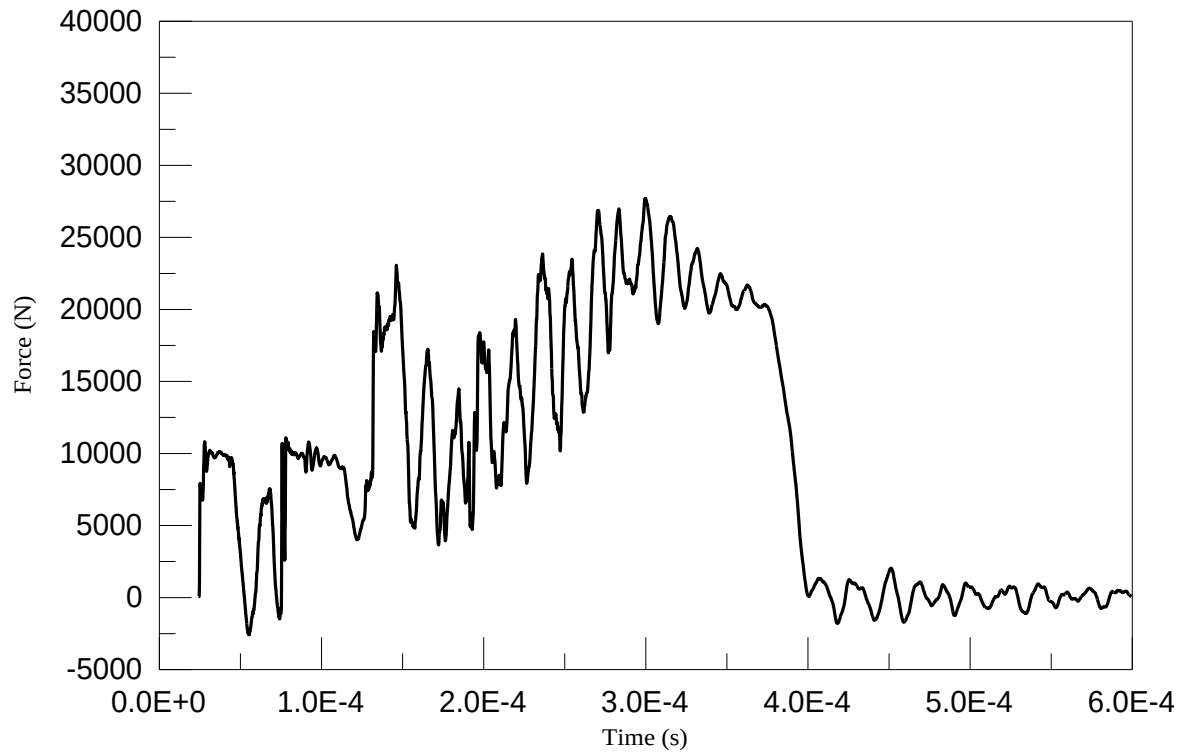


Figure 3.8 : Force versus time for sample 1.

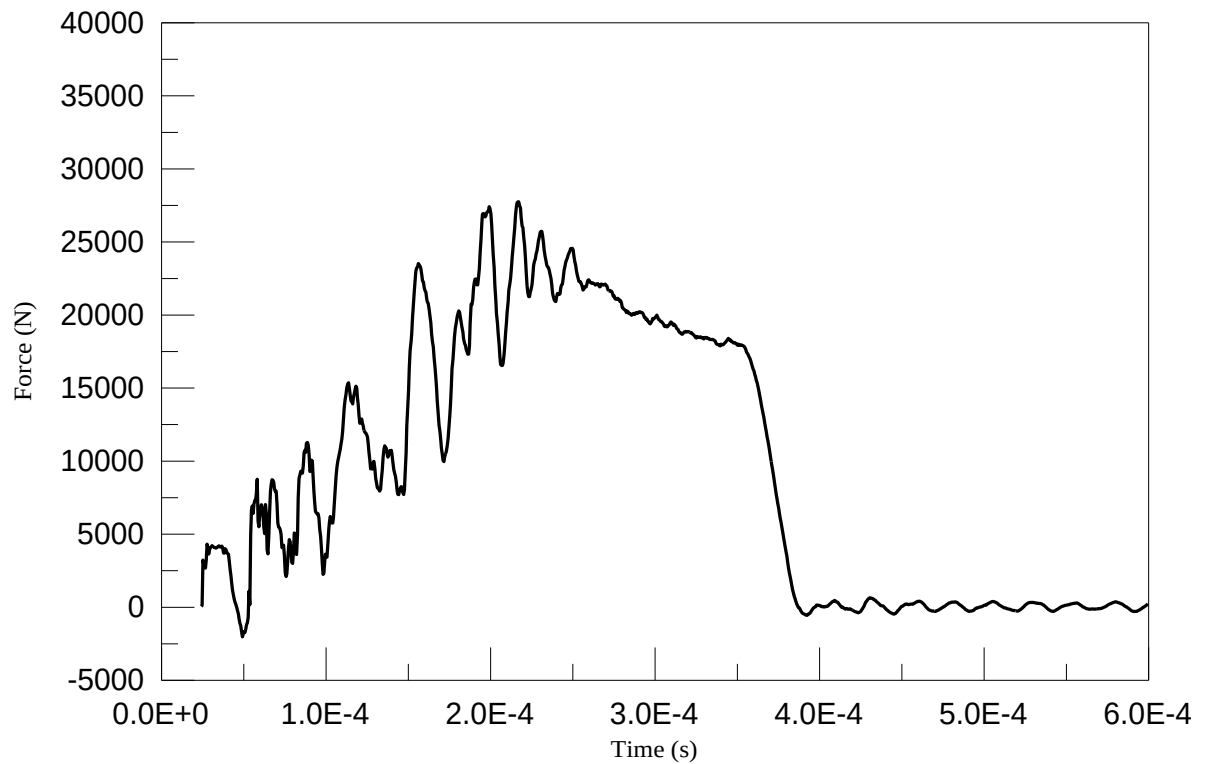


Figure 3.9 : Force versus time for sample 2.

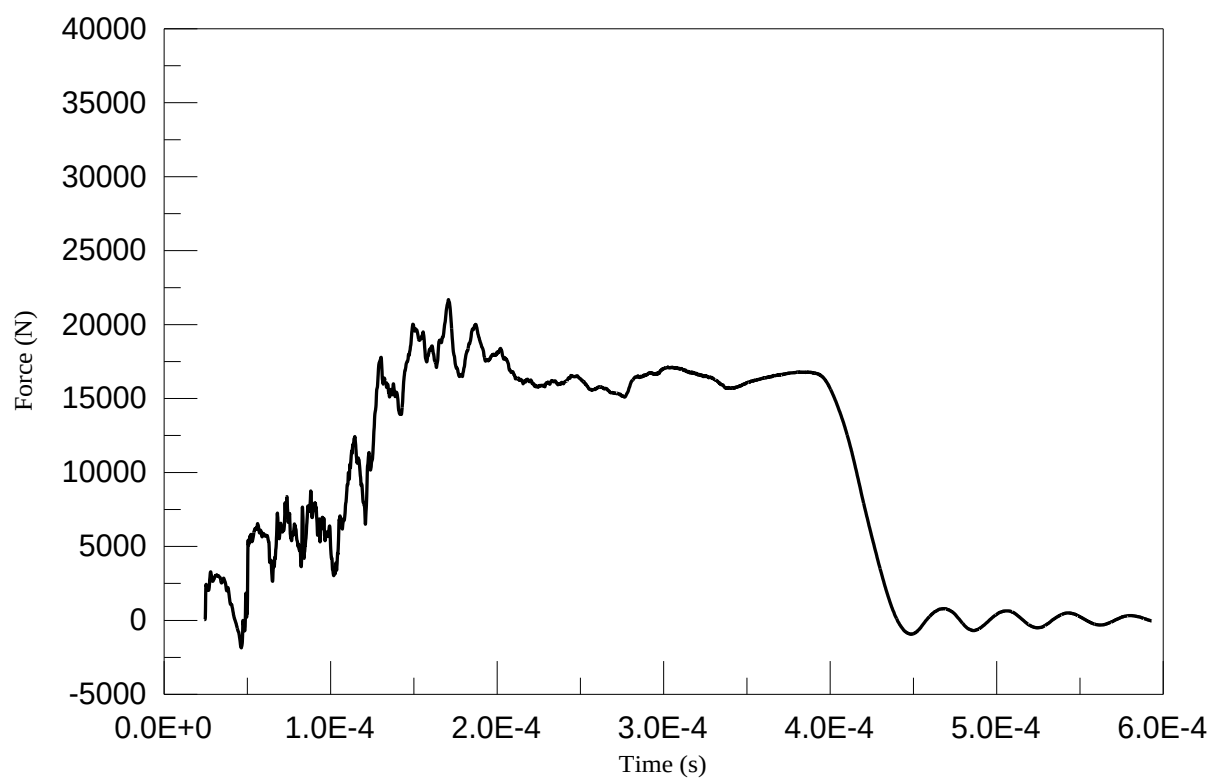


Figure 3.10 : Force versus time for sample 3.

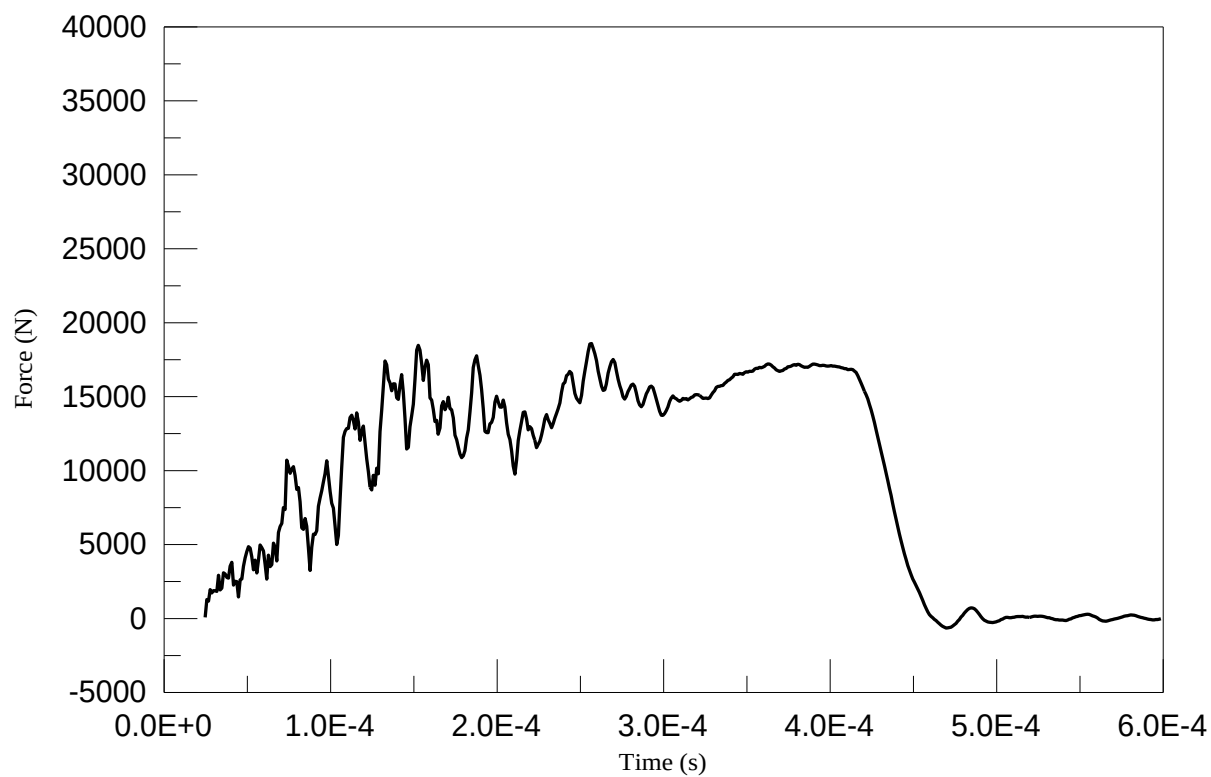


Figure 3.11 : Force versus time for sample 4.

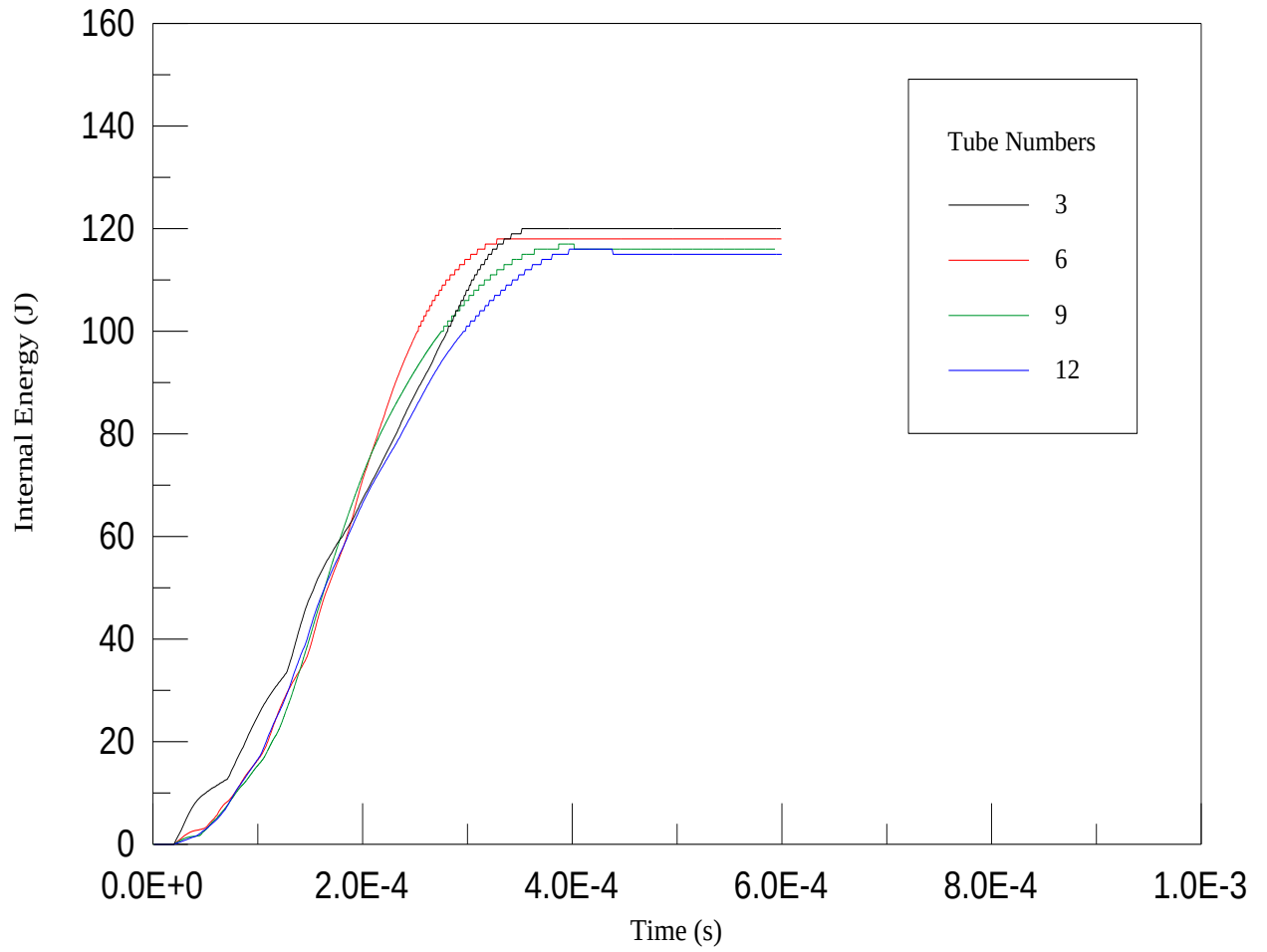


Figure 3.12 : Internal energy vs. time for all samples.

In Fig. 3.13, von Mises stress distribution and lengths of each samples after deformation are demonstrated. Deflection amounts are 10.6, 11.6, 10.7 and 11.2 mm, respectively.

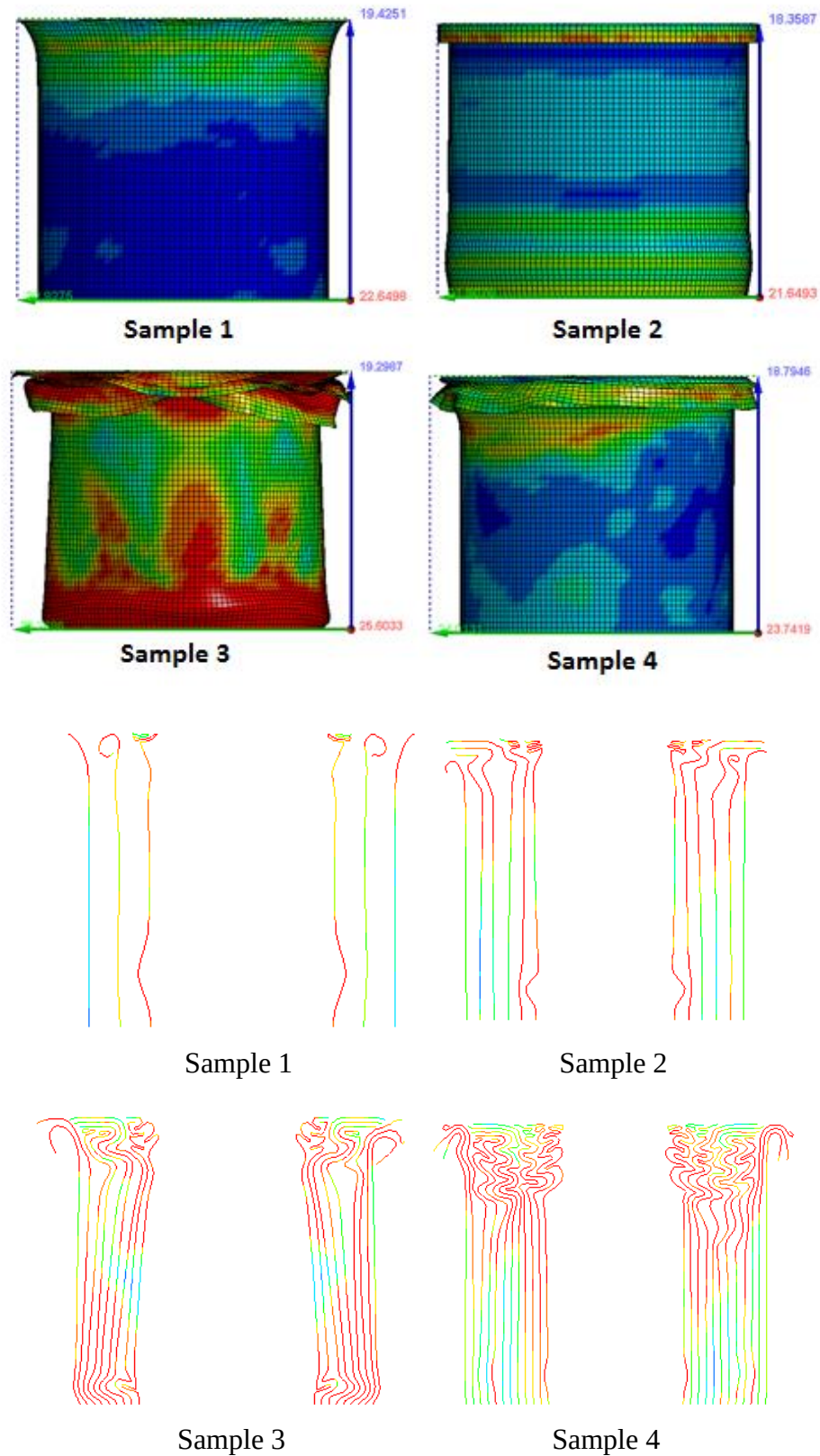


Figure 3.13 : Von Mises stress distribution and final lengths of each samples.

3.3 Behavior of Samples at Different Impact Velocities

In this section, the effects of impact velocity on stepped concentric tubes are investigated. In RIGIDWALL toolbar, impact velocities are selected 50, 60 and 70 m/s and without changing impact masses for each sample. Force, internal energy and total deflection are compared at different velocities.

3.3.1 Velocity effects on peak forces

It is seen from Fig 3.14-17 that solution time at higher velocity takes longer, also, peak forces get higher when velocity increases.

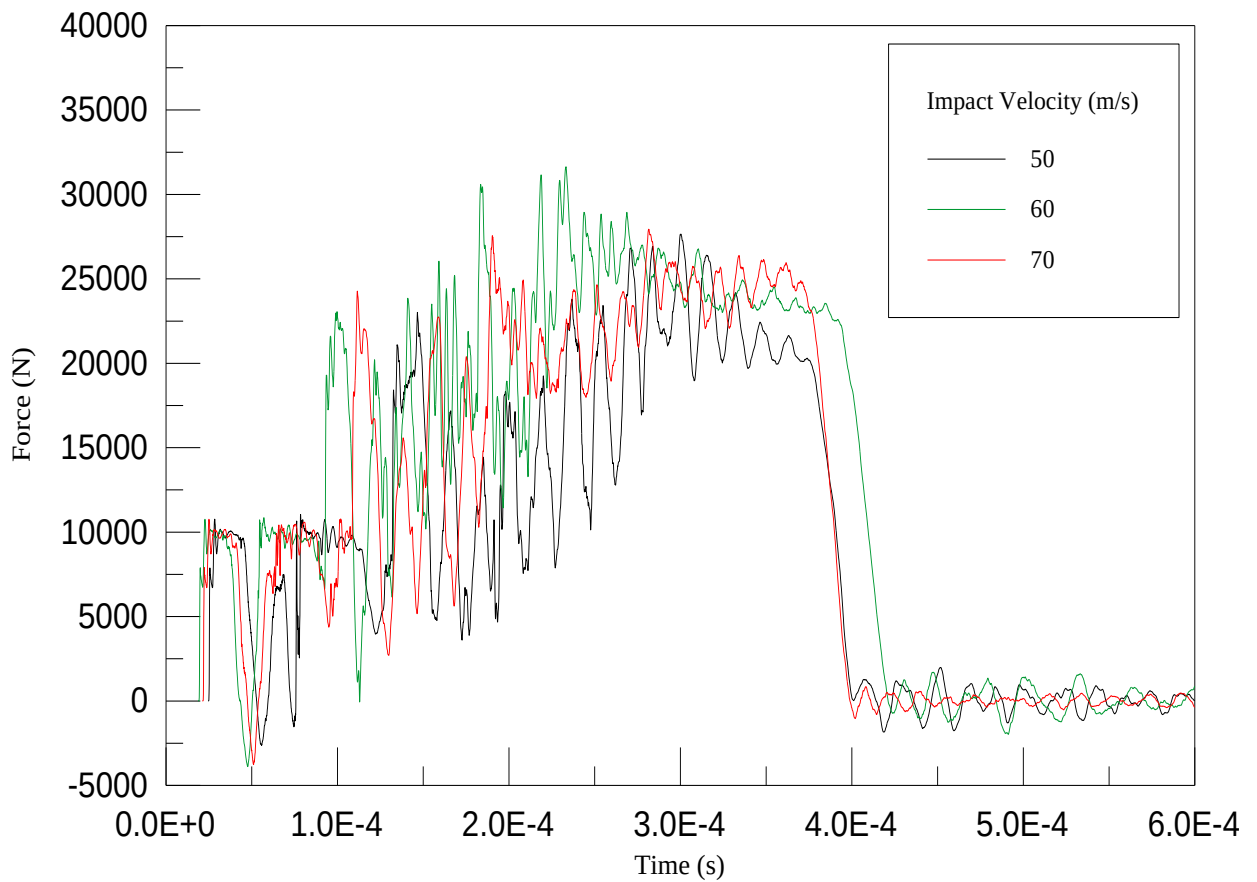


Figure 3.14 : Force versus time for sample 1.

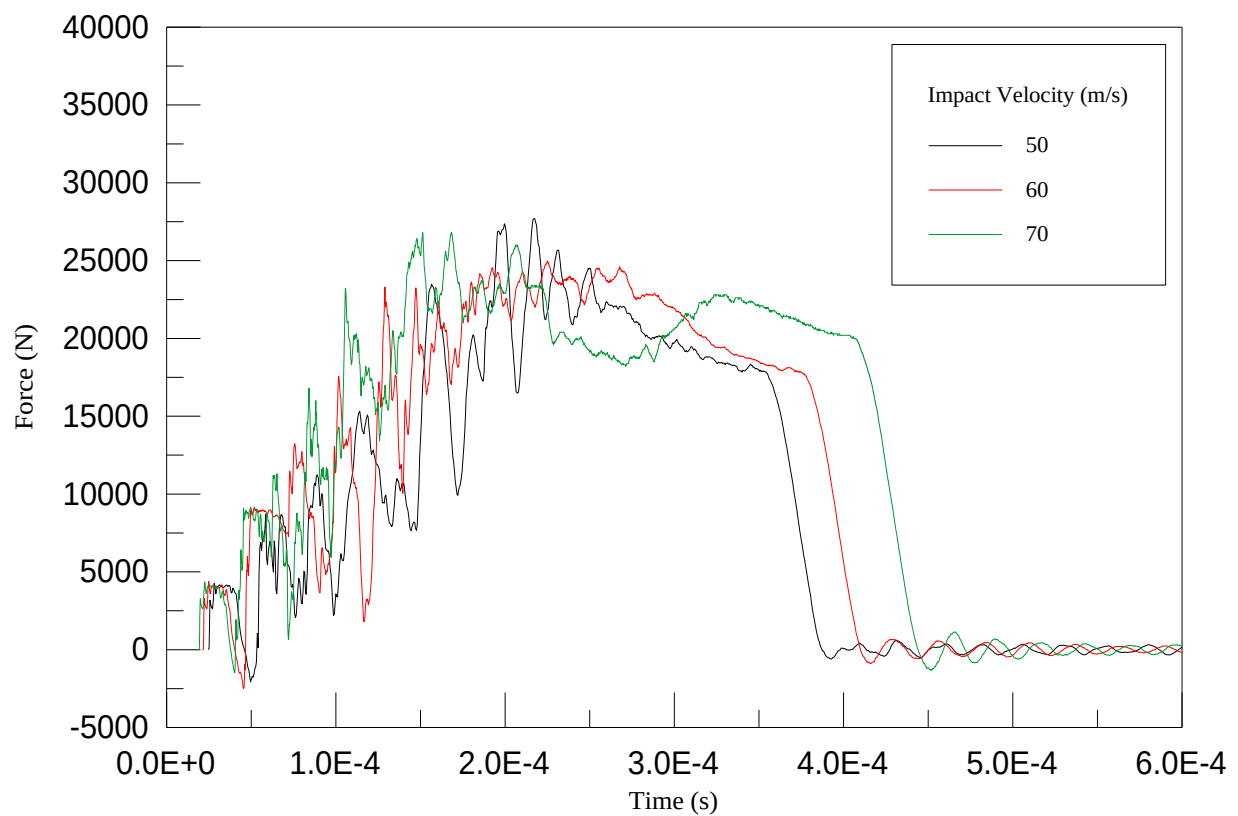


Figure 3.15 : Force versus time for sample 2.

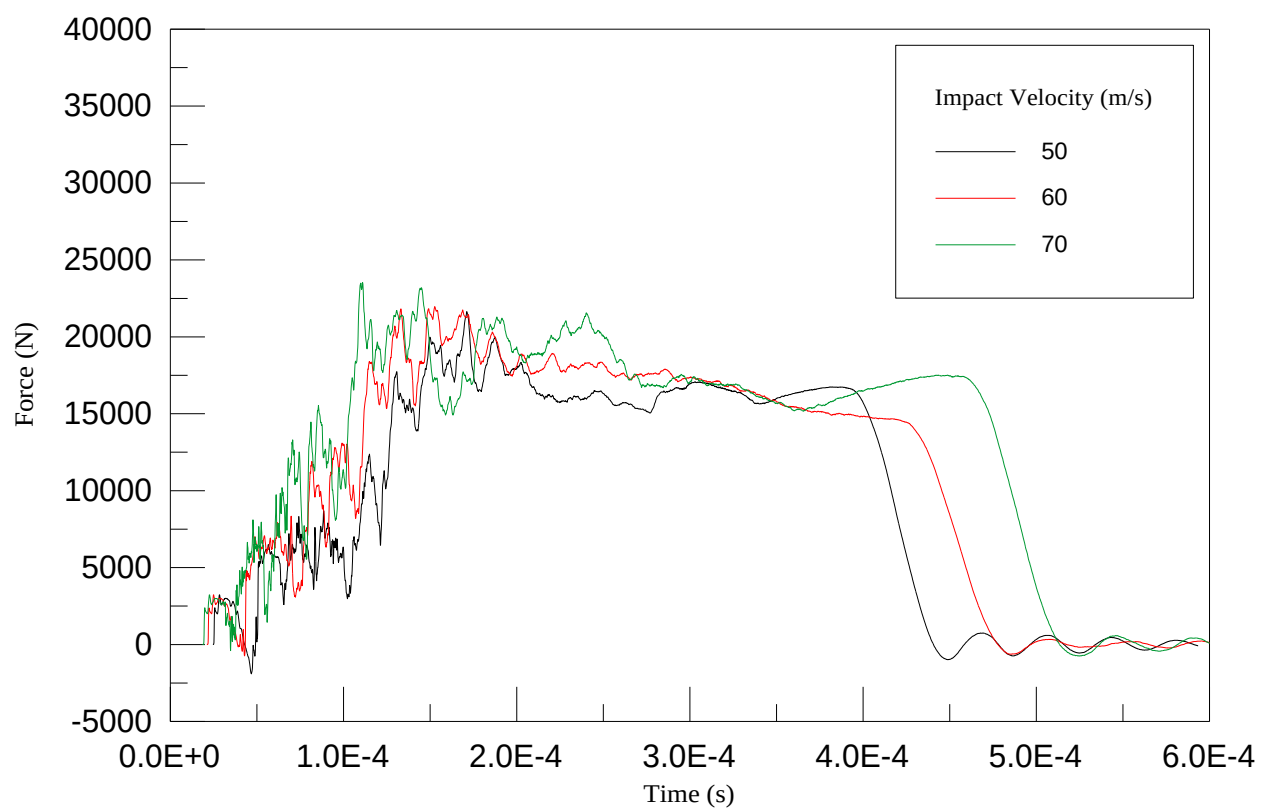


Figure 3.16 : Force versus time for sample 3.

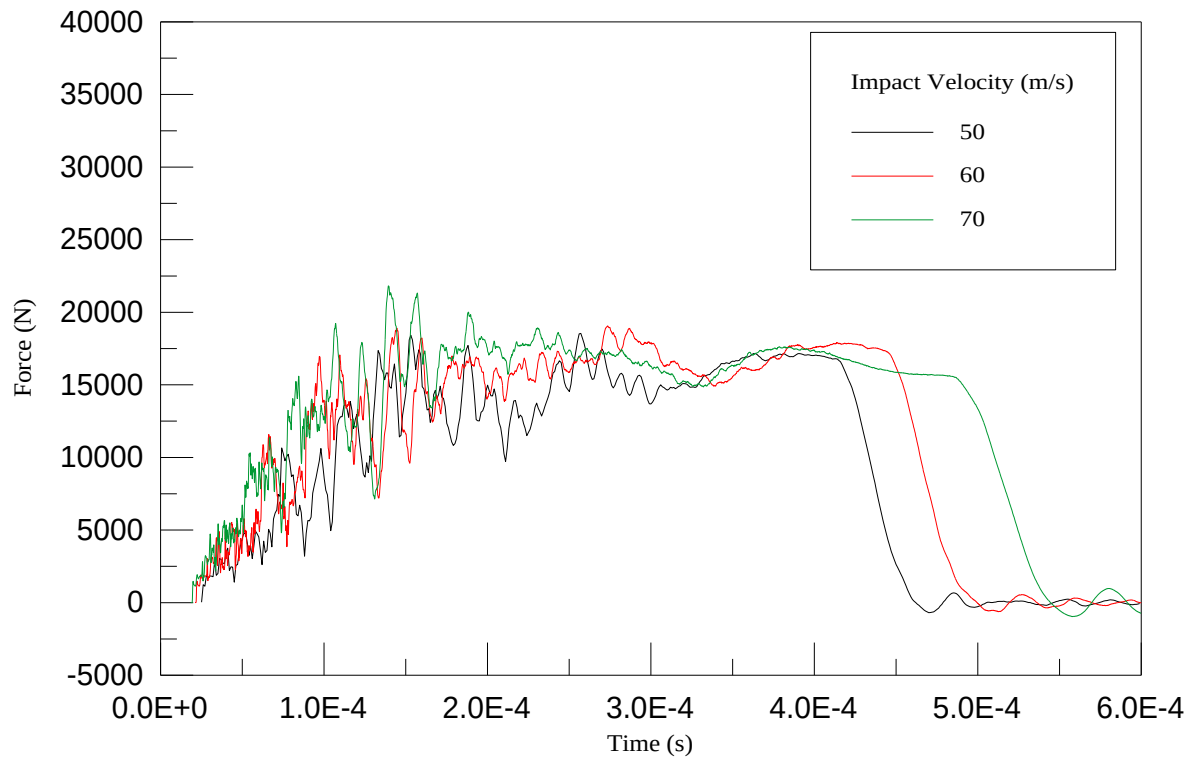


Figure 3.17 : Force versus time for sample 4.

3.3.2 Velocity effects on internal energy and amount of deformation

Naturally, the amount of internal energy increases at higher velocity. For sample 1, internal energy amounts are 120, 168 and 230 J in Fig 3.18, respectively. Besides, total deflections are 10.5749, 12.3167 and 15.0346 mm in Fig. 3.19.

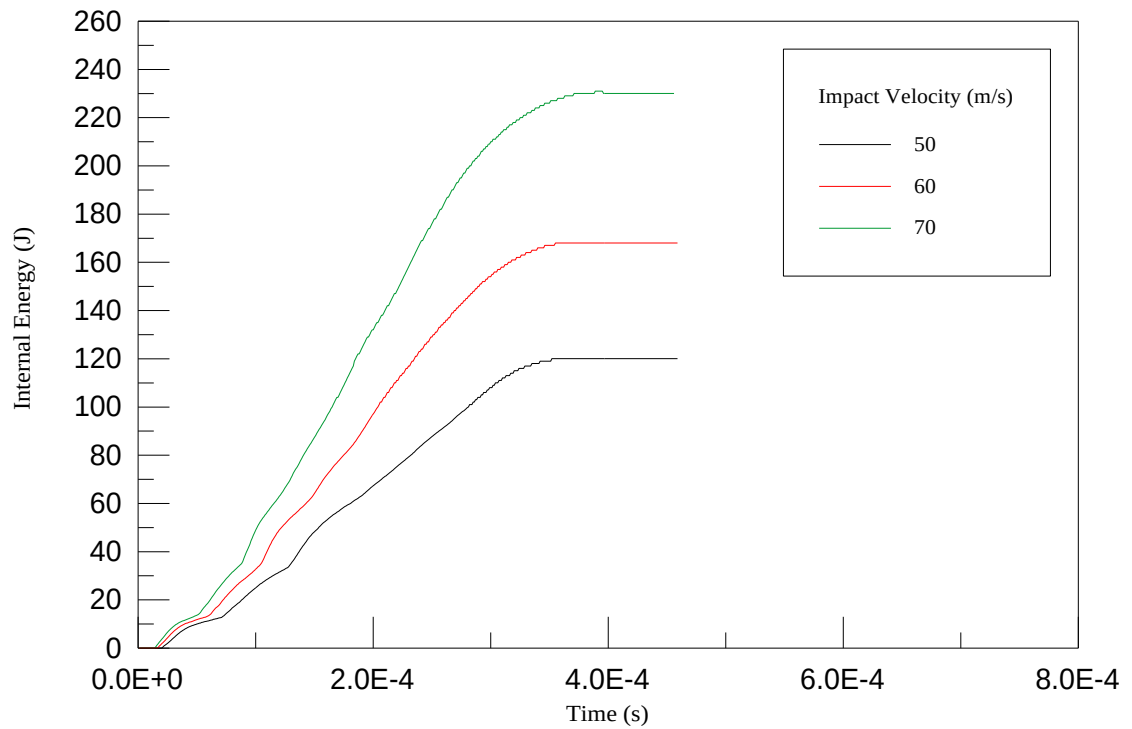


Figure 3.18 : Internal energy vs. time at different velocities for sample 1.

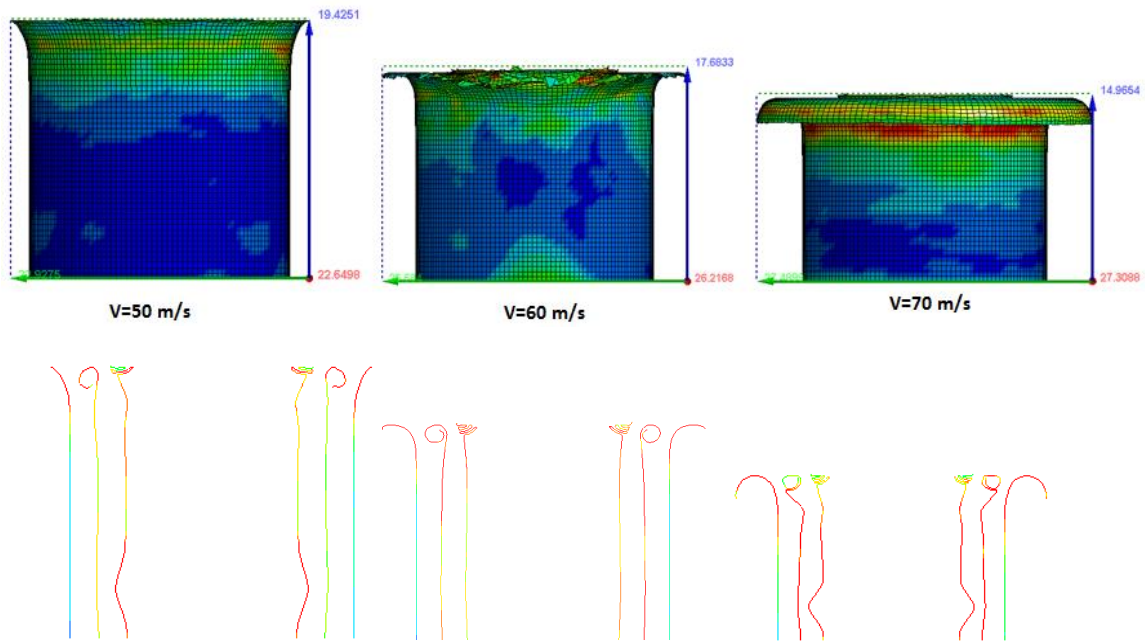


Figure 3.19 : Von Mises stress distribution and final lengths of sample 1.

For sample 2, internal energy amounts are 118, 171 and 279 J in Fig. 3.20, respectively. Besides, total deflections are 11.6, 12.4 and 15.1 mm in Fig. 3.21.

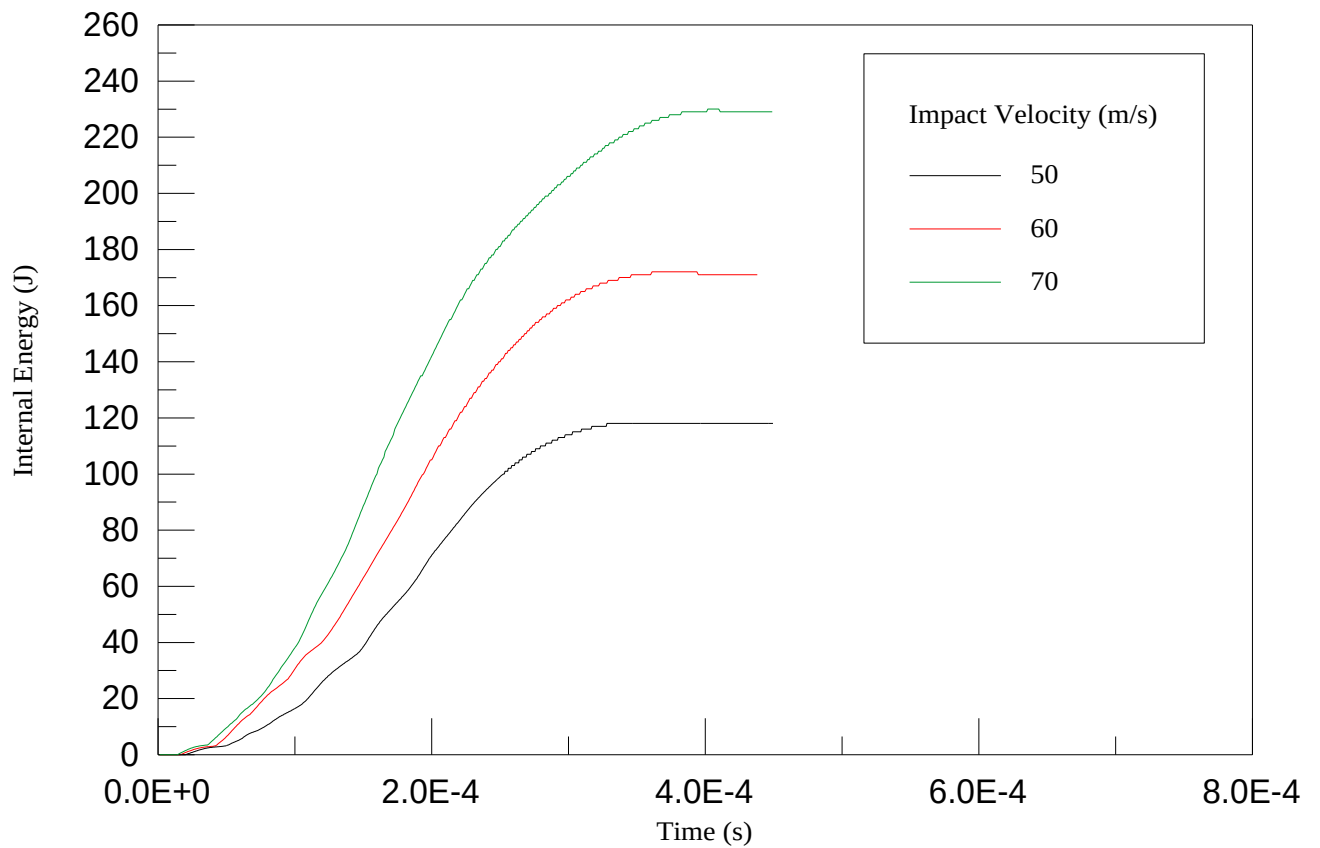


Figure 3.20 : Internal energy vs. time at different velocities for sample 2.

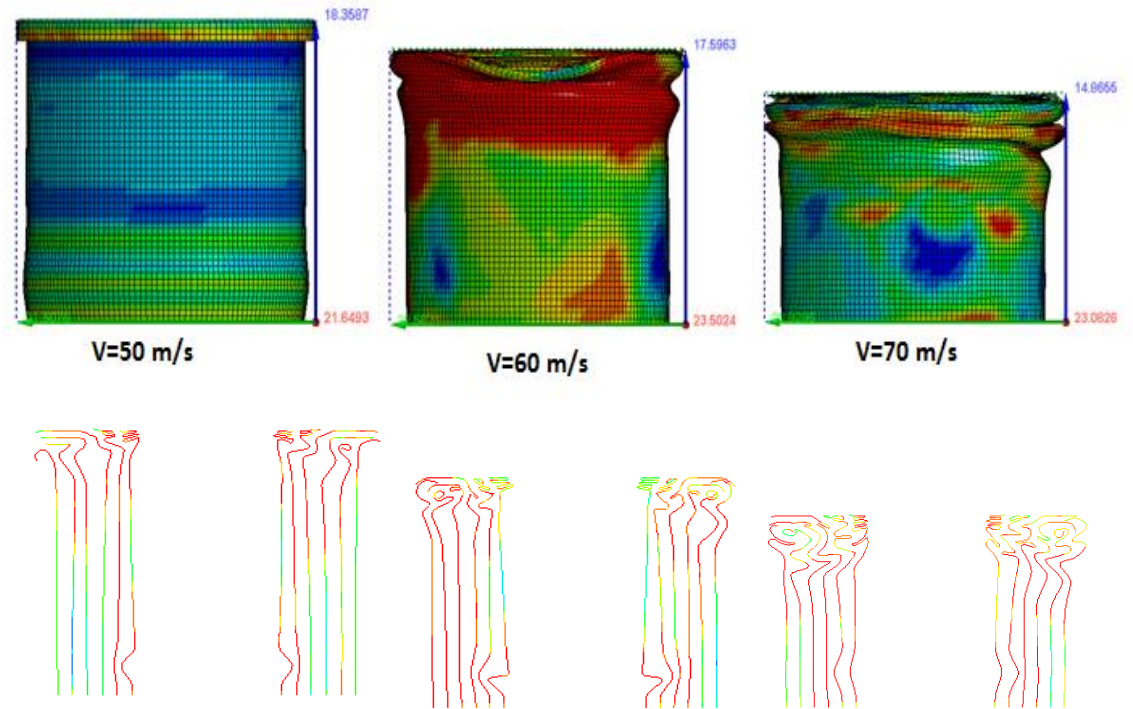


Figure 3.21 : Von Mises stress distribution and final lengths of sample 2.

For sample 3, internal energy amounts are 116, 168 and 226 J in Fig. 3.22, respectively. Besides, total deflections are 10.7, 13.0 and 16.4 mm in Fig. 3.23.

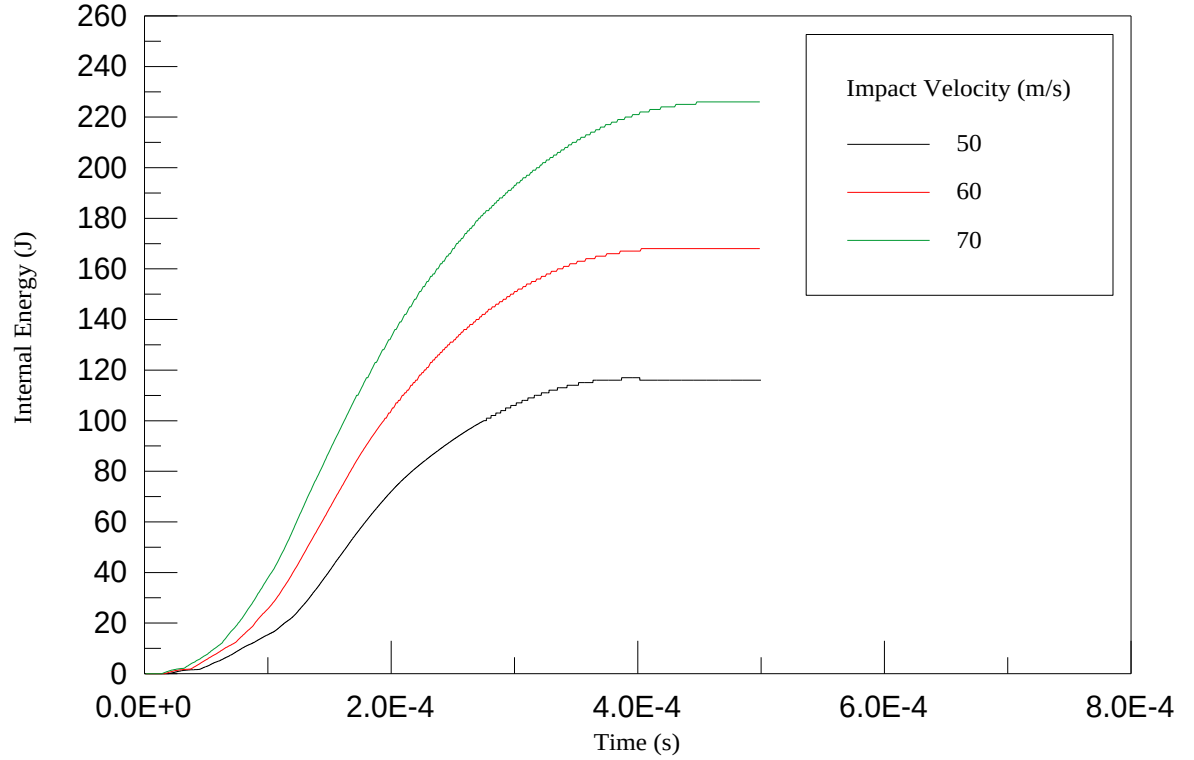


Figure 3.22 : Internal Energy vs. time at different velocities for sample 3.

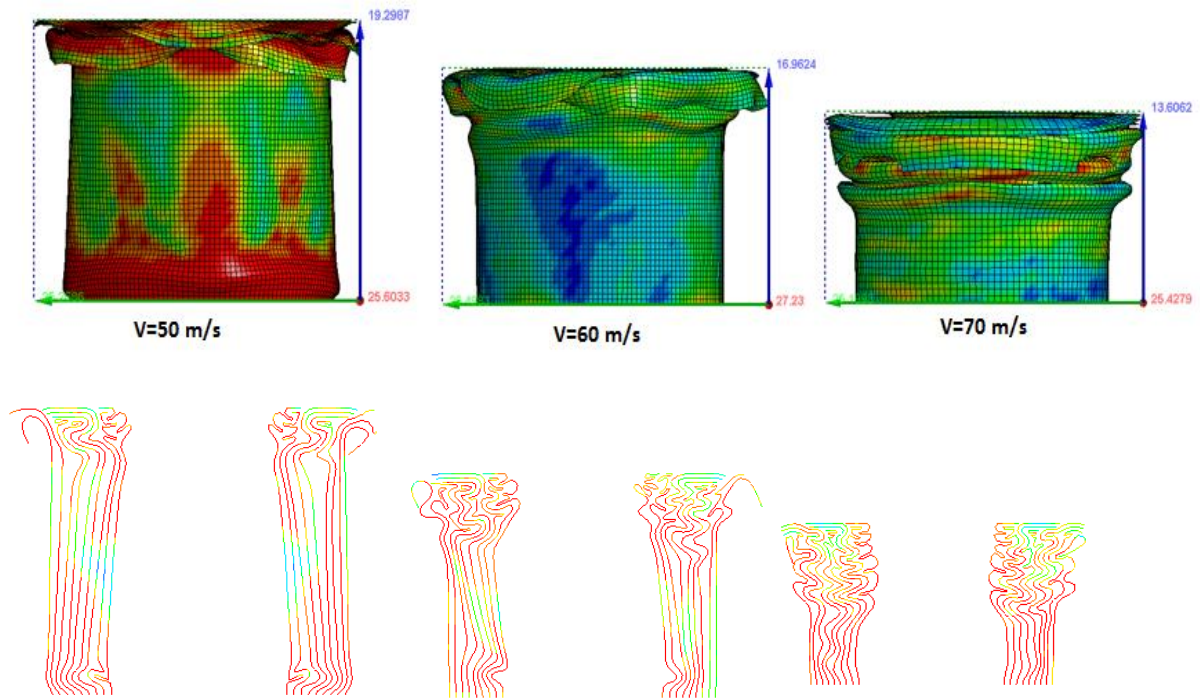


Figure 3.23 : Von Mises stress distribution and final lengths of sample 3.

For sample 4, internal energy amounts are 115, 163 and 224 J in Fig. 3.24, respectively. Besides, total deflections are 11.2054, 14.1296 and 17.4430 mm in Fig. 3.25.

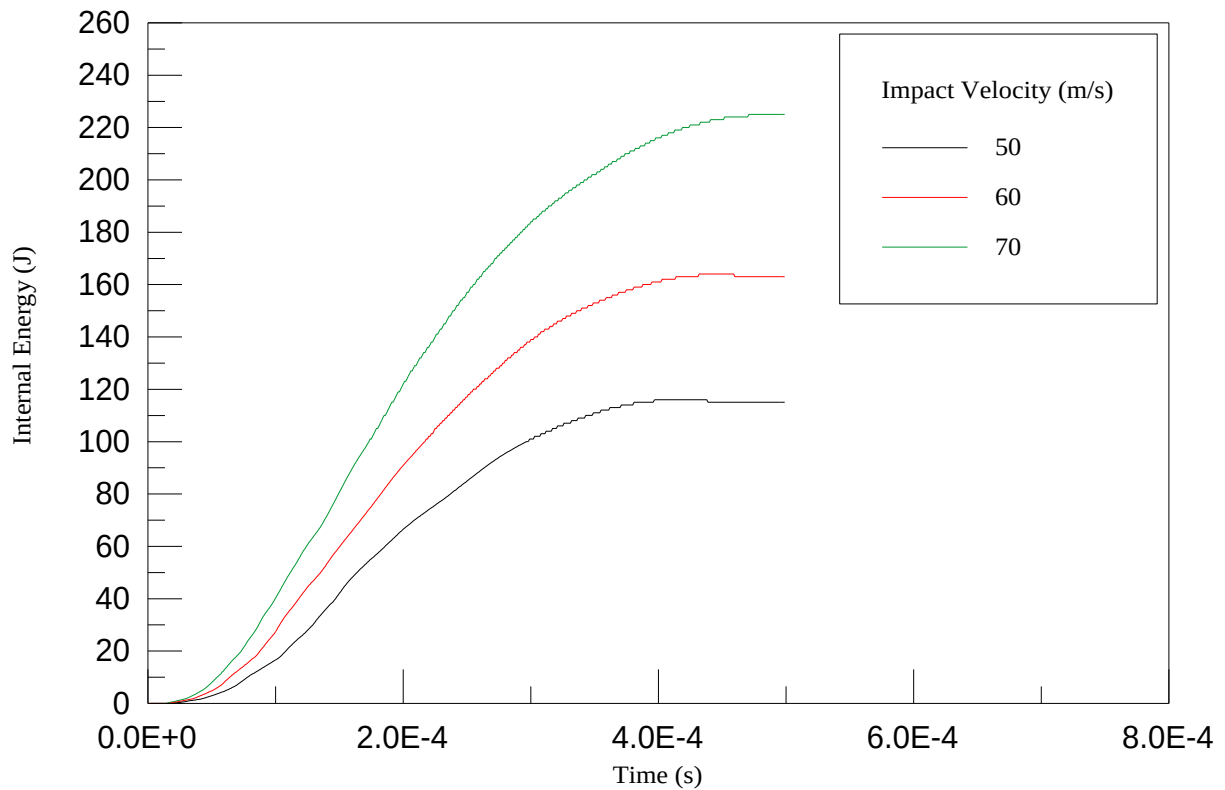


Figure 3.24 : Internal Energy vs. time at different velocities for Sample 4.

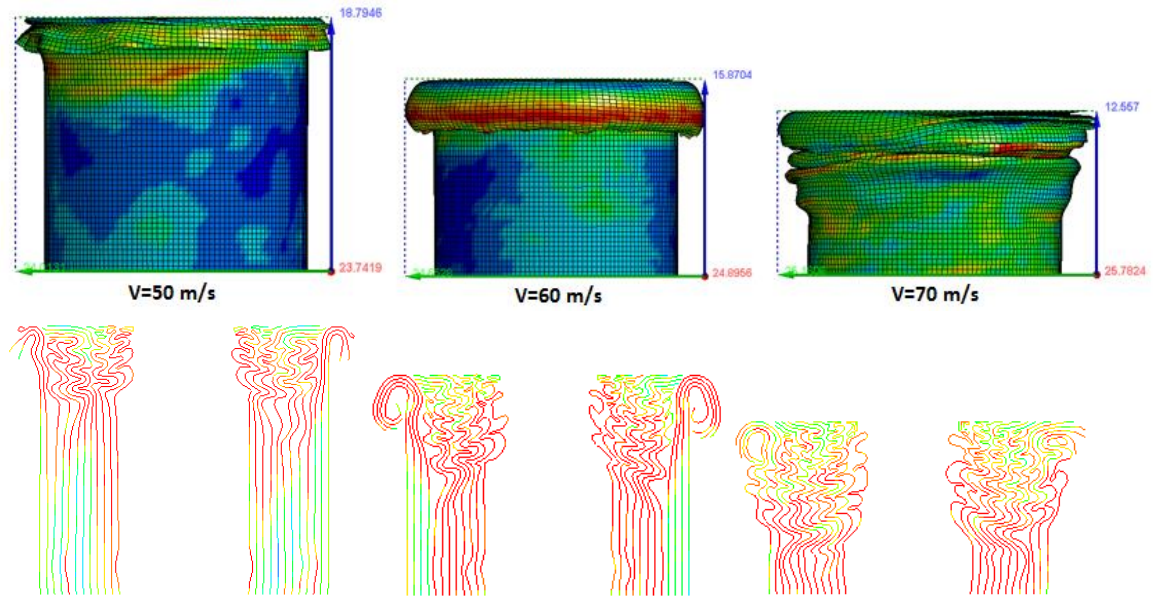


Figure 3.25 : Von Misses stress distribution and final lengths of sample 4.

3.4 Comparison of Foam Filled and Empty Crash Tubes

3.4.1 FEM of foam material in LS DYNA

Material of foam is selected as Aluminum. Stress-strain curve is shown in Fig. 3.26. Young modulus of aluminum foam is equal to 64.8 GPa and density is equal to 270 kg/m^3 . Foam material has too low density. Also, its poison ratio is too low which is equal to 0.011 [20]. Therefore, under axially impact loads, longitudinal deformation of tubes is higher than its lateral deformation. Material properties in LS DYNA is defined with 063 CRUSHABLE FOAM under MAT toolbar.

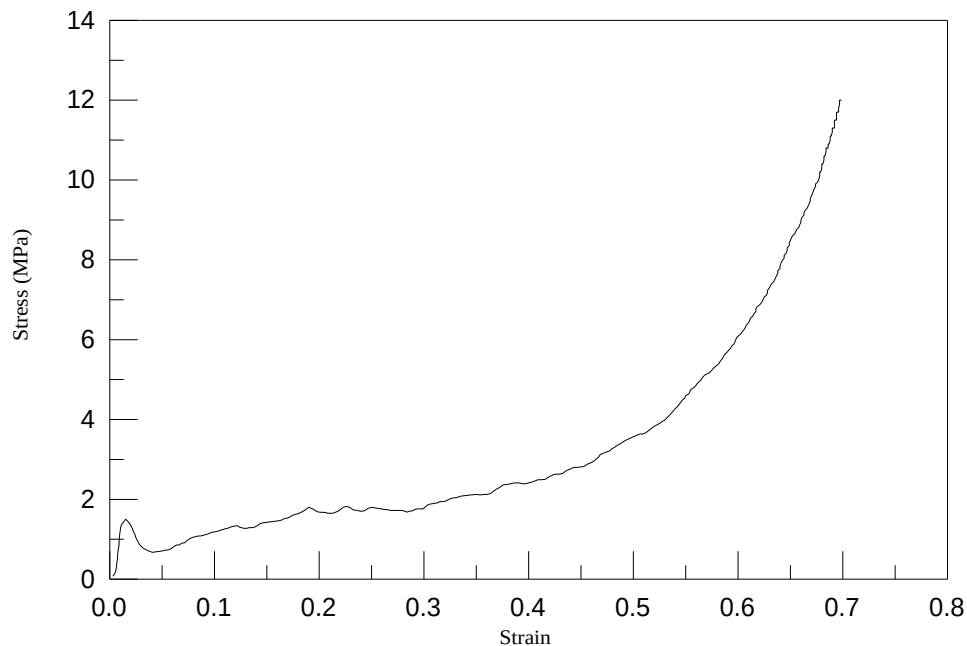


Figure 3.26 : Stress vs. strain curve of foam material made of aluminum.

3.4.2 Analyses and comparison of foam filled tubes with empty tubes

In Fig. 3.27, view of four models with foam material are shown before and after crashing. Results of these analysis are compared with results of empty tubes' analysis. “Force vs. Time” and “Internal Energy vs. Time” curves are drawn for each sample in Fig 3.28-3.35. According to these comparison, it is seen that peak forces of tubes with foam models are higher especially for 3rd peak forces.

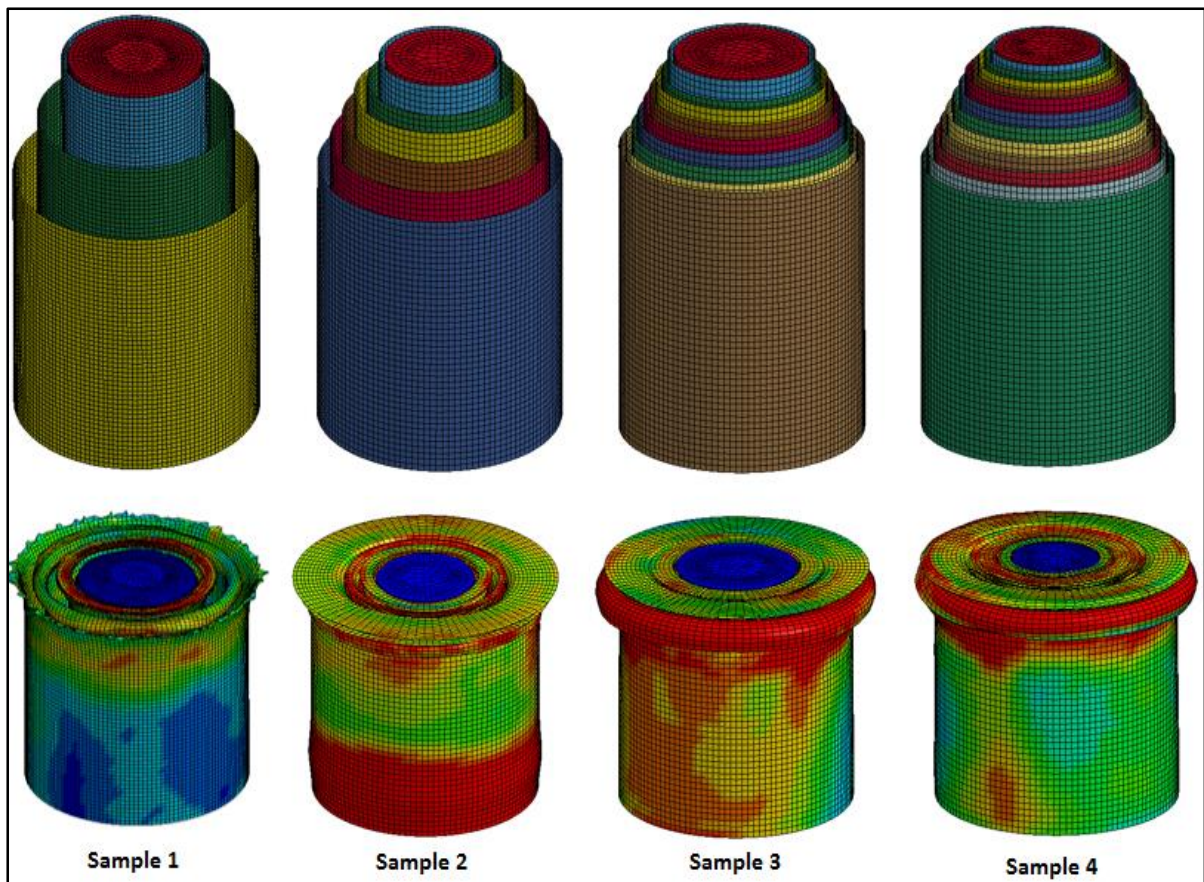


Figure 3.27 : FEM and von Mises stress distribution of foam filled tubes.

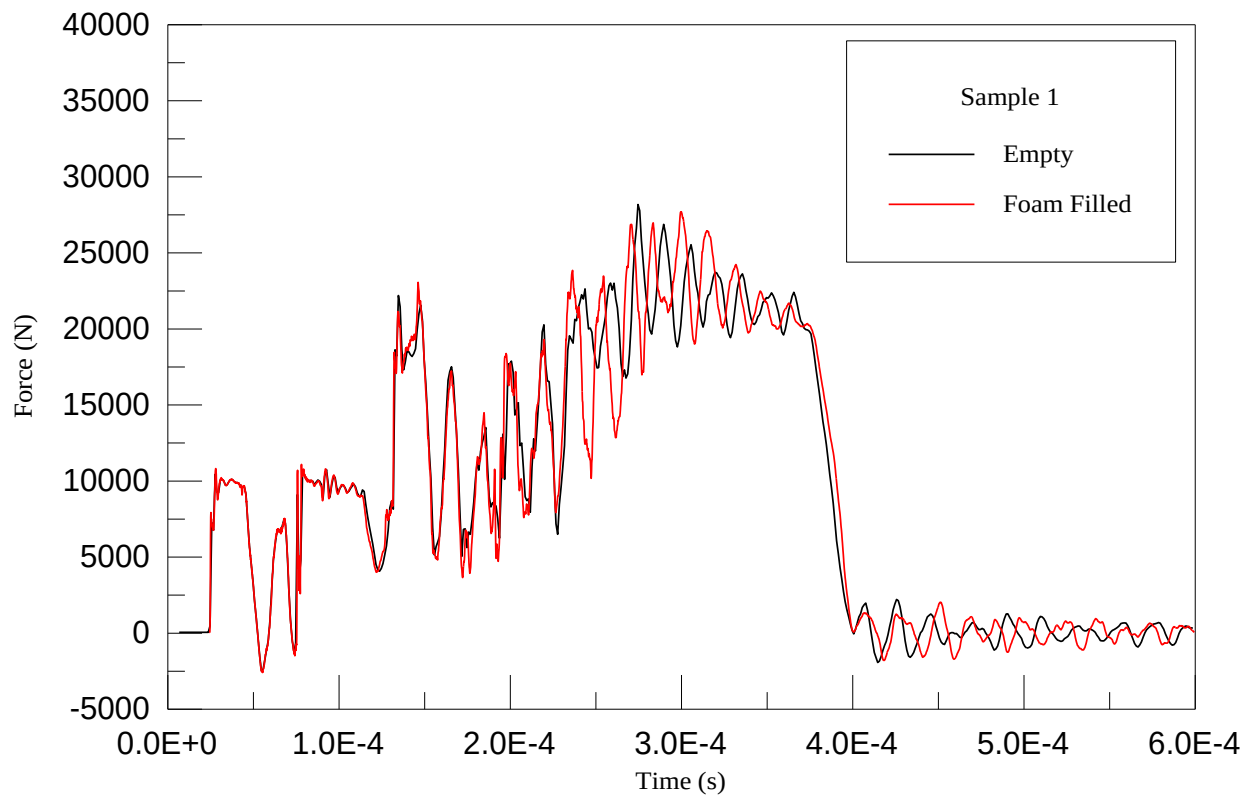


Figure 3.28 : Force vs. time curves of sample 1.

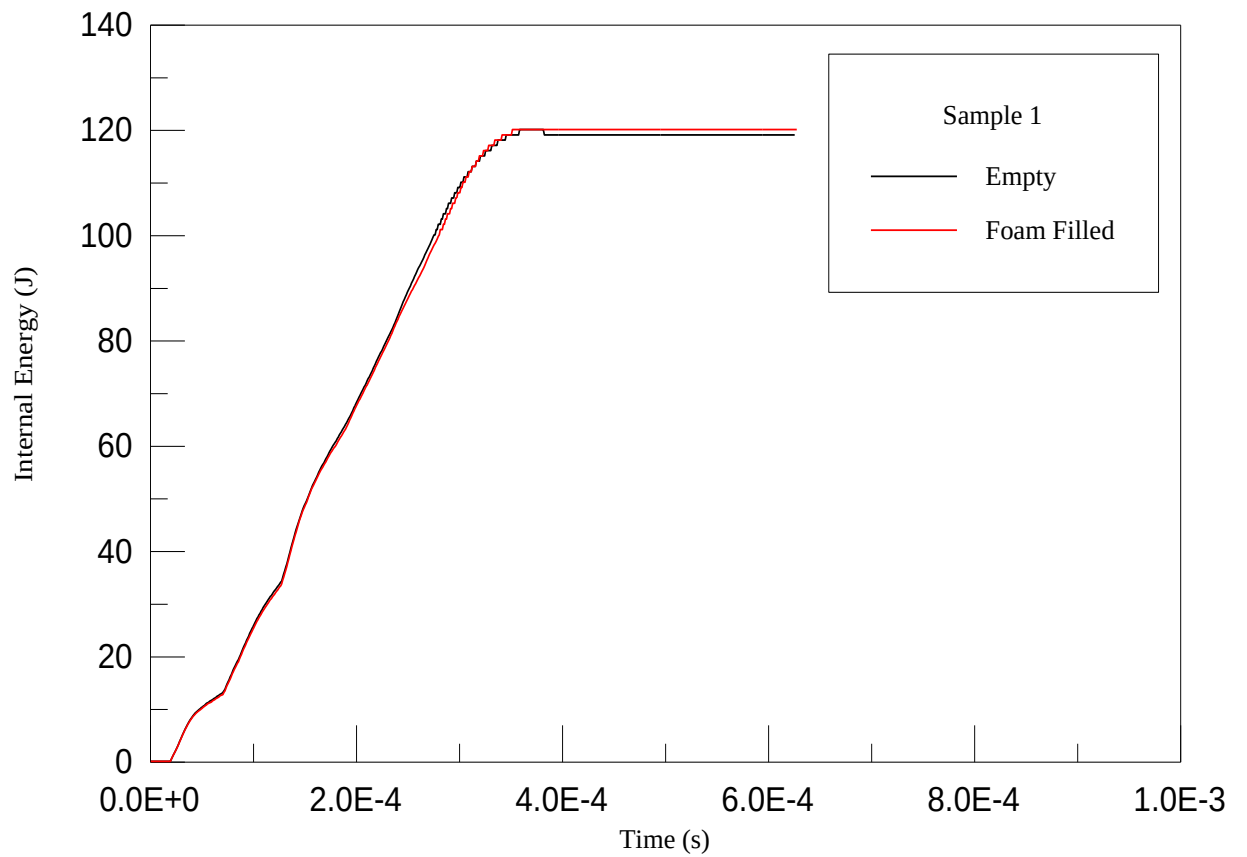


Figure 3.29 : Internal energy vs. time curves of sample 1.

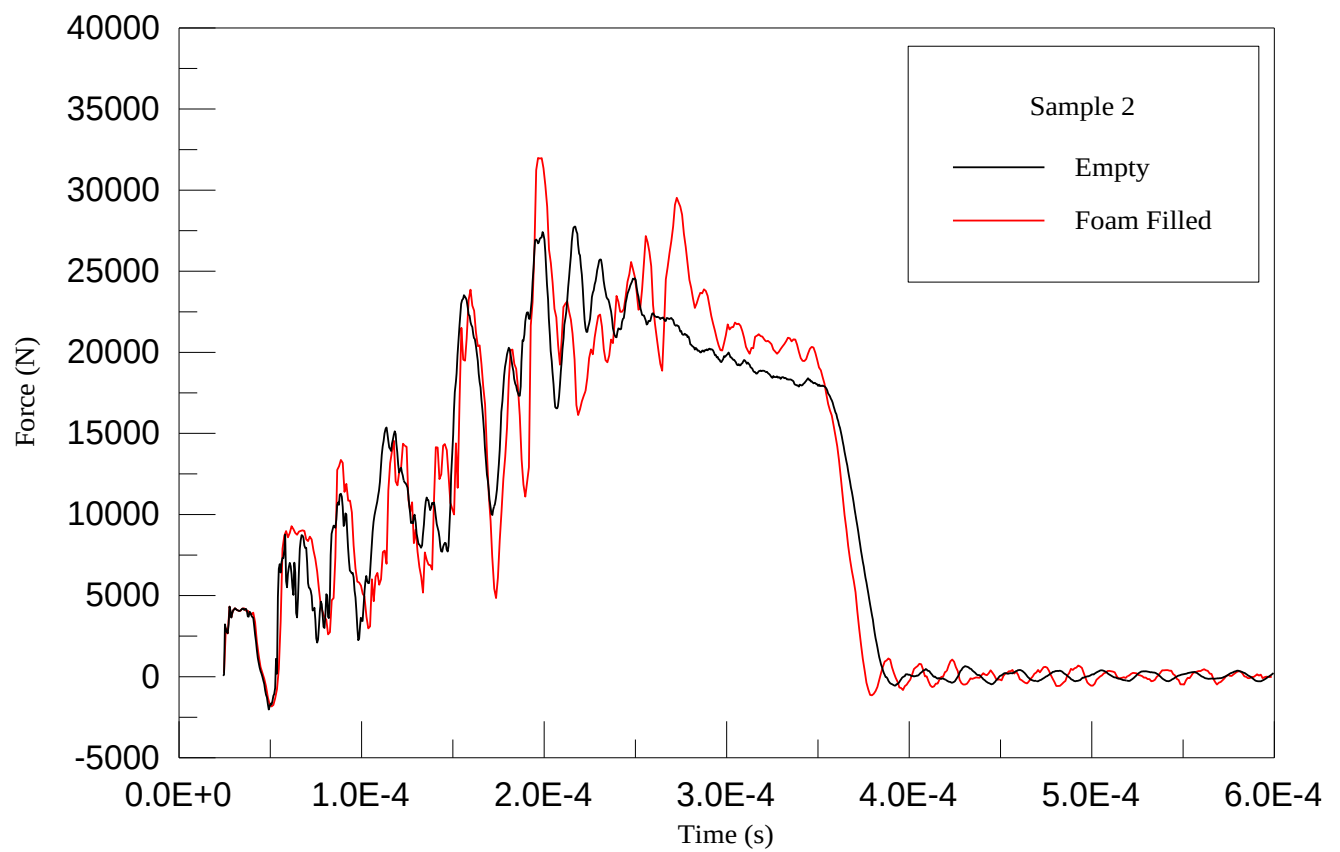


Figure 3.30 : Force vs. time curves of sample 2.

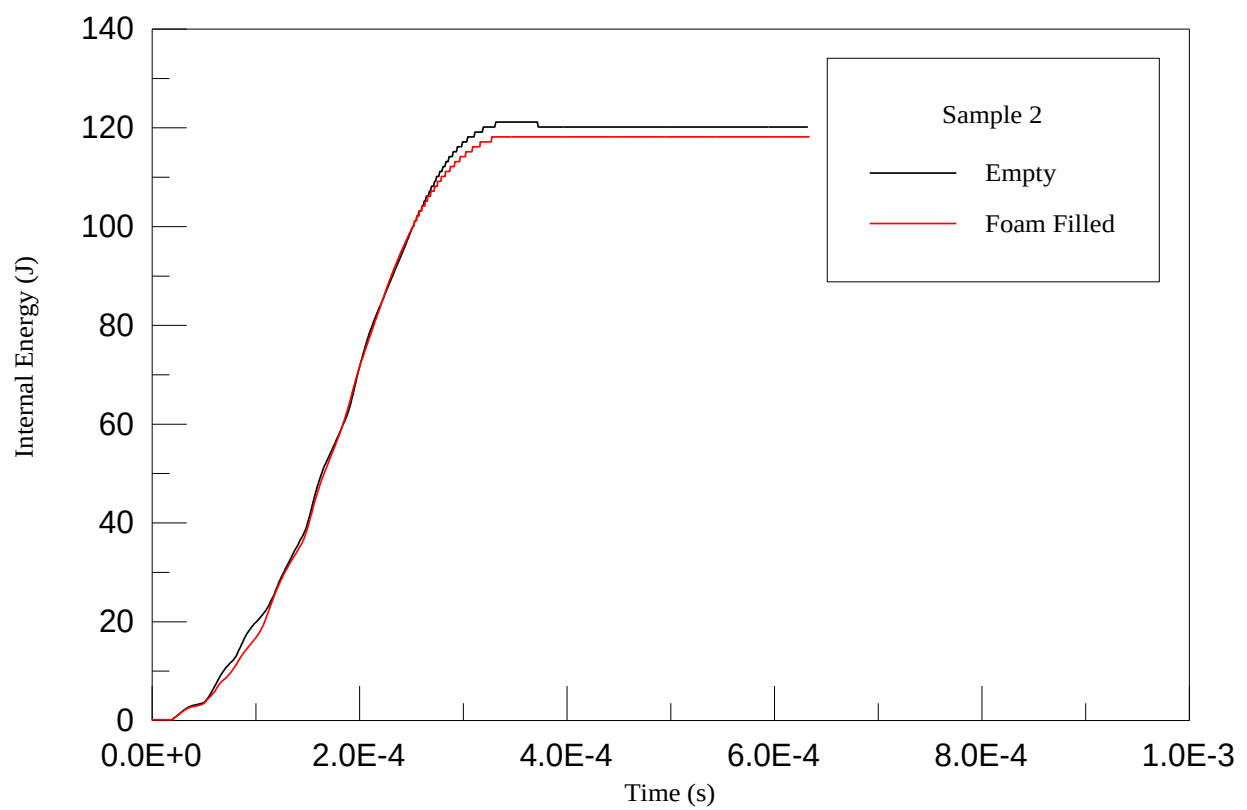


Figure 3.31 : Internal energy vs. time curves of sample 2.

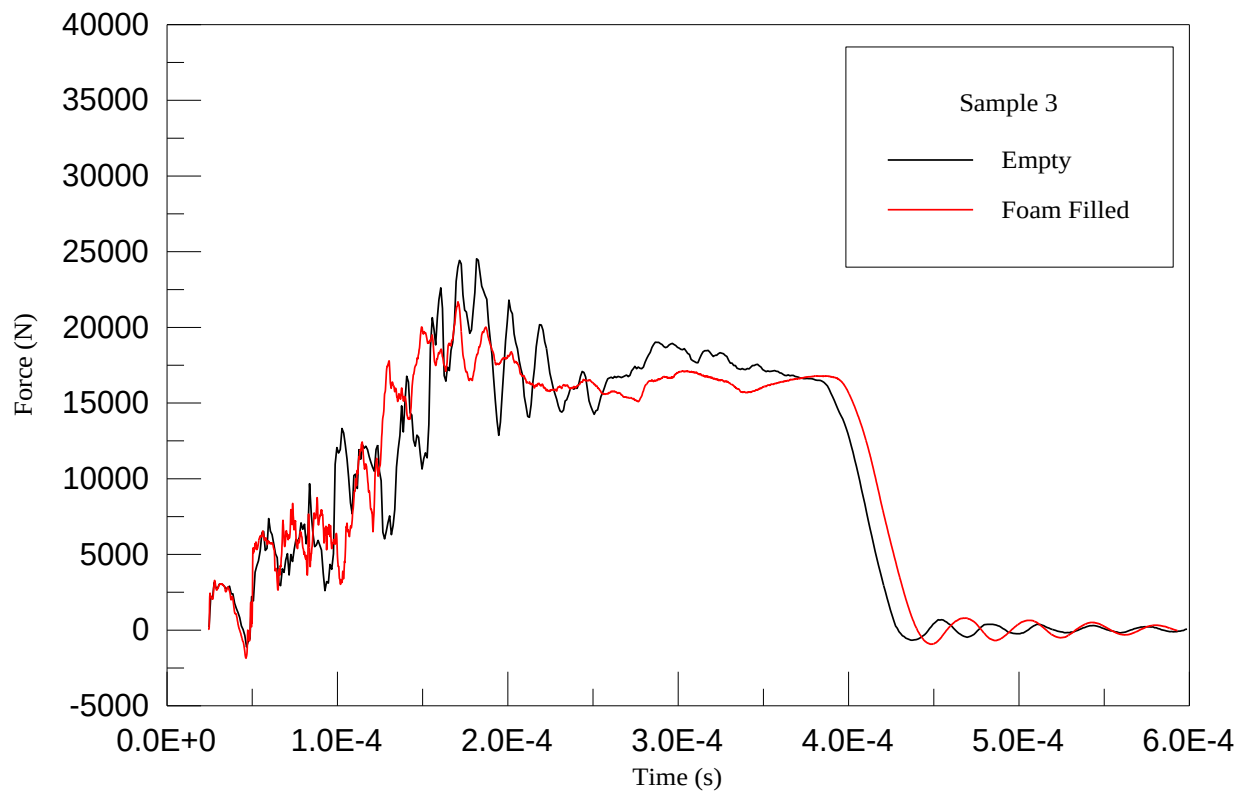


Figure 3.32 : Force vs. time curves of sample 3.

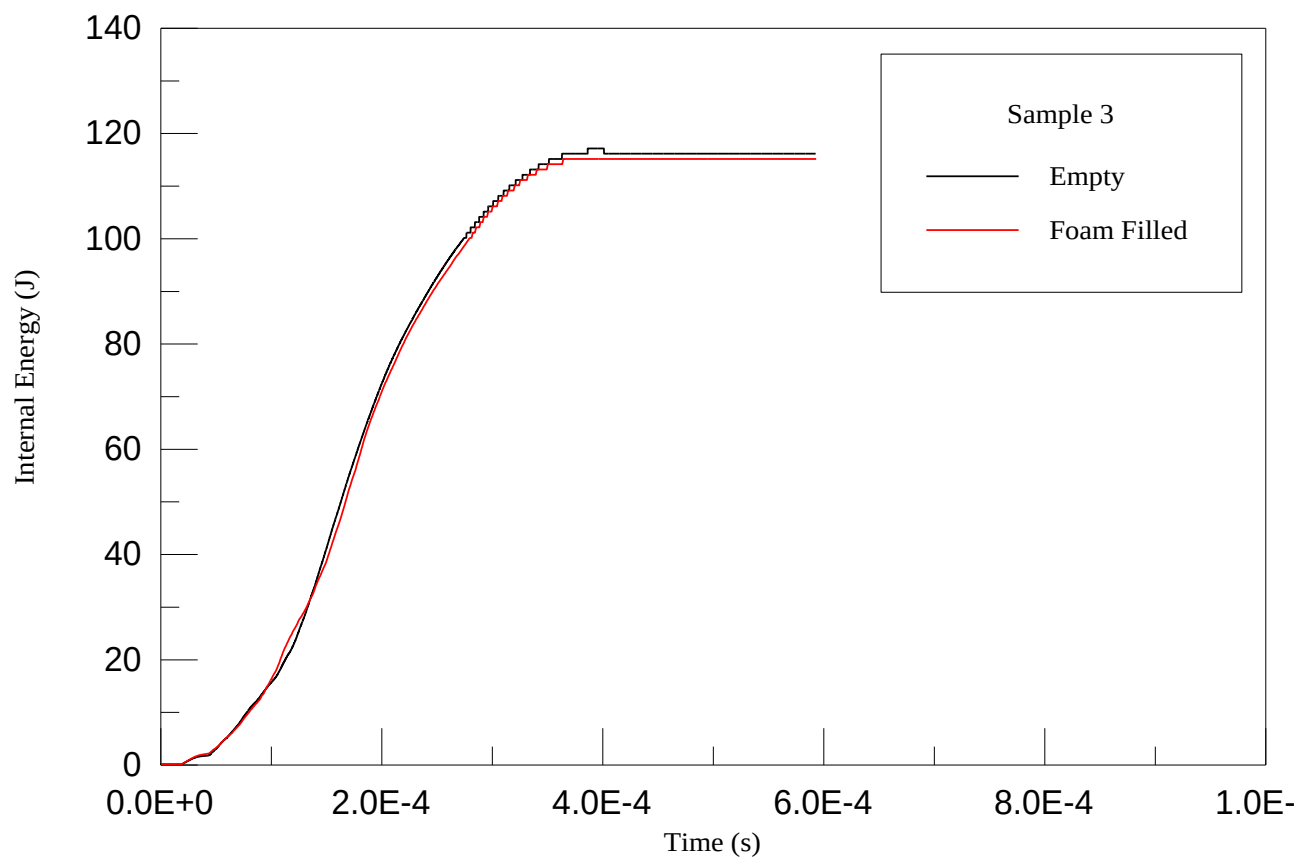


Figure 3.33 : Internal energy vs. time curves of sample 3.

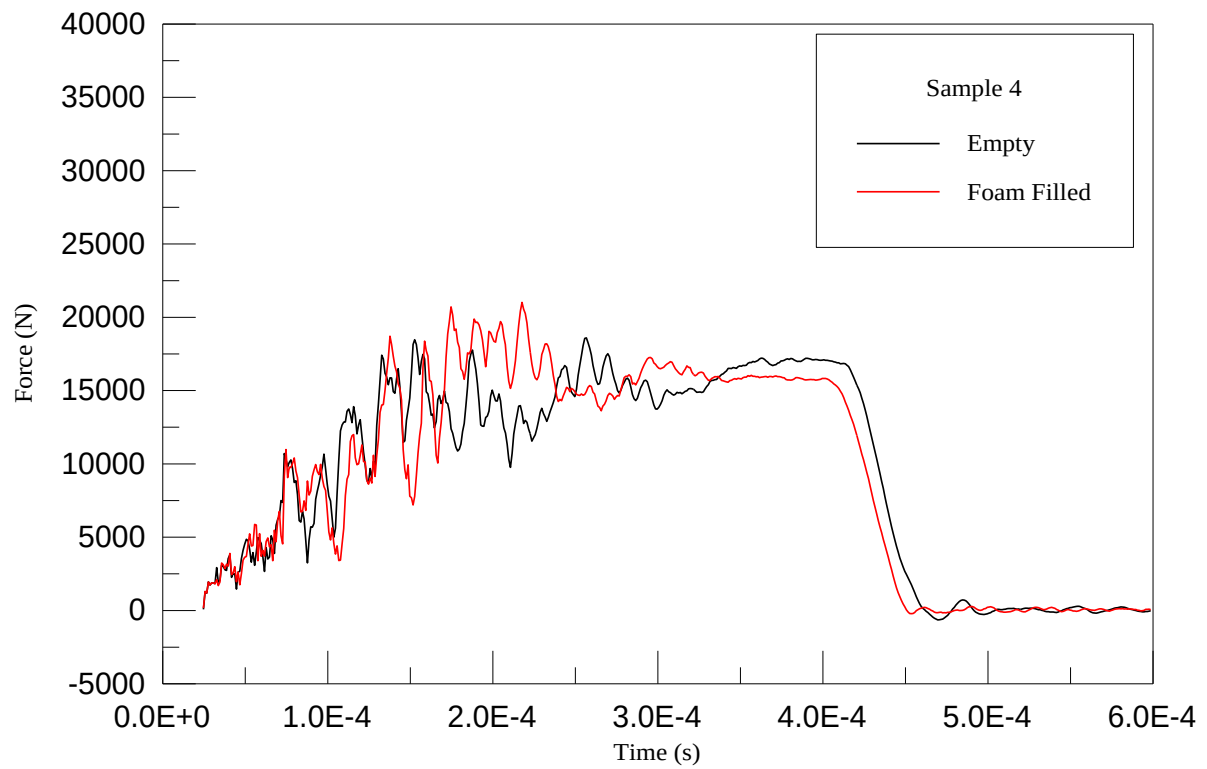


Figure 3.34 : Force vs. time curves of sample 4.

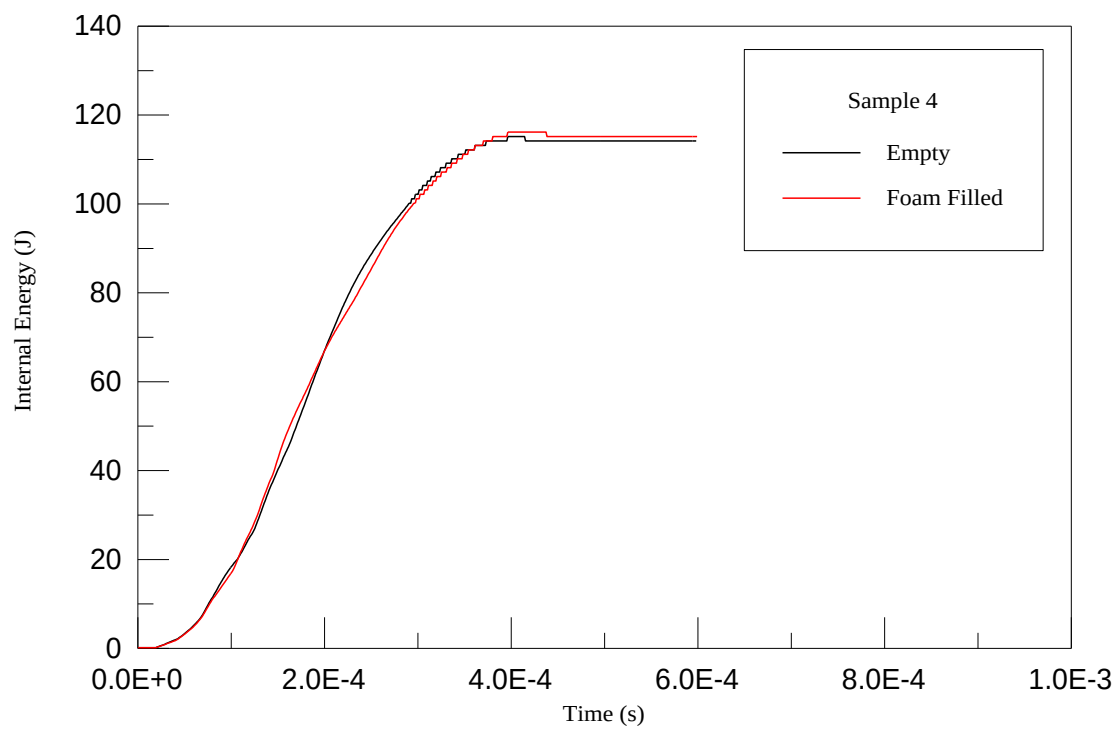


Figure 3.35 : Internal energy vs. time curves of sample 4.

4. CONCLUSION

In this thesis, stepped concentric crash tubes made of aluminum alloy are analyzed under axial loads and investigated the effect of the number of tubes in LS DYNA software program. Total mass and volume of all samples are restricted to observe efficiency of crashworthiness properties such as peak crushing force and energy absorption capability.

As the number of concentric tubes is increased, it is observed a smooth transition of the peak forces during the impact. Beside this, increasing the number of tubes results in reducing the maximum peak force. Also, it brings about a reduction of the initial peak force due to lower wall thickness of the tubes. It can reduce the inertial effects because of peak forces on vehicles and people. These results show that increasing the number of stepped concentric tubes improves crashworthiness properties in terms of peak forces. Furthermore, minimizing the size of concentric tubes can prevent or reduce the probability of penetration of impact objects. Analyzing models at different impact velocities gives similar results. In addition to these, crash tubes with aluminum foam have higher the peak forces in comparison with empty tubes.

4.1 Future Works

There might be implemented three future works. First study is comparison of the solution time at quasi-static speed by using LS-DYNA and ADINA. Second one is an experimental study on foam filled crash tubes and validation of experimental results by using numerical methods. Final future work is considered as an experimental study on small-sized crash tubes in sandwich plates as an energy absorber.

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APPENDICES

APPENDIX A: Information of articles on crash boxes

Table A1: Information of articles on crash boxes

Paper Year	software										Speed		Geometry							Material			Configuration				
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit				Experimental Theoretical		Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular Square		Rectangular Hexagonal Other			Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled
									Quasi static (m/s)	Dynamic (m/s)				Circular	Square												
1986 [4]								x	x	136	x	x	x	x				23.3-300.3	0.87-1.65	x			x		x		
1993 [21]				x				x			1.67E-4		x	x				100	1.6	MS	x		x	x	x		
1996 [13]								x	x		1.67E-4		x					12.7-127	2.3-5.7			x	x		x		
1997 [22]						MARC K6.2		x		7.92		1.4 2.8 3.7		x				100	1.0		A6063		x		x		
1997 [5]								x	x	210	1.0E-4 1.0E-3	12.14	x	x				20-1800	0.96-1.56	MS			x		x		
1989 [23]								x	x		1.67E-4			x				124.7-133.5	0.74-1.52	x			x		x		
1999 [14]	x						x			10-100	x	15.0		x				310	1.8-2.5		A6060-T4 A6060-T6		x		x		
1998 [24]			x					x	x	394		5.0		x				250	1.9	MS			x		x		
2000 [11]				x			x			0.2-335		4-180	x					38.1-152.4	0.91-6.35		A6061-T6		x		x		
2000 [25]								x	x		6.67E-4			x				800	1.76 1.90 2.46		A6060			x	x		

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software										Speed		Geometry						Material			Configuration						
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit				Experimental Theoretical	Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell
2000 [26]										x					2.1E-4			x				150	5.0			x	x	
2000 [27]										x			2.0E-4				x			350 657	2.0		HS5754		x	x	x	x
2000 [28]									x	x			5.5E-4 8.33E-4	12.6- 24.2		x				295	1.43 2.46		AA6060		x	x	x	
2001 [7]				x				x			0.0352 0.103			17.5-80	x					106.68	1.0- 1.65	x	x		x		x	
2001 [29]			x						x				2.0E-4			x				675	2.0		HS5754		x	x	x	
2002 [30]								x			200	x		5.7 13.33		x				80-300	1.2-1.6	HSS			x		x	
2002 [31]						Optivar					500			13.9	x					400	1.15- 1.30	fep06			x		x	
2002 [15]			x				x			x	600			13.4112	x	x				400	1.0, 2.0		A6063-T7		x		x	x
2002 [32]			x				x			x				2.0		x				330 490	0.3 3.0		A6060-T4		x	x	x	
2003 [33]								x					1.17E-4			x				50 100 125	2.63 3.51 4.39			CFRP	x		x	

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software								Speed		Geometry						Material			Configuration								
	LS-DYNA	ADINA	PAM-CRASH	ABAQUS	ANSYS	other			Explicit	Implicit	Experimental	Theoretical	Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular
2003 [34]				x					x		2.4		60		x				300	2.0		x						
2003 [2]	x						x		x		100		10	x	x		x	x	200	1.0-3.0		A6063		x		x		
2003 [35]	x						x		x			5.0E-5		x					245	1.47-1.51		A6060-T4		x	x	x		
2003 [36]	x						x		x			2.7E-4			x				199	2.0-4.5		A6060-T4 A6060-T6		x		x		
2004 [37]	x						x		x	x	211	x	<16		x						HSS MS			x		x		
2004 [38]	x						x		x		1400	2.5E-3	13 20		x				400-1920	2- 4.5		A6060-T6		x		x		
2004 [39]									x			1.6E-4	5.4		x				50 100 125	2.64 3.51 4.39			CFRP	x		x		
2004 [34]				x			x		x				14.84-98.27	x	x				146	1.14		A6063		x		x		
2004 [40]	x						x		x			1.38E-4			x				199	1.77		A6060-T4 A6060-T6		x	x	x		
2004 [41]	x			x			x			x	80 90	x	<30			x			300	1.5 2.0 2.5	MS			x		x		

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Speed		Geometry						Material			Configuration							
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit			Experimental Theoretical		Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell
2004 [42]									x				2.5E-4							x	165	5.0			x	x		x
2004 [43]	x							x		x		x				x				300	2.0 2.5 3.0		A6061-T4		x	x	x	
2005 [44]	X							X		x		82		18			x				3.0 3.5			FRC		x		x
2005 [45]				x				x					x			x				300	1.5 2.0 2.5	MS			x		x	
2005 [46]									x				2.5E-4		x				x	150				x		x	x	
2005 [47]	x							x		x	x		8.3E-5			x				200	1.5	MS			x	x	x	
2005 [48]									x				4.17E-5 1.6E-3		x					40	0.22, 0.29		x		x			
2006 [49]									x				4.1E-5			x				240- 645	1.40- 1.59		x			x		
2006 [50]				x				x		x			x	1.49 -3.33				x		100 200	1.0 2.0		A6063-T6		x		x	
2006 [51]			x					x			35 0			16			x			300	1.335		TRIP800		x		x	

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software											Speed		Geometry								Material			Configuration			
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit					Experimental Theoretical	Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular
2006 [52]										x					4.16E-5													
2006 [53]			x		x			x		x			1.6E-3		x					40	0.23-0.29		x		x	x	x	
2006 [54]	x							x			x			10		x				150	0.6		A6060 T4		x			x
2007 [55]				x					x	x			1.2E-3		x					200	3.5	MS			x		x	
2007 [56]	x							x			92			12.5		x		x		150 91	2 2.4 2.7		x	woven fiber polyamid	x		x	
2007 [57]	x							x			250			1					x	127	1.52	x				x		
2007 [58]									x				1.0E-3		x	x				27	0.53 0.85 1.32		hybrid Al-Comp.	CFRP	x	x	x	
2007 [59]	x							x					x			x				120	1.2		A6060		x		x	
2008 [16]			x		x	x							4.16E-5			x		x		25 35	2.5		x		x	x	x	x
2008 [60]	x							x			x	500		10		x				400	1.4-3		A6061-T4		x		x	x

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Speed		Geometry							Material			Configuration					
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit			Experimental Theoretical	Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell
2008 [61]	x						x		x				128														
2008 [62]				x			x		x			10E-4 10E-1	16			x			300-500	3	MS			x		x	
2008 [63]	x						x		x		154		7-10		x				270	2		6060		x	x	x	
2008 [64]	x						x		x		28		2 4		x				70-100	0.5 0.7 0.9	MS	x		x		x	
2008 [65]	x						x						10				x		150	0.5-1.5		A6060		x			x
2008 [66]	x						x		x		154	x	5.1-9.2	x	x	x			240	2		A6060		x			x
2008 [67]							x		x	x	90 560	x	15		x				300	1.5	MS			x	x		
2009 [9]	x						x				600		20		x				200	2.5		A6060		x		x	
2009 [68]									x		200	x	13 10		x	x			300	1	DC02			x		x	
2009 [69]	x						x				500		10		x				400	1.4-3.0		A6060		x	x	x	

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Mass (kg)	Speed		Geometry							Material			Configuration				
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit				Experimental Theoretical		Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular
2009 [70]	x							x					10		x				130	1.2	HSS of SPRC40R			x		x	
2009 [71]	x							x				3.3E-5			x				250 100	3.0			GFRP	x	x		
2010 [72]	x							x		x		1.6E-3		x	x	x	x	x	100	1.0 1.5		A3003 H12		x		x	
2010 [73]	x							x		x	360		16	x	x	x	x	x	250	1.5	DP600			x		x	
2010 [74]	x										60 90		9 15	x	x		x		180	0.5- 2.5	MS			x		x	
2010 [6]	x							x				1.0E-1		x					250	1.0- 2.53	x			x		x	
2010 [8]	x							x		x	1400 600		13 20		x				638- 1920	2-4		A6060		x		x	
2010 [75]	x							x		x			15	x					200-300	1.5 2.0 2.5		x		x	x	x	
2010 [76]	x							x		x		8.3E-5 8.3E-3	5.5		x				120	2.0 2.5 3.0		1050H4 Al sheet alloy		x	x		
2011 [77]	x							x			250		10	x					200	2.2		A6061-T4		x	x	x	

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Mass (kg)	Speed		Geometry						Material			Configuration					
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit				Experimental Theoretical	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell
2011 [78]	x							x		x	100		10		x		x	x	50	0.6-1.4		AA6060 T4		x	x	x	x
2011 [79]				x				x				x	20 10	x					98.5 97.5	0.99 0.97		x			x	x	
2011 [3]									x			x		x	x		x	100	1.0 2.0			Synolit e 1408-		x	x		
2011 [80]			x					x			350		16			x			300	1.34 1.59	DP600			x		x	
2011 [81]				x				x				1.6667e-4		x					97.3 97.4 97.5	0.84-1.0		x		x	x	x	
2011 [82]	x							x				x			x				120	2.0 2.5 3.0		1050H1 4-A061T4		x	x	x	
2012 [83]									x						x				50 80 120	1.7 3.4 4.2			silk/epoxy	x		x	
2012 [10]	x	x						x			600	x	5 -15		x				310	1.17-1.20	HSS			x	x	x	
2012 [84]						x		x		x	500		15.6						1200	1.7		AL6260 T6		x		x	
2012 [85]	x							x					10		x				150	0.5-3.0		AA6060 T4		x			x

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Mass (kg)	Speed		Geometry							Material			Configuration				
	LS-DYNA	ADINA	PAM-CRASH	ABAQUS	ANSYS	other	Explicit				Implicit	Experimental	Theoretical	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled
2012 [86]	x						x		x		294		4	x	x				200 300	1.5 2.0 2.5			CFRP	x	x		
2012 [87]	x						x		x		400		15		x				250	2.0		A6063-T6		x	x	x	x
2013 [88]						x	x		x		500		15.60		x				1200	1.7		A6260-T6		x	x		
2013 [89]									x		250		4.44		x				250	1.94- 2.72			Al/CF RP	x	x		
2013 [90]	x						x		x		29		10		x				220	1.0		A1050-H24 A5052-H34		x		x	
2013 [91]				x			x					x	20					x	776.8	2.0	x	x		x		x	
2013 [92]	x						x				68.8 5		9.30	x					50 220	3.0			x	x		x	
2013 [93]				x			x		x		150		5 5.5 7		x				300	2.0		A6063 T4		x		x	
2013 [94]	x						x						6.94	x					75.1	0.8		A6061-T6		x		x	
2013 [95]	x						x						4.16	x	x			x	125 150 200	0.8 1.2 1.6	x			x		x	

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Speed		Geometry						Material			Configuration					
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit			Experimental Theoretical	Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular
2013 [96]	x						x		x			10		x				200	1.4 1.2 3.0		A6063 T6		x	x	x	
2013 [97]	x						x		x		1000	1.2E-3		x				160	1.65		A7075		x		x	
2013 [98]	x						x		x		110		6.5	x		x	x	200	0.7 0.85	x			x		x	
2013 [99]	x						x		x			2.0E-3			x		x	250	0.7	x			x		x	
2013 [100]	x						x		x			1.6E-4			x			200	1.00 3.15		A6060-T4		x		x	
2013 [101]									x			1.6E-4		x				144	1.0- 2.0	x			x	x	x	
2013 [102]									x			1.6E-4					x	320-470	1.0- 2.0	IF, DP, TRIP			x		x	
2013 [103]									x			3.3E-4			x			50	1.7			x	x		x	
2013 [104]	x						x		x			1.6E-4		x				100 200	1.5		A6060		x		x	
2013 [105]						x	x		x				6.10- 7.95		x			180	1.15 1.3		A6063 T1			x	x	

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software								Experimental Theoretical	Mass (kg)	Speed		Geometry								Material			Configuration			
	LS-DYNA	ADINA	PAM-CRASH	ABAQUS	ANSYS	other	Explicit	Implicit			Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell	
[2013 [106]	x						x		x		1000	1.2E-3						160	1.65		A7075		x		x		
2013 [107]						MSC Dytran	x		x			x		x				50 80 120	1.7 3.4 4.2			silk/epoxy	x		x		
2013 [108]	x						x				600		15		x			240	2.0		A6060 T4		x	x	x		
2013 [109]						x	x		x		45.5		4.36 - 4.40		x			180	1.15		A6063–T1		x		x		
2013 [110]	x						x						15.67	x				600			Al6260-T6		x		x		
2013 [111]				x			x		x		700		6.7			x			0.87-2.44	x			x	x	x		
2014 [19]	x						x		x		128		4.4		x			550	0.6-2.0		AlMg0.5 F22			x	x		
2014 [112]	x						x		x		600		5					410	1.2	DP800			x		x		
2014 [113]						x			x	x		x	5		x			180	6.0				x		x		
2014 [114]	x						x				60		20	x				200	1.5-2.5		x			x	x		

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software										Speed		Geometry							Material			Configuration					
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit				Experimental Theoretical	Mass (kg)	Quasi static (m/s)	Dynamic (m/s)	Circular Square Rectangular Hexagonal Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell				
									Quasi static (m/s)	Dynamic (m/s)																		
2014 [115]				x				x		x		x	20						17.2-40	1.0		x		x				
2014 [116]	x							x		x		600		15					780	2.0-4.0		A6060-T4		x		x		
2014 [117]	x							x		x	x		5.0E-4		x				120	1.2		A6061		x		x	x	
2014 [118]	x							x		x		600		5-15					310	1.2	DP800			x		x		
2014 [119]	x							x		x				10	x				200	1.2-2.8		A6060-T5		x	x	x		
2014 [120]	x							x				600		15		x			200	0.8 1.0 1.2		A6060T4			x	x	x	
2014 [121]										x			x			x			120	1.6		x	x	x		x		
2014 [122]										x			1.6E-4		x				96 129	2.4			FFRP - D64	x	x	x		
2014 [123]	x							x	x	x		60	x	7 10 15	x				135	1.4	DP800	A7005 A7003 A6061						
2014 [124]				x				x		x			5.0E-1		x	x			588	2.0				x		x		

Table A1: Information of articles on crash boxes (cont.)

Paper Year	software									Mass (kg)	Speed		Geometry								Material			Configuration			
	LS-DYNA ADINA PAM-CRASH ABAQUS ANSYS other						Explicit Implicit				Experimental Theoretical	Quasi static (m/s)	Dynamic (m/s)	Circular	Square	Rectangular	Hexagonal	Other	Length (mm)	Thickness (mm)	Steel	Aluminum	Composite	Empty	Foam-filled	Singular	Multi-cell
2014 [125]									x																		
2014 [126]	x							x					6.5			x			250	0.7			SPE- 220BH				
2014 [127]								x		x	500		15.56		x				600	1.7		AL6260-T6		x		x	
2014 [128]				x				x			125		10	x					300	2.0		EN AW- 7108 T6		x		x	
2014 [129]	x							x			1000	1.2E-3							140	1.65	x	x		x		x	
2014 [130]			x					x				3.3E-4			x				150	2.08			CFRP	x		x	
2014 [131]	x							x			600		15	x					240	2.0		A6060 T4			x	x	

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- Usta F., Eren Z., Turkmen H.S., Kazancı Z., Mecitoglu Z., 2015. Numerical Investigation of Stepped Concentric Crash Tubes Subjected to Axial Impact: The Effects of Number of Tubes. *International Congress – RAST* June 16-19, 2015 Istanbul, Turkey