MARMARA UNIVERSITY

INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES

SIMULATION AND FAILURE ANALYSIS OF A DROP TESTED WALL-MOUNTED AIR CONDITIONER INDOOR UNIT

Mehmet Fazlı TEKNECİ

MASTER THESIS

Department of Mechanical Engineering

Thesis Supervisor

Prof. Dr. Paşa YAYLA

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Mehmet Fazlı TEKNECİ, a Master of Science student of Marmara University Institute for Graduate Studies in Pure and Applied Sciences, defended his thesis entitled "**Simulation and Failure Analysis of a Drop Tested Wall-Mounted Air Conditioner Indoor Unit**", on **18th of September 2019** and has been found to be satisfactory by the jury members.

Jury Members

Prof. Dr. Paşa YAYLA (Advisor)
Marmara University ....(SIGN)................

Prof.Dr. Bülent EKİCİ (Jury Member)
Marmara University ....(SIGN)................

Prof.Dr. Şafak YILMAZ (Jury Member)
Marmara University ....(SIGN)................

APPROVAL

Marmara University Institute for Graduate Studies in Pure and Applied Sciences Executive Committee approves that Mehmet Fazlı TEKNECİ be granted the degree of Master of Science in Department of Mechanical Engineering, Mechanical Engineering Program on .... (Resolution no: ....).

Director of the Institute

Prof. Dr. Bülent EKİCİ

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SEPTEMBER, 2019 **Mehmet Fazlı TEKNECİ**

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BİR DUVAR TİPİ KLİMA İÇ ÜNİTESİNİN DÜŞÜRME TESTİNİN SİMÜLASYONU VE HASAR ANALİZİ

Tüm ev aletleri ve elektronik cihazlar, nakliye sırasında düşme, çarpma ve ezilme gibi bazı kazalara maruz kalmaktadır. Uygun olmayan taşıma koşulları, yerden kaldırma ve yere indirme sırasındaki dikkatsizlik bazı plastik parçaların kırılmasına, bazı sac levha parçaların çarpılmasına veya bükülmesine neden olabilir. Bu durum sadece müşteri memnuniyetsizliğine değil aynı zamanda şirketlerde para kaybına da neden olmaktadır. Bu sorunları önlemek için, birçok ürünün paketlemesinde Genişletilebilir Polistiren (EPS: Expanded Polistren) malzeme bazlı parçalar kullanılır. EPS malzeme bazlı parçalar darbe emici özelliklerinden dolayı en yaygın kullanılan parçalardır. Fırın, çamaşır makinesi, bulaşık makinesi, buzdolabı gibi ev aletleri ve optik pikap, televizyon, test tahtası ve cep telefonu gibi elektronik cihazlar için düşme testi ile geçmişte bazı çalışmalar yapılmıştır. Bu çalışmada ise bir duvar tipi klima iç ünitesinin düşme anındaki dinamik davranışı analiz edilmiştir. Sonlu Elemanlar Analizi için ANSYS yazılımı kullanılmış, ASTM D5276 (1998) ve ASTM D880 (2002) standartlarına göre düşme testi yapılmıştır. Gerilme ölçerler hasara maruz kalan dekor tırnağı ve hava çıkış kanalı tırnağına yapıştırılarak etkin gerilme değerlerini ölçmek için kullanılmıştır. Düşme testi yüksek hızlı kamera ile kayıt altına alınarak ürünün sert zemin ile temas süresi tespit edilmiş, bu süre sonlu elemanlar analizinde girdi olarak kullanılmıştır. Düşme testinde deforme olan dekor tırnağı üzerindeki gerilim değeri 255,2 MPa, hava çıkış kanalı tırnağı üzerindeki gerilim değeri 97,1 MPa olarak ölçülmüştür. Sonuçlar sonlu elemanlar analizden ölçülen değerlerle karşılaştırılıp analiz doğrulanmıştır. Hasarlı alanlar için iyileştirmeler yapılmış ve bu iyileştirmelerin yeterliliği düşme testi, nakliye testi ve sıkıştırma testleri ile de doğrulanmıştır. Gerinim ölçerler ile düşme testi yapmak ve sonlu elemanlar metodundan faydalanmak, ürün geliştirme ve pazara sunma sürelerini azaltmış, maliyetleri düşürmüş ve tasarımın erken aşamalarında önlem alınmasını sağlanmıştır. Bu çalışma salon, tavan vb. diğer türdeki klimaların paketlenmeleri ve olası hasarların ve aşırı şekil değişimlerin engellenmesi için de referans bir rehber olma niteliği de taşımaktadır.

ABSTRACT

SIMULATION AND FAILURE ANALYSIS OF A DROP TESTED WALL-MOUNTED AIR CONDITIONER INDOOR UNIT

All of the home appliances and electronic devices are exposed some incidents such as dropping, striking and crushing etc. during transportation. Unsuitable carrying conditions, carelessness during picking up from floor and putting down may cause breaking of some plastic parts, wrapping or bending of some sheet metal based parts. This situation cause not only customer dissatisfaction but also loss of money for the company. In order to prevent these problems, Expandable Polystyrene (EPS) material based parts are used on the packaging of a wall-mounted air conditioner indoor unit. The EPS material based parts are the most commonly used ones because of their impact absorber properties. There are some studies about drop test for home appliances such as oven, washing machine, dishwasher, and refrigerator and for electronic devices such as optical pickup, television, test board and mobile phone. In this study dynamic behaviour of a wall-mounted air conditioner indoor unit was analysed under drop impact condition. To perform Finite Element (FE) analysis, ANSYS commercial software was used and the drop tests were performed according to ASTM D5276 (1998) and ASTM D880 (2002) standards. Strain gauges were used to measure the effective stresses at the bottom edge of decor hook and at the back side of discharge grille hook which were subjected to excessive deformation. A high speed camera was employed to record drop test, special attention is paid to detect contact duration between the product and rigid ground. This duration was used as an import value at Finite Element analysis. During drop test, the stress values were measured as 255,2 MPa for decor hook and 97,1 MPa for discharge grille hook. The FE and physical test strain gauge results were compared to validate the FE analysis. Improvements on the wall-mounted air conditioner indoor unit were made at damaged locations and those improvements were validated by drop test, transportation test and clamping test. Conducting the strain gauges instrumented drop test and utilizing the FE results decreased lead time of product development, reduced the product development costs and eliminated the potential risks in the product

in advance. This approach presented with this work can be a reference guide for developing more effective packing types and preventing failure and accidents for cassette, floor standing etc. air conditioners in future studies.

SYMBOLS and UNITS

Symbols	Explanation	Unit
F	Force	N
A	Area	mm^2
σ	Stress	N/mm^2
ΔL	Total deformation	mm
L	Length	mm
ε	Strain	
E	Elastic modulus	GPa
v	Poisson's ratio	
K	Stiffness matrix	
u	Vectors of unknowns	
η	Efficiency	
ΔT	Temperature difference	K
R32	HFC blend	
R22	HFC blend	
R410A	HFC blend	
V_0	Initial velocity	mm/s
H	Height	mm
G	Gravity	mm/s^2

Subscripts

FR-4	Glass-Reinforced Epoxy Laminate Material
in.	Inch
Imp.	Improvement

ABBREVIATIONS

EPS	Expandable Polystyrene
ASTM	American Society for Testing and Materials
FEA	Finite Element Analysis
ODD	Optical Dick Driver
TV	Television
ESL	Equivalent Static Loads
JEDEC	Joint Electron Device Engineering Council
LCD	Liquid Crystal Display
FEM	Finite Element Method
ABS	Akrilonitril Bütadien Stiren
PP	Polipropilen
BASF	Badische Anilin Soda Fabrik
CFD	Computational Fluid Dynamics
MEMS	Micro Electromechanical Systems
DTM	Drop Test Module
GF	Gauge Factor

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1. INTRODUCTION

1.1. AIR CONDITIONERS

Air conditioner is a machine that changes temperature and humidity values of air in a closed area. This process is made in order to improve thermal comfort of occupants and air quality. These machines are used both on domestic and commercial areas. Air conditioner removes moisture and decrease temperature by blowing cold air to enclosed area especially during hot weather. This process can be achieved by vapor compression cycle in which R32, R22 and R410A are used as refrigerant separately. Compressor increases temperature and pressure of refrigerant. Condensing is the second step of process. Refrigerant gives its heat to outside air and switches to liquid form at same pressure. At the third stage an expansion valve decreases pressure of refrigerant. At the last stage refrigerant takes heat and humidity from inside air by the help of evaporator. A schematic diagram of air conditioner working cycle is shown in Figure 1.1.

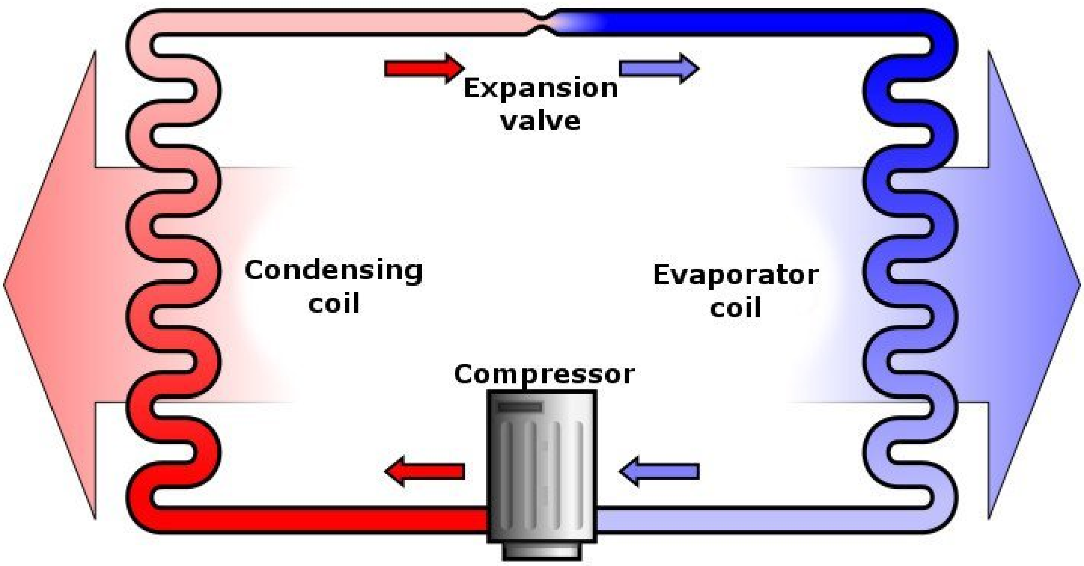


Figure 1.1 Simplified Diagram of the Air-Conditioning Process

When considering all purposes of air conditioner, these can be ranked as;

- Cooling of air or water;
- Heating of air or water;
- Air dehumidification;
- Air humidification;
- Air filtering/purification;
- Mixing of air indoor/outside air;
- Ventilation.

1.2. TYPES OF AIR CONDITIONERS

There are many different types of air conditioners based on their used area such as cars, buildings, markets, workplaces etc. It is usually decided by the volume of space in which air conditioner is used. These different types are;

- Wall mounted
- Window type
- Floor standing
- Cassette
- Portable
- Duct
- Air conditioners for cars

Some of these air conditioners can be shown in Figure 1.2.

Wall-Mounted **Floor Standing** **Cassette Type**

Figure 1.2 Types of Air Conditioners

1.3. TESTS OF AIR CONDITIONERS

In order to start mass production, all products must complete some tests successfully. In this context, air conditioners are exposed some test during design stage. Cooling and heating test are made in order to measure capacity of product. In a closed and sound- insulated chamber noise test is hold as shown in Figure 1.3.

Figure 1.3 Noise Test Chamber

Sweating test is hold to check whether there will be any dripping on surface of product in dump whether or not. Transportation test gives the results that vibration causes any damage on product or not as shown in Figure 1.4.

Figure 1.4 Transportation Test

Clamping test are hold to determine if any damage occur when floor standing type air conditioners are exposed to compress shown in Figure 1.5. While putting these products to trucks or any other carrying vehicle, usually clamping machine is used. Product must be strength enough to withstand these loads.

Figure 1.5 Clamping Test

Drop test is leaving the product to its different point or surface from a certain height in order to detect is there any deformed part or can these parts continue to perform their intended functions. In this study drop test was taken in consideration.

1.4. TRANSPORTATION PROBLEMS OF AIR CONDITIONERS

All of the home appliances and electronic devices are exposed some incidents such as dropping, striking and crushing etc. during transportation. Unsuitable carrying conditions, carelessness during picking up from floor and putting down may cause breaking of some plastic parts, wrapping or bending of some sheet metal based parts. This situation cause not only customer dissatisfaction but also loss of money for the company. In Figure 1.6 there is a front glass broken indoor unit and in Figure 1.7 there is a broken top cover of an outdoor unit of air conditioner as example. Selling products to customer with these deformations is impossible and precautions must be taken before mass production approval.

Figure 1.6 Front Glass Broken Indoor Unit

Figure 1.7 Top Cover Broken Outdoor Unit

1.5. BACKGROUND AND LITERATURE SURVEY

In order to prevent these transportation problems, Expandable Polystyrene (EPS) material based parts are used on the packaging of a wall-mounted air conditioner indoor unit. The EPS material based parts are the most commonly used ones because of their impact absorber properties. To check whether EPS parts are enough to prevent possible damages or not, drop test is made according to ASTM D5276 (1998) [1] and ASTM D880 (2002) [2]. Whether test result is good or not, the product becomes scrap. Not able to see weak points of the product which encounter damages on drop test in advance causes to repeat the test again and again. This trial and error process costs very much and causes time consuming.

There are some studies about drop test for home appliances such as oven [3, 4], washing machine [5], dishwasher [6, 7], refrigerator [8] etc. and for electronic devices such as optical pickup [9], television [10], test board [11] and mobile phone [12]

At a study performed by Asa [3], an oven was modelled numerically and its behaviour for various drop scenarios were examined. The model, created using the Hypermesh program, was solved for various fall situations using Radioss solver. When determining the number of elements during finite element analysis, the thickness of the parts was taken into consideration. Screws were defined as rigid connection and considered as moving together. Crash time of product was determined by recording the crash moment by high speed camera. The initial velocity calculated and used as input at analysis. The ground was thought as rigid also. When comparing the results shearing stress value was taken as reference. Four different side of the product were exposed to drop while experiment; bottom, front edge, right edge from 40 cm and bottom from 70 cm. Analysis time is shortened by using multi-zone approach. For better analysis result triangular elements were preferred as shown in Figure 1.8. Numerical model is verified with the experimental drop test results.

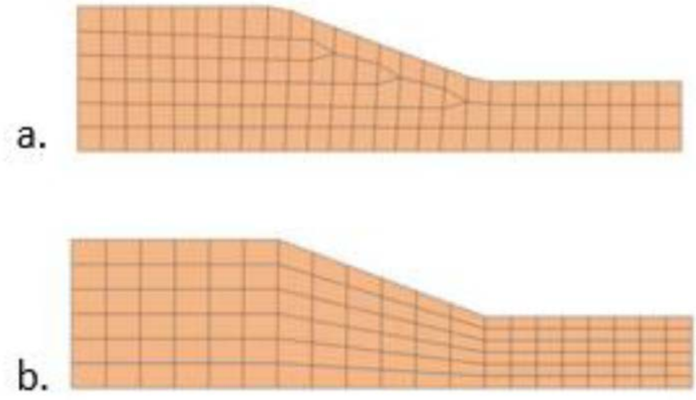


Figure 1.8 a. Element Shape for Impact Analysis

b. Element Shape for Static Analysis [3]

At a study carried out by Kim et al [4], dynamic behaviour of a package of a microwave oven under the drop-impact conditions was evaluated by the finite element analysis and tests. PAM-CRASH software was used for analysis. Direction and sequence of drop tests were clearly explained as shown in Figure 1.9.

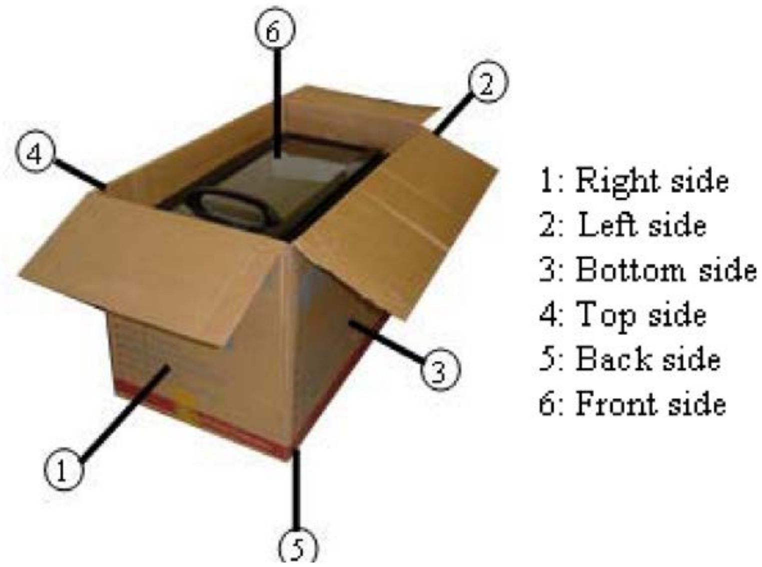


Figure 1.9 Direction and Sequence of Drop Tests [4]

Drop tests were performed according to the ISTA (International Safe Transit Association) specification. Experiment set up can be shown in Figure 1.10.

Figure 1.10 Drop Test Set Up [4]

Only first touch of product and rigid ground was taken into consideration but not followings. Results of the analysis are compared with those of the tests and accuracy is shown to be favorable. Comparison of simulation and experiment for deformed shape of magnetron base plate after bottom-side drop is can be shown in Figure 1.11.

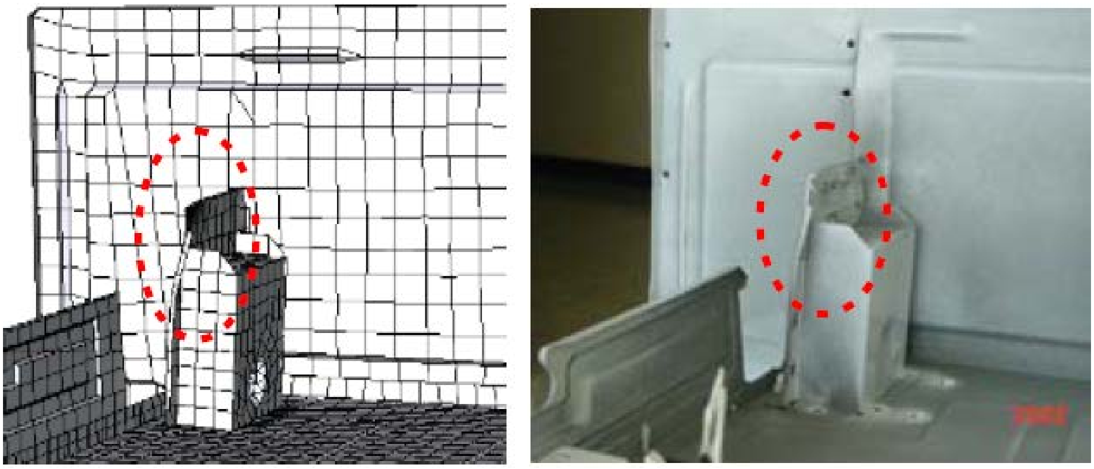


Figure 1.11 Comparison of Simulation and Experiment [4]

Kim and his co-workes examined cushion performance of a drum washing machine at their study [5]. Under the drop impact conditions they analyzed the dynamic behavior of the packaging. For performing the finite element analysis, LS-DYNA software and explicit method were used. For detection cushion characteristics and the design parameters of the original packaging they performed a series of test including drop test, vibration test, stacking test, squeeze test. Cushion curve is obtained as in Figure 1.12.

Figure 1.12 Cushion Curve of EPS [5]

On drop test they measured impact acceleration and effective stress with strain gauges and accelerometers by recording the test with high speed camera in order to make validation of test and analysis results. Test set up can be shown in Figure 1.13.

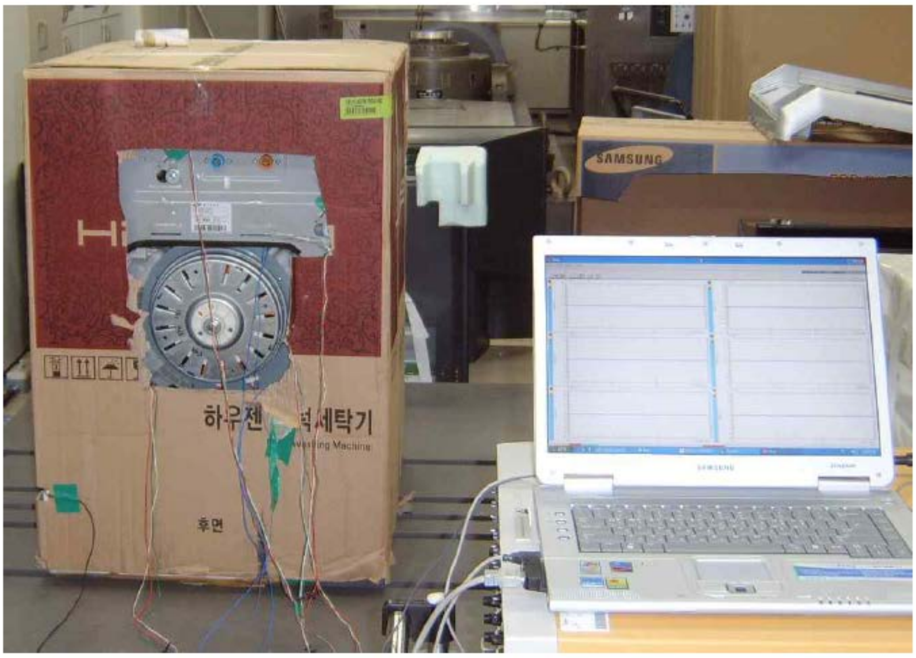


Figure 1.13 Drop Test Experiment Set Up [5]

Acceleration of simulation and experiment were compared via a graphic shown in Figure 1.14.

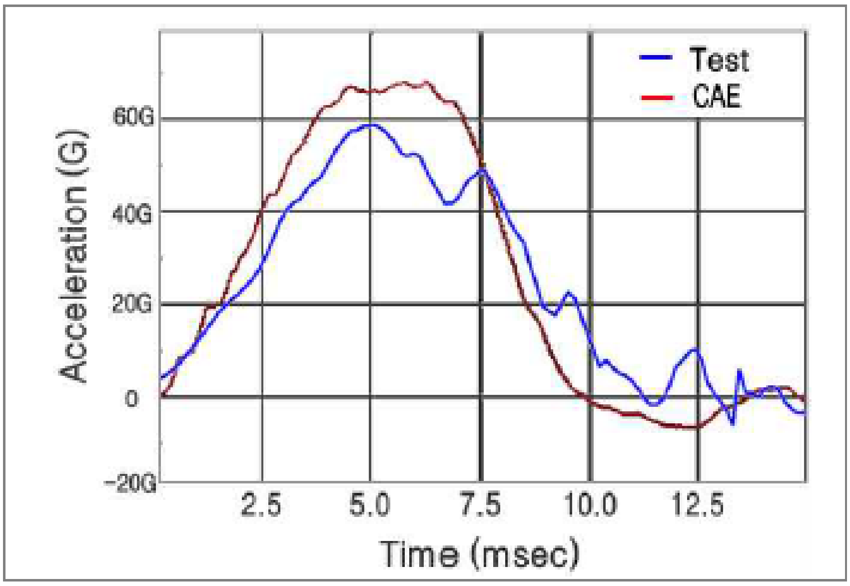


Figure 1.14 Acceleration of Simulation and Experiment [5]

Von Mises stress values measured from strain gauges were compared via a graphic shown in Figure 1.15

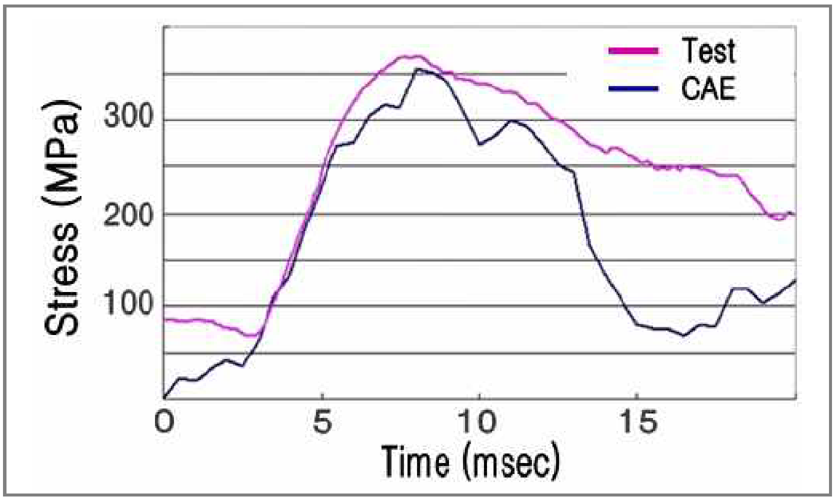


Figure 1.15 Comparison of von Mises Stress Values with Simulation and Experiment

Mulkoglu and his co-workers performed another study in this area [6]. The main purpose was designing a new door hinge system and checking it by drop test and analysis whether it is strength enough or not. For detecting critical parts of dishwasher at design stage a finite element model was created and then analyzed by LS-DYNA.

Different mesh sizes were chosen for parts of dishwasher according to their deformation situation exposed during drop test and HYPERMESH was used to generate mesh. Two different types of drop test were conducted; vertical and inclined. For selecting a foam model at analysis stage, firstly mechanical properties of the EPS were detected by a ball impact test shown in Figure 1.16.

Figure 1.16 Ball Impact Test Machine [6]

Fully integrated shell element formulation was used to decrease analysis time and inertia effect *PART_INERTIA card was used at simulations. Drop test was recorded by a high speed camera and results were used to validate the FEA with comparison shown in Figure 1.17.

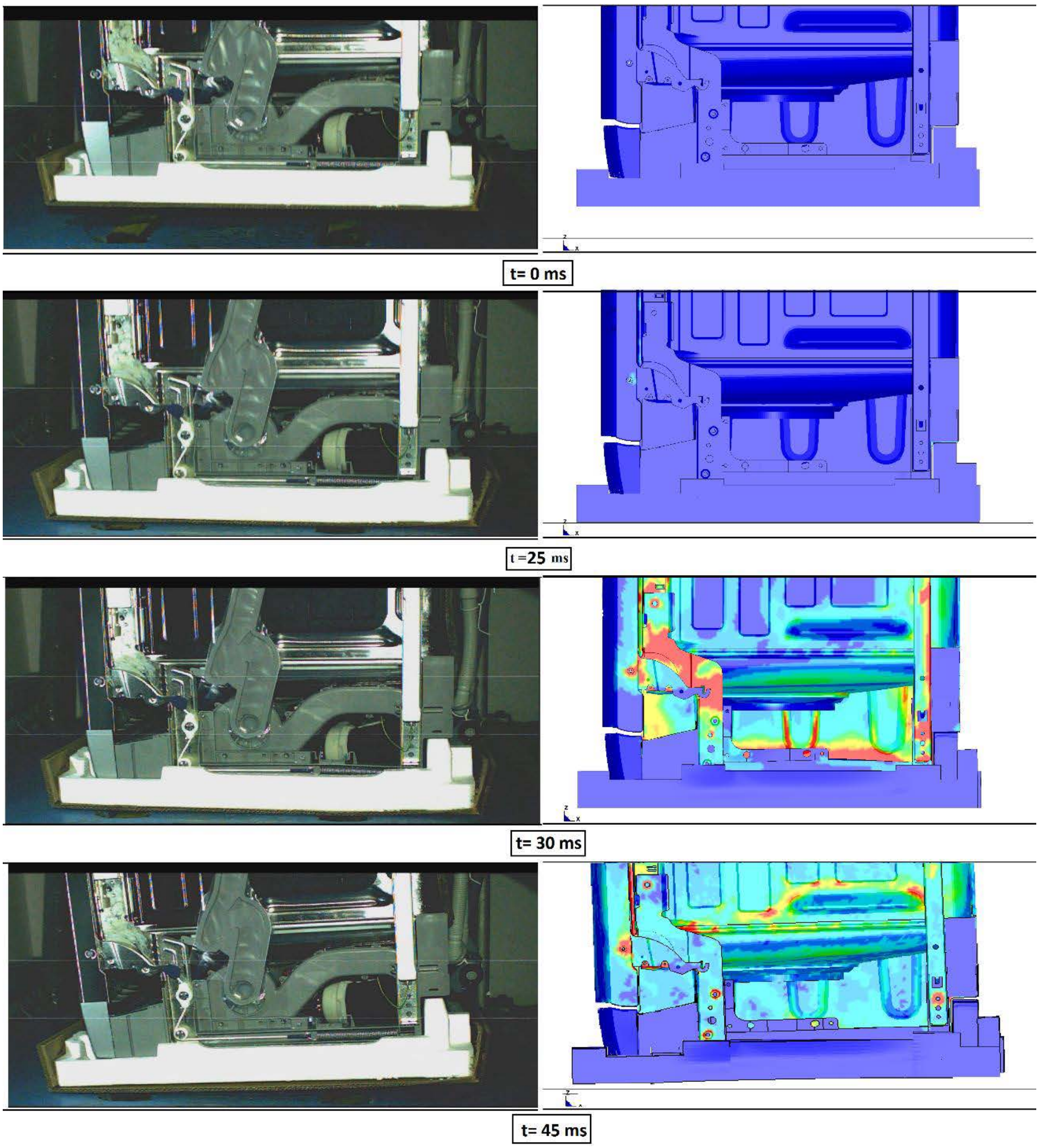


Figure 1.17 Comparison of Drop Test and FEA Results [6]

At the study carried out by Eraslan [7], determination of the mechanical properties of the foam material at desired strain rates was examined. So they developed a drop test rig which consists of force sensor, laser displacement sensor and accelerometer. A mass was free fell from 25 cm, 40 cm and 70 cm heights into EPS sample with dimensions 50 x 50 x 50 mm^3 with varying densities (20, 24, 26 and 30 kg/m^3). By this test strain rate curves defined. Additionally in order to detect effects of strain rates at 200, 500 and 1000 mm/min to mechanical properties a series of tests were performed according to Zwick standard as shown in Figure 1.18.

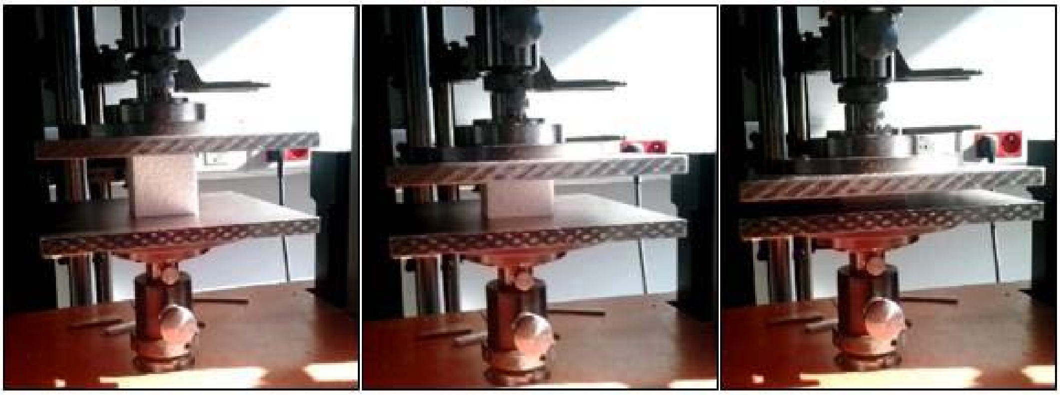


Figure 1.18 Zwick Z020 Compression Test [7]

During analysis hexahedral elements and tetrahedral elements were used to obtain accurately results. Four groups of materials defined as the components of dishwasher that are sheet metals, plastic components, auxiliary components and packaging materials. For 25 cm height no damage was detected but for 40 cm there was some deformation at the plastic bottom chassis. Drop test results compared with ones of analysis and validated.

Hong and his co-workers focused on mainly performance of hinge during drop test instead of whole product at their study [8]. By the help of bending and compression tests velocity dependency and lower packing materials were determined at several dropping speed. These properties were used on Finite Element Analysis as input values. By obtaining displacement-time curves for each critical point which are shown in Figure 1.19 design accuracy of validation was provided.

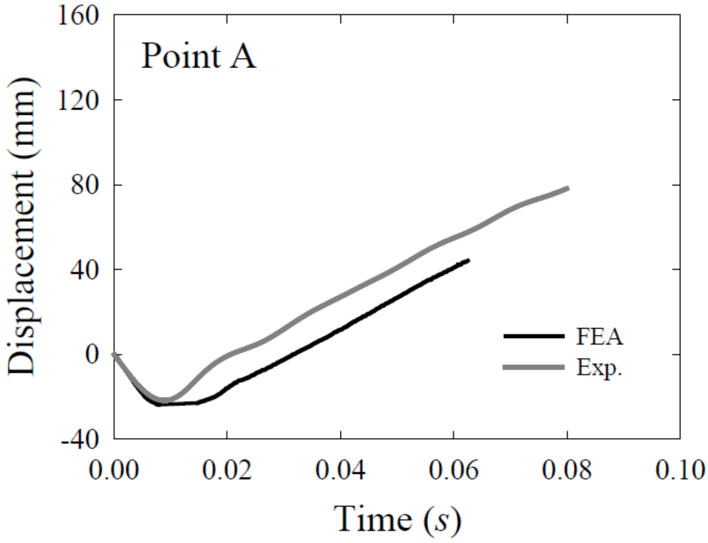


Figure 1.19 Displacement-Time Curves for Critical Point A

At a study carried by Oh et al [9], it was mentioned that the optical disc drive is damaged during transportation because of harsh shipping conditions, extremely large impacts and amplified shock accelerations and this situation also causes difficulties in cd writing and reading process. To make better shock isolator finite element analysis was performed and results were verified with a linear drop test series. According to test results improvement were made via the design of experiment methodology by taking into account of maximum stress. Geometries are simplified for ease of analysis. They combined the degree of freedom of the disk assembly and chassis to move the parts together in the analysis. They determined criteria that maximum stress must not be higher than 85% of yield stress. They got the 18 % better shock isolation performance from modified design.

Lee and his co-workers performed another study [10] in this area which describes the developing of television (TV) packing system that prevents the damages caused by dropping using the equivalent static loads (ESLs) as shown in Figure 1.20. For the optimization process nonlinear dynamic response system was proposed. At concept design stage topology optimization and at detailed design stage shape optimization was used for virtual model. LS-DYNA was used as software analysis program and an actual sample was used on real drop test in order to validate.

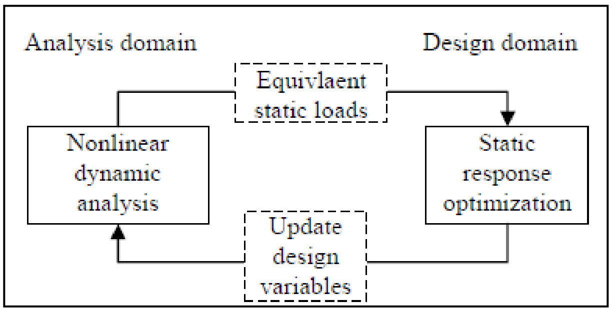


Figure 1.20 Schematic Flow of Equivalent Static Loads Method [10]

Yeh and Huang studied basic mechanical properties and variations of stress and strain of test board by making drop test of FR-4 according to the JEDEC standard (Figure 1.21) at their study [11]. The finite element software ANSYS/LS-DYNA was used to simulate the drop test. In order to decrease analysis duration time they used quarter model. Results from both drop test and analysis were compared and validation obtained.

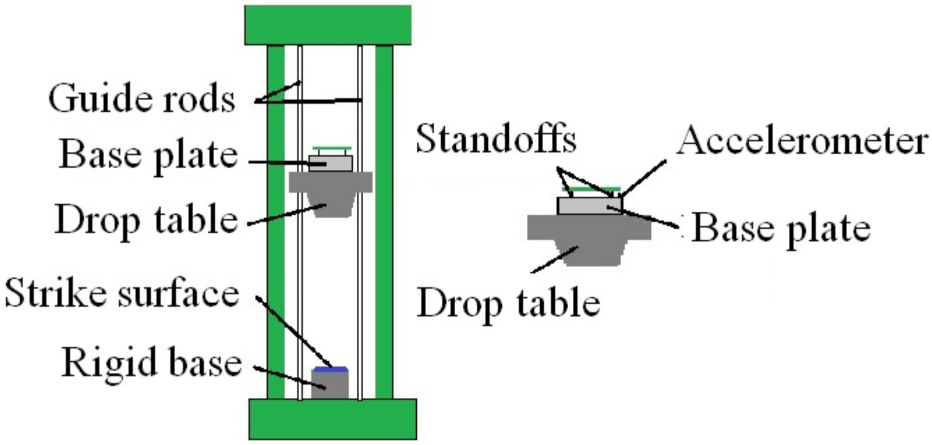


Figure 1.21 Drop Test Facility under JEDEC Standard [11]

Lacroix and Safran focused on the durability of mobile phone screen (LCD) at their study [12]. They made several drop tests from determined height in order to detect shock resistance of screen. LCD is equipped with strain gauges. Strains are then measured on the LCD during the shock and compared with those computed with the simulation shown in Figure 1.22. This method allowed estimating the probability of rupture on the LCD

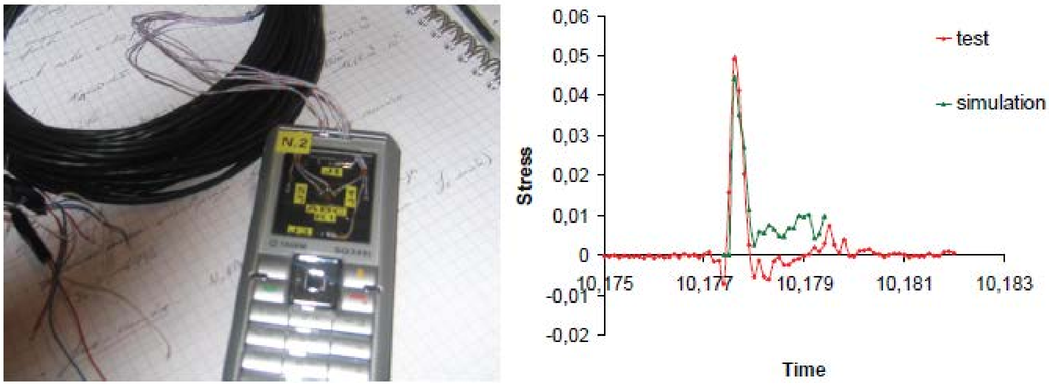


Figure 1.22 LCD Equipment and Comparison of Signals [12]

At a study performed by Shah and Topa [15], quasistatic compression tests were made in order to detect strain stress curves of EPS foam at low rates such as 0,0083 and 0,083 s^{-1}. Results were compared with the ones from previous studies. At the next stage numerical analysis was carried out for validation as shown in Figure 1.23.

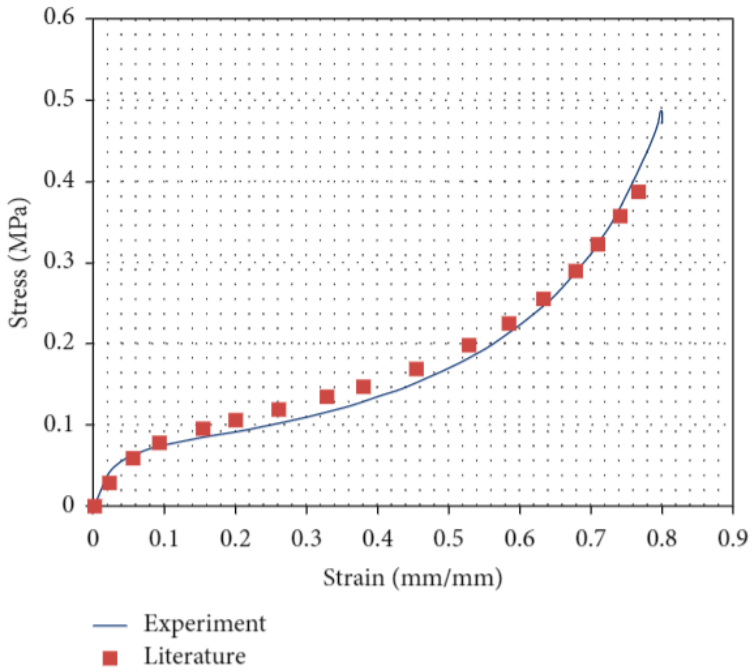


Figure 1.23 Comparison of Test and Literature [15]

After that they made a gravity driven drop test by using a long rod projectile. That specimen has a semispherical end and got into EPS foam at test and compressed it a while shown in Figure 1.24.

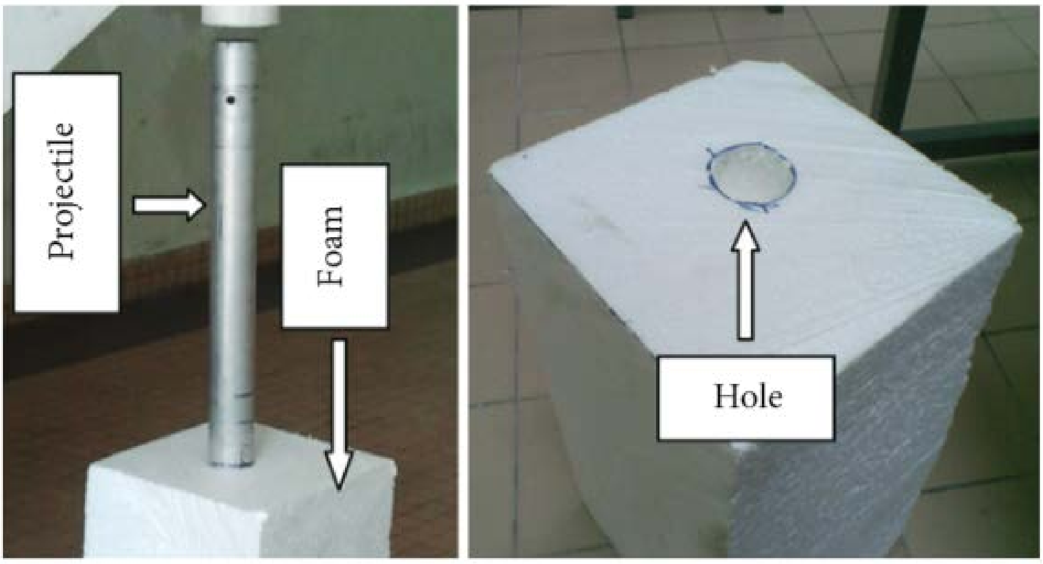


Figure 1.24 Damage at EPS Foam [15]

This test was also simulated by LS DYNA and results were compared as shown in Figure 1.25. Results showed similarity.

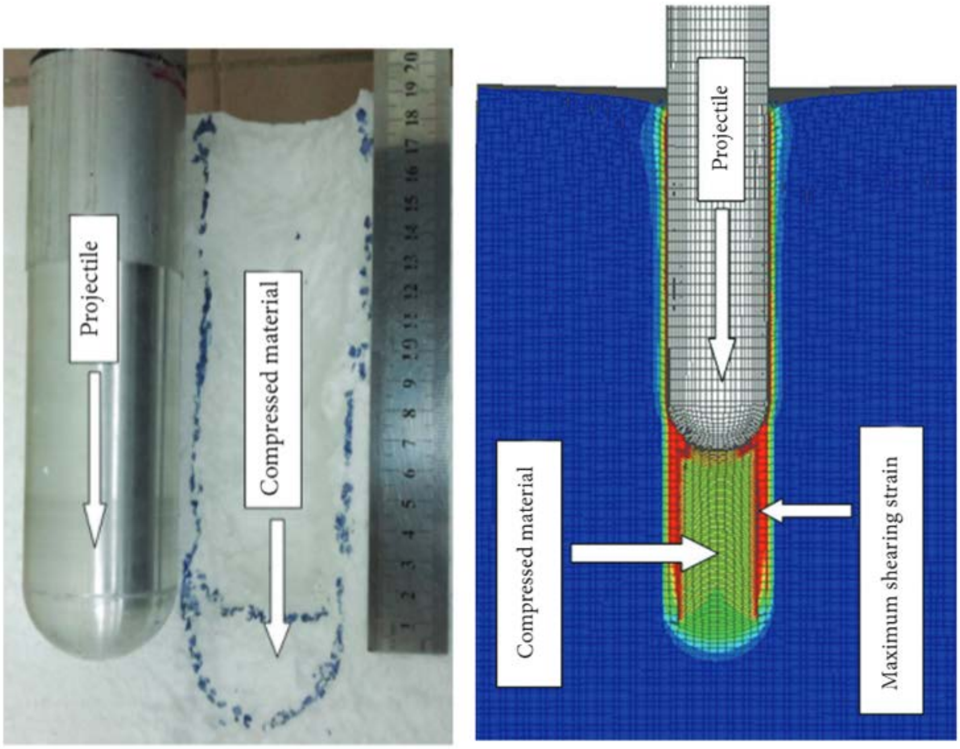


Figure 1.25 Comparison of Experiment and Analysis [15]

Lee and Son performed a study [16] in order to determine behavior of a package of microwave oven under clamping conditions by tests and finite element analysis. PAM-CRASH software was used for analysis and results were compared with those of tests. When some deformation occurred under clamping conditions on original design, a few improvements were made and verified with finite element analysis. After getting similar fine results on real test with prototype, accuracy of two methods confirmed and plastic deformation was removed totally.

Another study was performed by Yi and his co-workers [17] in which they mainly focused on the optimization of cushioning material which is used for preventing damages of external forces but also causes increasing the volume and weight of product. For achieving this goal axiomatic design was used in which a design flow is defined and a software system was developed. LS DYNA was used for impact analysis as a nonlinear finite element analysis program. During drop test in order to minimize the maximum acceleration the process of design of experiments using orthogonal array was installed. During the design of the program independence of axiom of axiomatic design was taken as reference. Design flow of the design system for EPS cushioning package is shown in Figure 1.26.

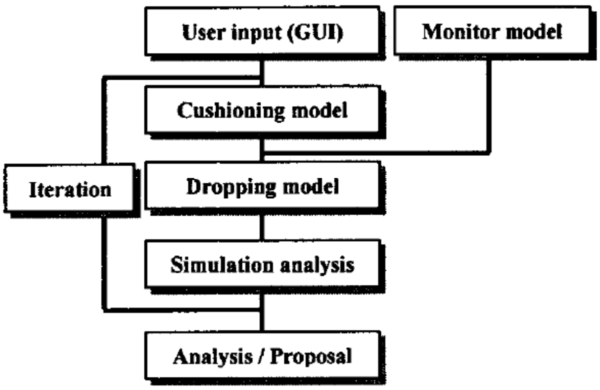


Figure 1.26 Design Flow of the Design System for EPS Cushioning Package [17]

Huang prepared a thesis [18] in which he mainly focused on three rib design of EPS cushioning material by comparing them using a cushion tester and computer aided engineering simulation. Firsts of all design cycle was created as shown in Figure 1.27 and improved topology design cycle which used to optimize the design of the cushion was shown in Figure 1.28. By the help of this method, both time and money saved.

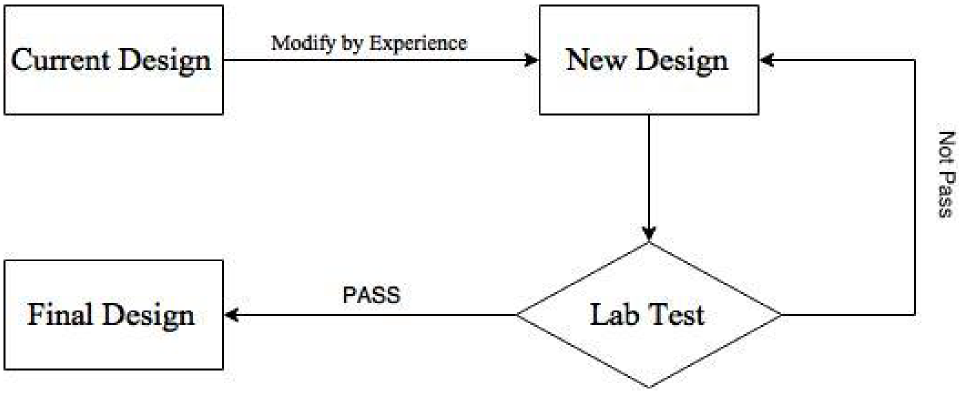


Figure 1.27 Old Design Cycle [18]

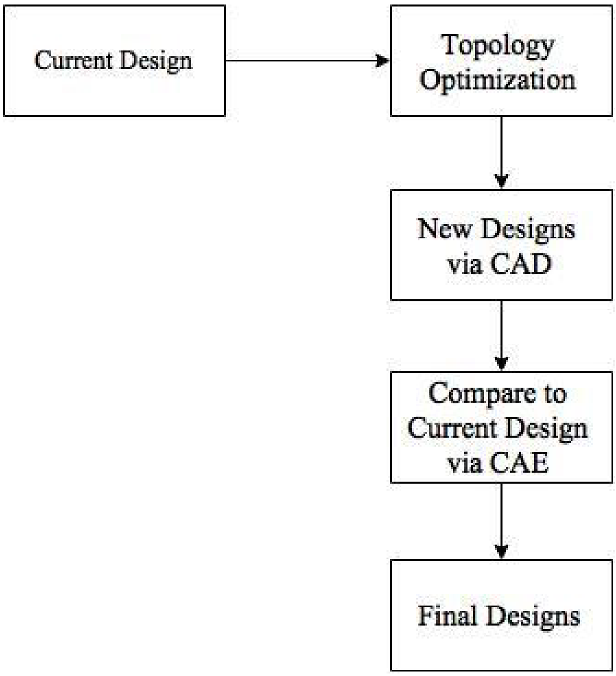


Figure 1.28 New Design Cycle with Topology Optimization [18]

At a study performed by Keltie and Falter [19], it was focused on determining the approximation and simplification used in finite element analysis of electronic component shock response. Therefore excessive run time of computer program and effort for creating 3D models were tried to reduce. In this method common proposals were neglecting the lightweight parts and considering some assembled parts as rigid connection. At the study instead of confiding the experiences and feelings guidelines were tried to detect for approximation. In order to define compliance of simplification two important questions asked; when consider a parameter what must the difference for real and approximate system and how can define the value of tolerance.

At a study carried out by Low and his co-workers [20] the subject of suffering impact inducing failure of electronic devices was handled. Because of time and money consuming of making drop tests, the importance of finite element analysis was emphasized. A Hi-Fi audio devices small in volume was used to examine. For finite element software program PAM-Crash was used and bottom plate part was considered the focus of the study. Deformation of this part was measured by 3D probe and G-force was also calculated. For the validation of the analysis test result were used. The process flow for the study is shown in Figure 1.29.

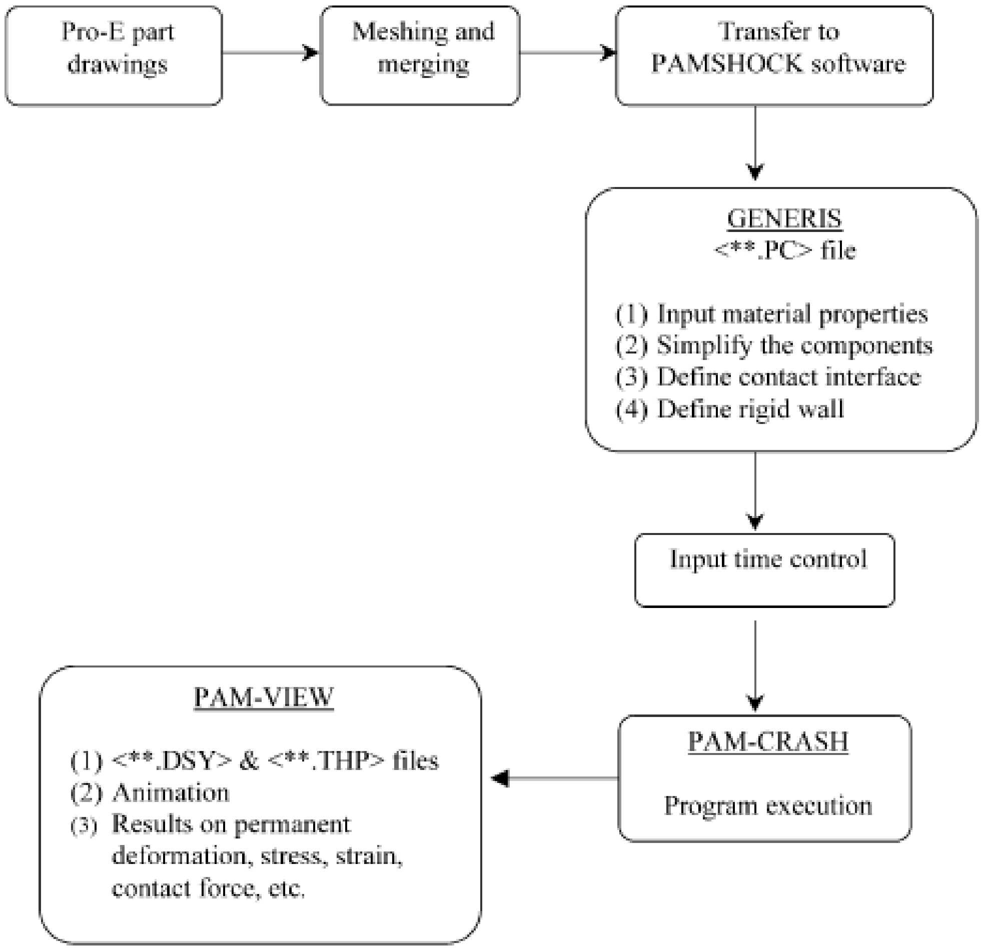


Figure 1.29 The Flowchart of the Study [20]

The subject of monolithic design of cushion package for airdrop system was examined at a study performed by Chen and Zhang [21]. Firstly airdropping was defined as releasing a subject or human being with a parachute or a decelerating system that put the carrying devices to ground slowly. When a disaster such as earthquakes, tsunamis, happen in a certain area of world, it is necessary to help them by supplying foods, drinks and goods for life. Mostly these are dropped from a helicopter. Because of cushioning materials are not strength enough internal materials are damaged. The details of airbag cushion packaging, dock buffer and airdrop were explained. For the most effective solution a combination of these systems was recommended.

Han and his co-workers emphasized the importance of packaging process for protecting electronic devices during distribution at their study [22]. In order to detect mechanical properties and obtain strain stress curve dynamic drop tester was used shown in Figure 1.30.

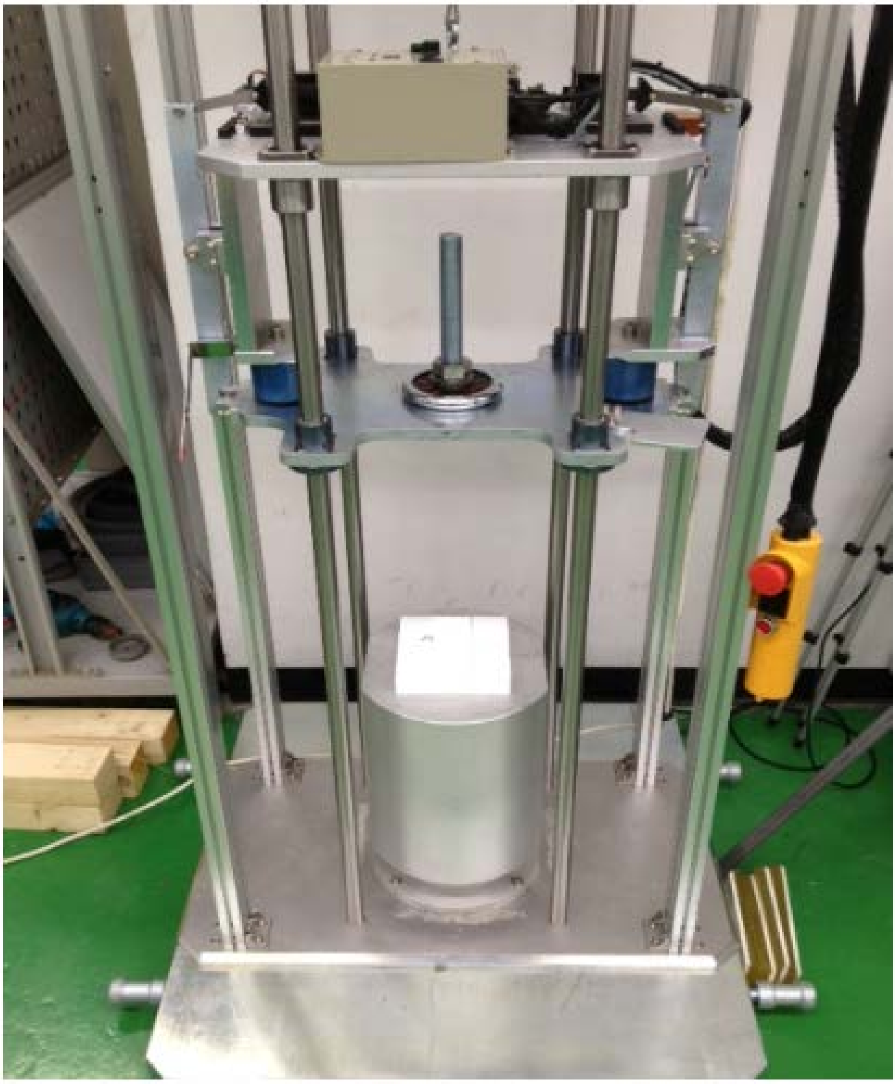


Figure 1.30 Drop Tester [22]

Firstly difficulties of impact optimization were mentioned because of non-linearity and cost of analysis. Instead of nonlinear dynamic response structural optimization, the equivalent static loads method for nonlinear static response structural optimization was used. Because they give same results in terms of displacement at a given time gap, equivalent static loads method was used. They determined a convergence criterion and implemented the analysis until satisfaction. For decreasing weight of a TV they made a design optimization. The most fragile of the product was glass panel. For the analysis LS-DYNA and for the optimization NASTRAN were used.

A study carried out by Martinez et al [23] in which they mainly focused on the improving a packaging design to protect the product from external forces and damages by making computer modeling. Firstly project plan was developed as shown in Figure 1.31.

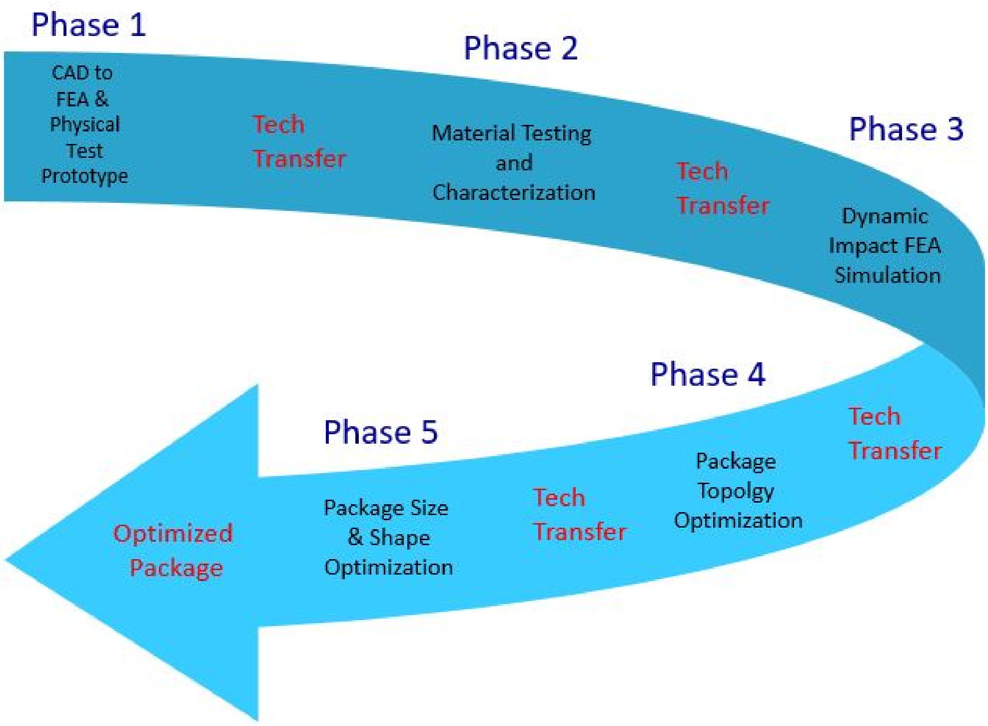


Figure 1.31 Project Work Plan [23]

By simulating the effect from outsource improvement was made early and lead time of the product decreased. The reference external forces were;

- Straight Drop
- Front Side Impact
- Right Side Impact
- Back Side Impact
- Front Edge Drop
- Back Edge Drop
- Left Edge Drop
- Front Left Corner Drop
- Back Left Corner Drop

Firsts of all mechanical properties of EPS were determined by a simple test as shown in Figure 1.32 and the results were used in finite element analysis in order to validate accuracy of simulation.

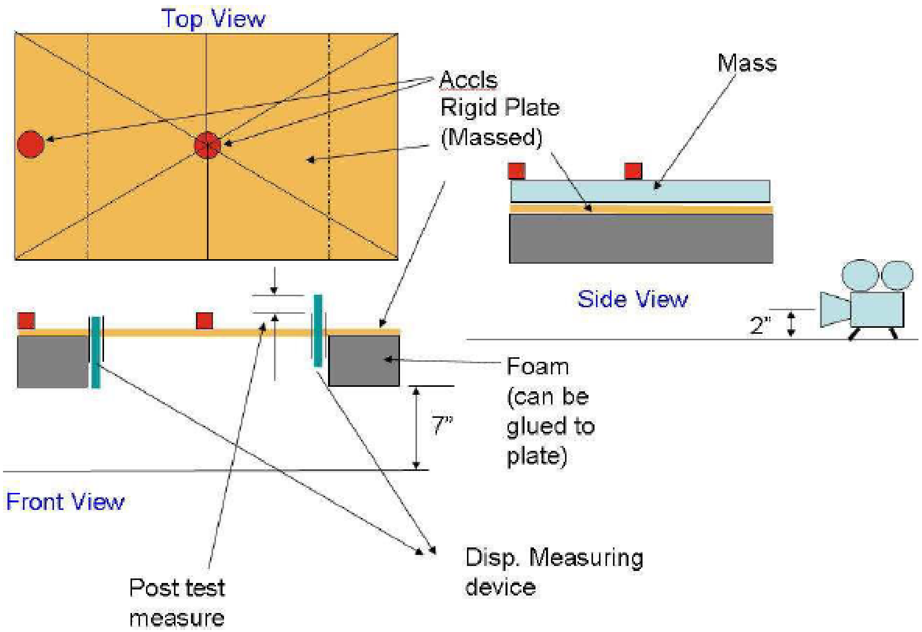


Figure 1.32 Simplified Physical Test Setup [23]

Also high speed video camera was used to record drop test compared with simulation as shown in Figure 1.33.

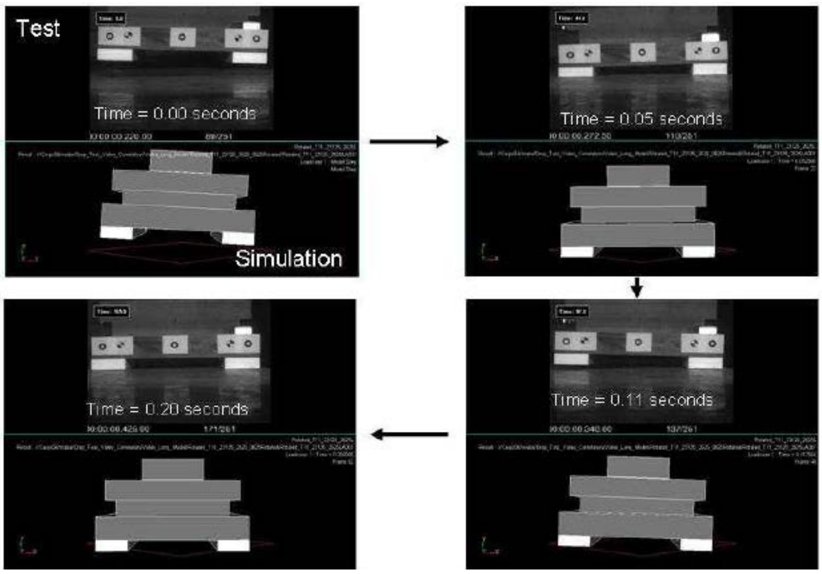


Figure 1.33 High Speed Video and FEA Correlation [23]

For different materials below models were used on simulation;

- Steel: Material Law 36 (Elastic Plastic Piecewise Linear)
- Plastic: Material Law 1 (Linear Elastic)
- Foam: Material Law 33 (Visco-Elastic Plastic Closed Cell Foam)
- Corrugate Board: Material Law 19 (Linear Elastic Orthotropic)
- Laminated Paper: Material Law 36 (Elastic Plastic Piecewise Linear)

Most importantly below assumption were made during computer simulation;

- Foam through thickness properties, or density assumed to be consistent
- Impact surface modeled as completely rigid
- Used post-vibration tested foam properties
- Load cases do not account for accumulated damage
- Strap tension is applied prior to impact loading
- Clamping was determined to be non-critical and was not included in the dynamic impact simulations
- Foam density remained unchanged throughout all dynamic impact simulations
- Main corrugated box and top cover parts remained unchanged throughout all dynamic impact simulations

Performance improvement was carried out by optimizing package structure. Some external force transmitting on different location of product was decreased.

A similar study was performed by Low and his co-workers about this subject [24]. In the study it was mentioned also about dropping caused damages. Firstly the study stated that in order to make effective improvement for preventing drop impact caused damage there are some methods such as finite element analysis. But simulation takes much time. Especially cushioning materials have complex shapes and hard to create mesh. A new virtual boundary condition method was proposed in order to decrease analysis time that provides to designer. Advantages and reliability of the virtual method was shown by the analysis of TV model in Figure 1.34.

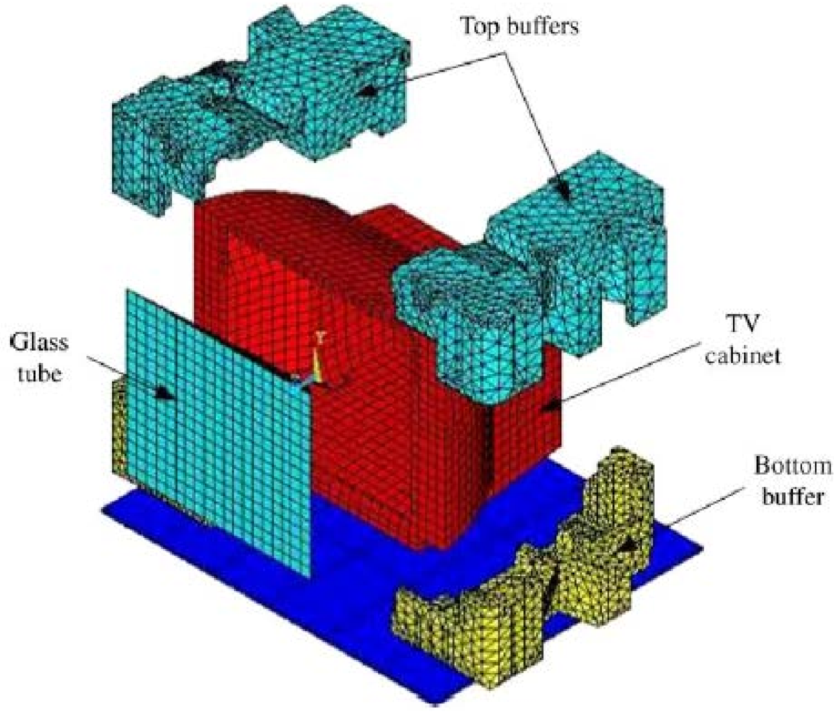


Figure 1.34 FEM Model of TV with Packaging Materials [24]

Steps of virtual boundary methods are establishing a virtual boundary model and creating an objective model and attach it to the virtual one. Schematic form of virtual model was shown in Figure 1.35.

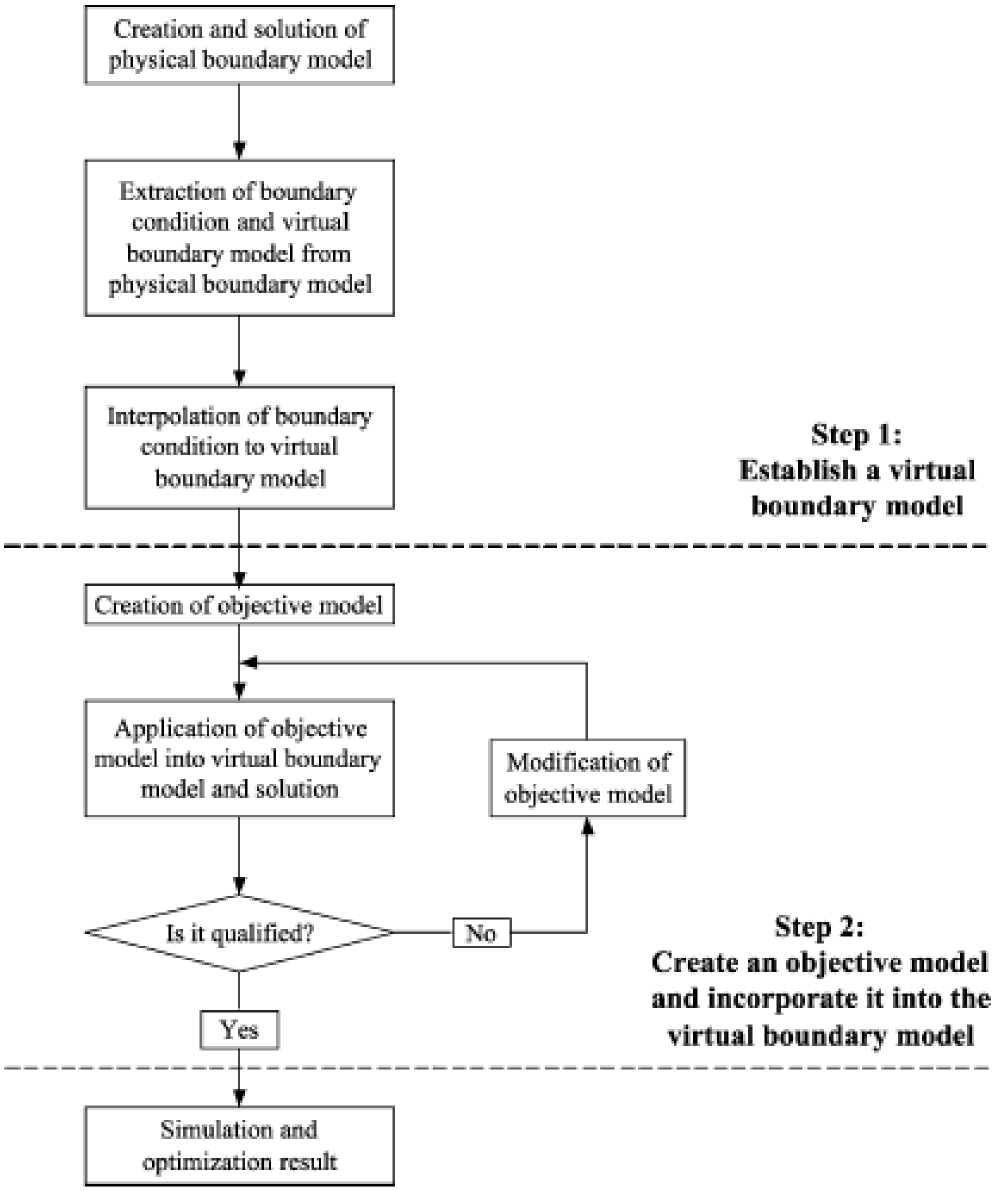


Figure 1.35 Analysis Steps in Virtual Boundary Method [24]

The method provided to the designers to make optimization of PCB location in order to prevent external damages.

At the study performed by Lv and Chen [25], honeycomb materials was used for cushioning purpose as distinct from other studies. Impact model of honeycomb packaging system is shown in Figure 1.36. Firstly study shows that physical dimensions of paper honeycomb have important effect on cushioning performance by a series analysis. Energy absorption capability of honeycombs increases by dimensions.

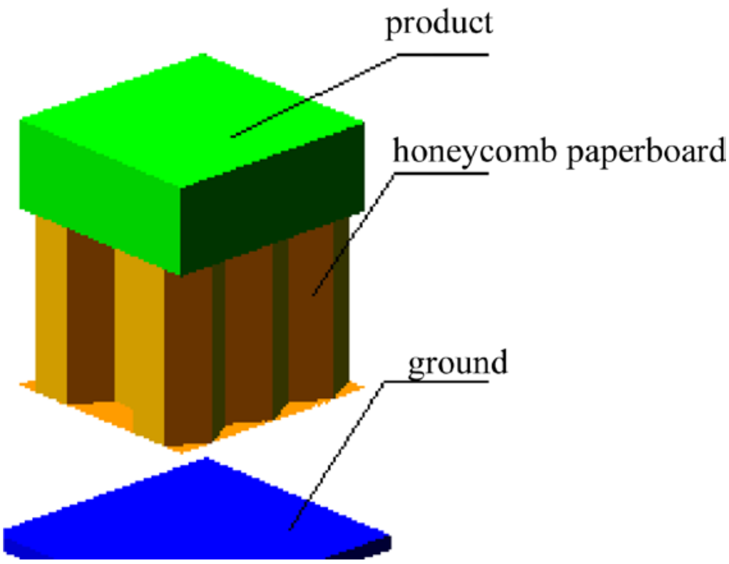


Figure 1.36 Impact Model of Packaging System [25]

A study carried out by Zhou et al [26] in which they tackled the dropping caused damages of electronic product which effect the performance of printed circuit board (PCB). These external forces may be transmitted to PCB and interrupt its connection with other ones. So this study mainly focused on dynamic behavior of a portable electronic device. Firstly a specimen was prepared. It included an outer case and a PCB with a package, The Hopkinson test system shown in Figure 1.37 was used to measure actual impact force pulses. In order to detect relationship between strain and pulses, dynamic strains of PCB were measured. Than for validation analysis were made.

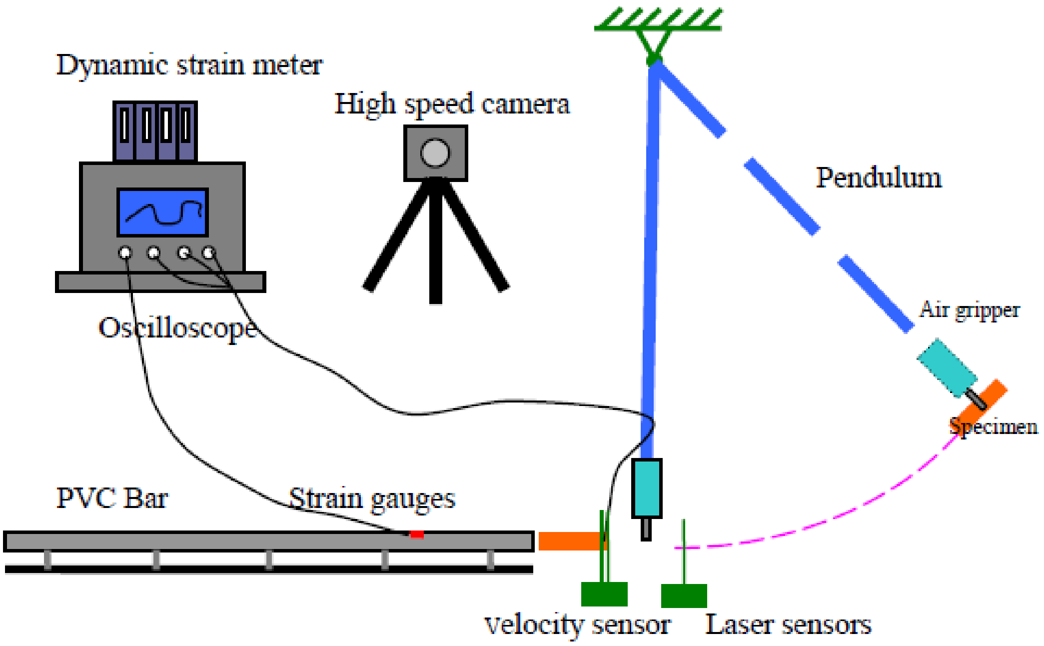


Figure 1.37 Schematic Illustration of the Hopkinson Drop Tester [26]

Jadhav and Manjunath made a study [27] about this subject and gave details about impact response performance of unpackaged laundry machine. The methodology used at this project is shown in Figure 1.38.

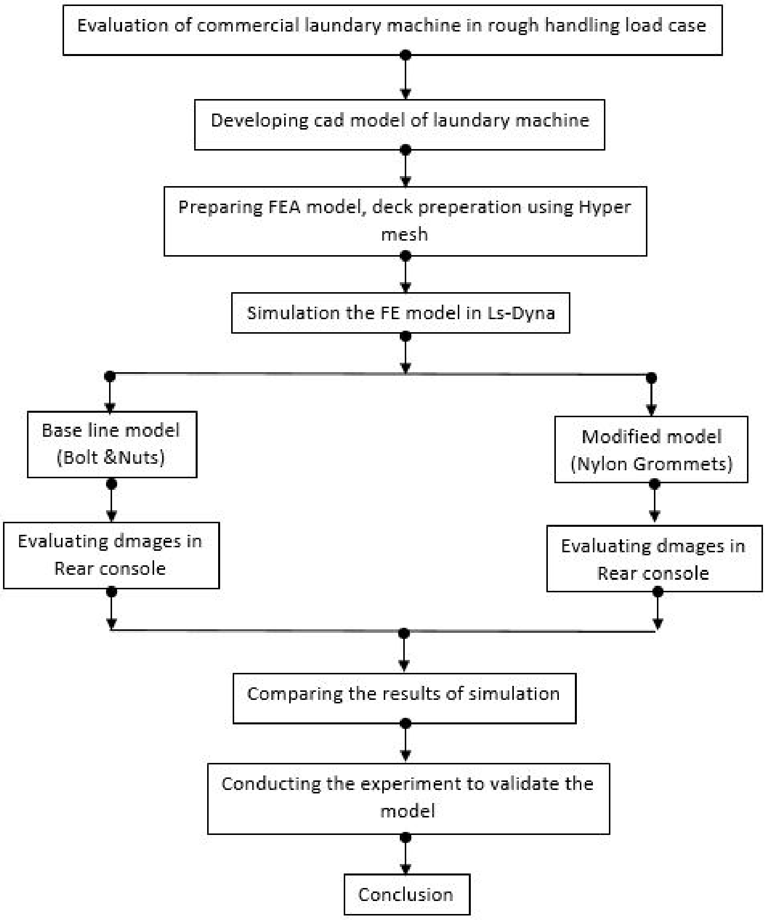


Figure 1.38 Flowchart of Methodology [27]

Drop test and analysis were performed at first and detected that some parts at rear are not strength enough. When some improvements were made such as using nylon grommet part that are good for energy absorption and removing nut and bolds, analysis repeated. LS DYNA software was used for finite element analysis. For comparison max von Mises and max strain values were taken into consideration. Using Grommet decreased the G value transmitted to internal part from the value of 189 g to 95 g. Results of test were 101 g and difference was 5,94 %, so, that was considered as satisfactory. In order to perform experimental analysis Rough Handling standards (T-7) were used. During drop test, accelerometer was used to measure acceleration with respect to time at impact moment shown as in Figure 1.39.

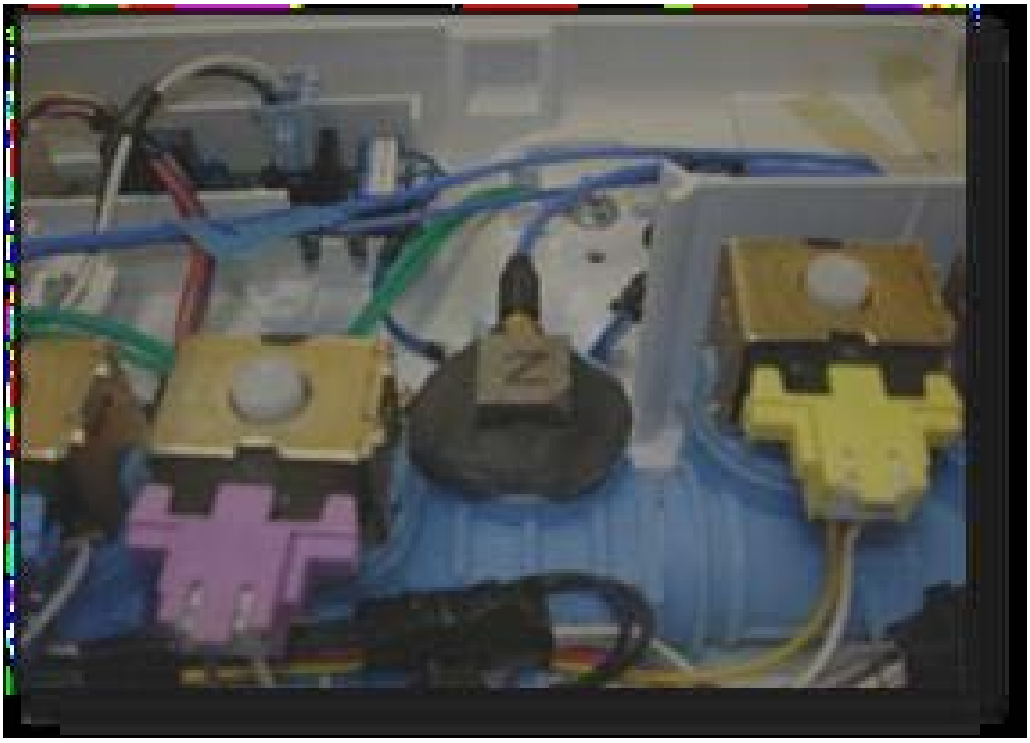


Figure 1.39 Accelerometer [27]

Another study which was performed by Shah and Topa [28] exhibits important results about mechanical properties of foam. By implementing projectile impact to compressed and uncompressed foams, impact resistance of foams was evaluated at low velocity. Finite element analysis was carried out by LS DYNA and results were validated by projectile impact tests. At the analysis stage a 80 x 100 x 100 mm foam block and a 9,5 mm diameter projectile were used as shown in Figure 1.40. Foam was compressed %50.

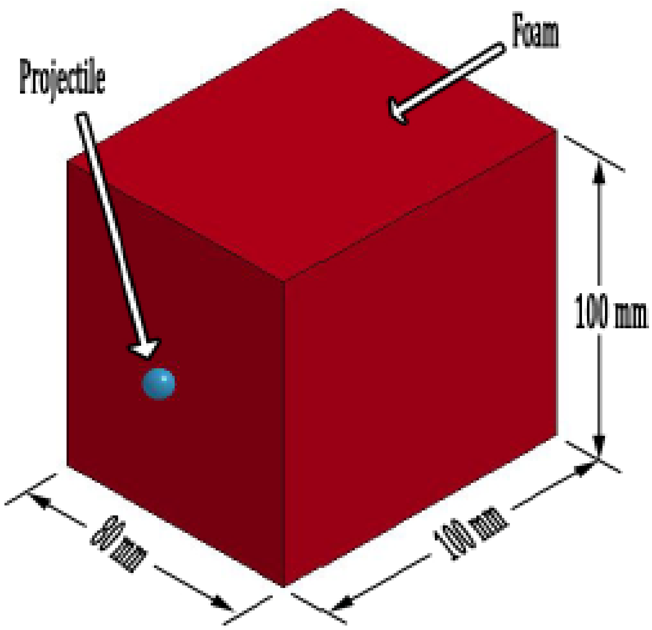


Figure 1.40 The Foam Block and Projectile [28]

According to these inputs, analysis was implemented and penetration became nearly 54,6 mm as shown in Figure 1.41.

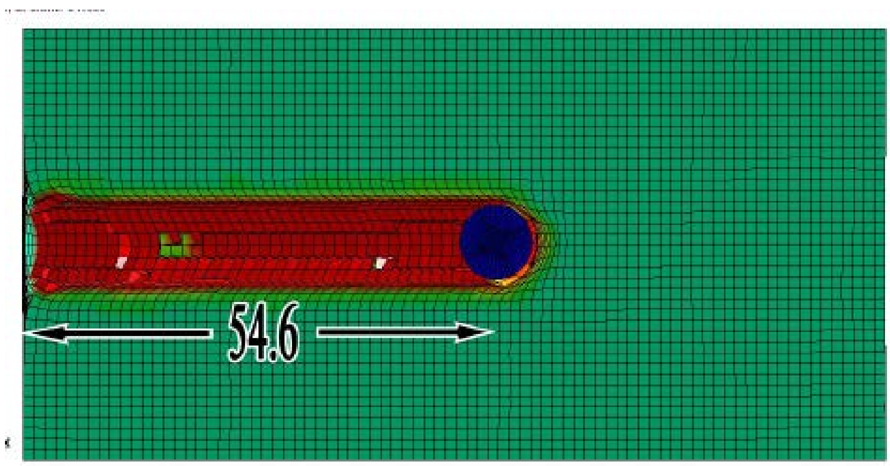


Figure 1.41 Penetration Depth for Compressed Foam [28]

Same analysis was carried out for uncompressed foam and projectile penetrated through foam specimen as shown in Figure 1.42.

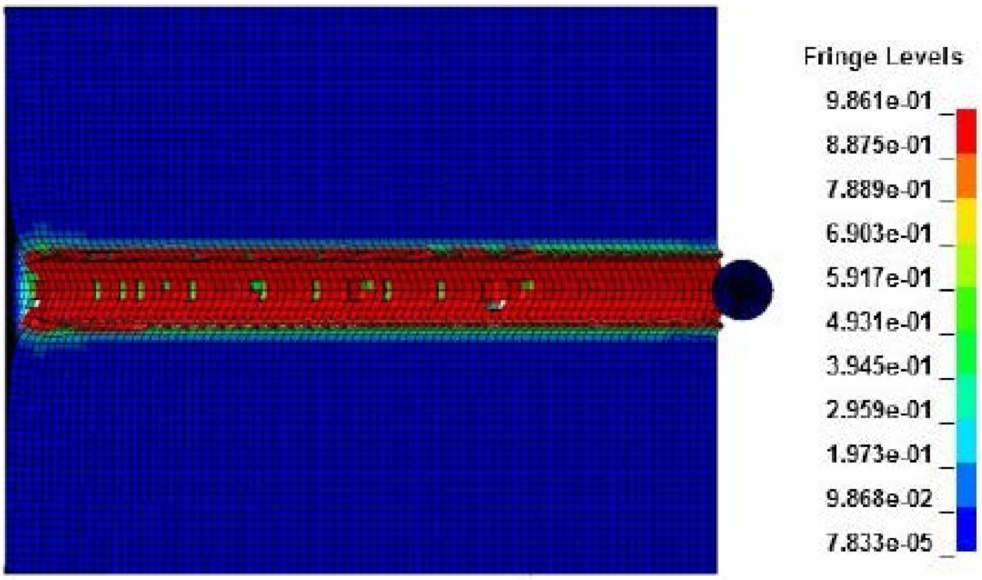


Figure 1.42 Penetration Depth for Uncompressed Foam [28]

Comparison of penetration rate of projectile for compressed and uncompressed foam is shown in Figure 1.43.

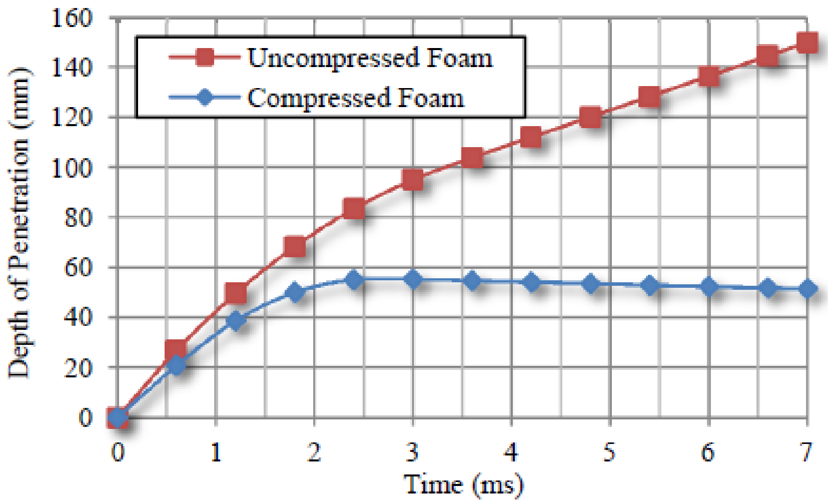


Figure 1.43 Comparison of Penetration Rate [28]

They emphasized the importance of energy absorption property of compressed foam with respect to uncompressed foam and showed the difference in Figure 1.44.

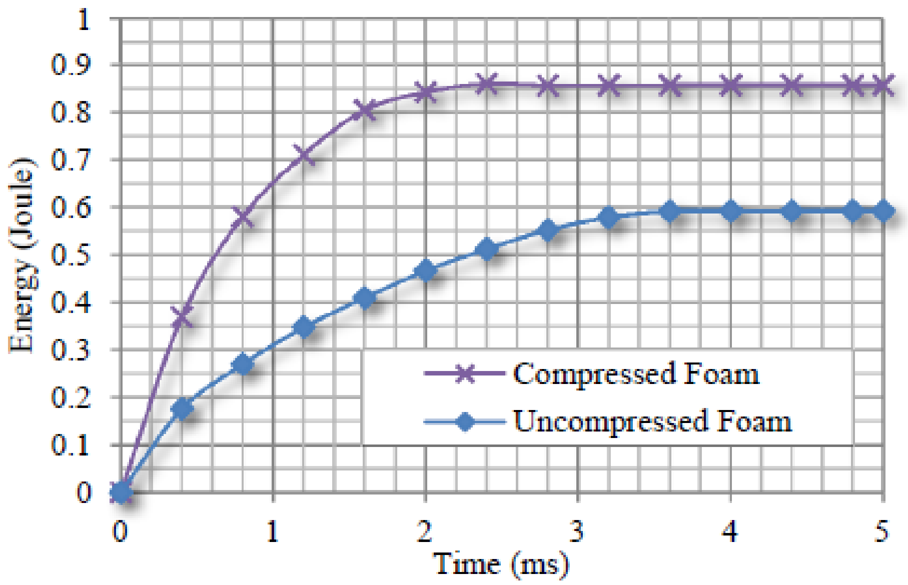


Figure 1.44 Comparison of Energy Absorption [28]

Validation of analysis was provided by real specimens shown in Figure 1.45.

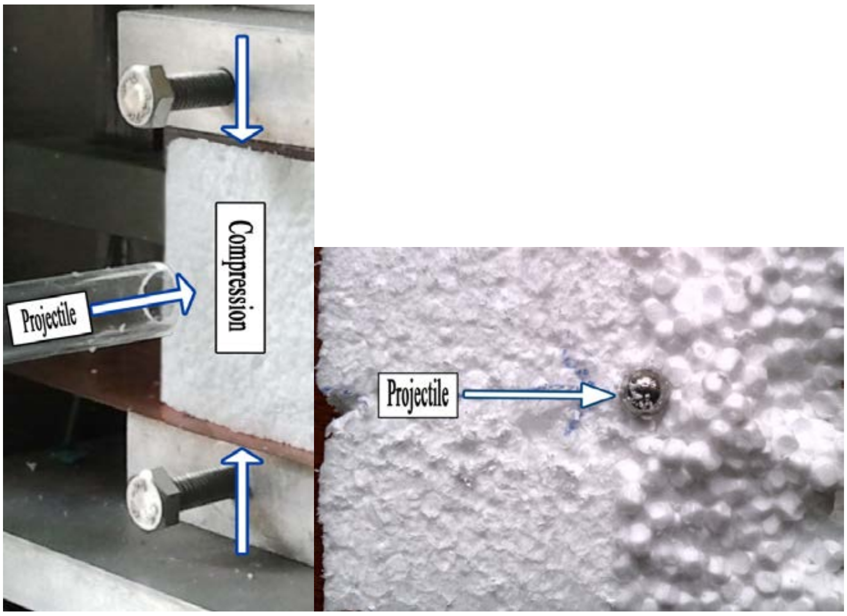


Figure 1.45 Validation of Results [28]

At the end of the study two important results were obtained. First one is the increasing of resistance against projectile penetration of compressed foam by projectile impact and second one is compressing increases both density and rate of energy absorption at per unit time.

There is another study about this subject carried out by Hagara et al [29]. In this study a high speed digital image correlation method was used to perform drop test of smart phone. By the help of this method it is possible to measure stresses occurred on surface of mobile phone because it provides detecting of impacts at high frequencies. The name of system is Q-450 Dantec Dynamics. It is used for designing airbags, drop tests, detection of crack possibilities, fatigue analysis etc. The product was exposed to drop from one meter which simulates the height of a man's hand height. Five different parts of the mobile phone was considered as dropping location such as;

- Bottom edge (controlled)
- Upper edge (controlled)
- Left bottom corner (controlled)
- Right upper corner (controlled)
- Lateral edge (uncontrolled)

And shown in Figure 1.46.

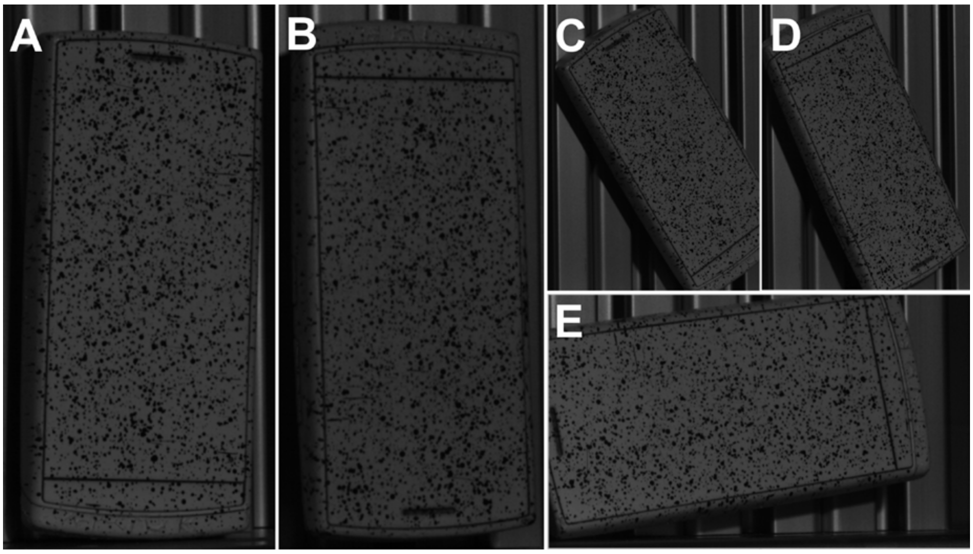


Figure 1.46 Five Impact Exposed Location during Drop Test [29]

Deformation and von Mises stresses were calculated used to determine which smart phone impact is the most dangerous one.

Another study about this subject was performed by Wei and his co-workers [30]. The product in this study is cabin of a heavy truck. Also a manikin was placed to inside of cabin as shown in Figure 1.47.

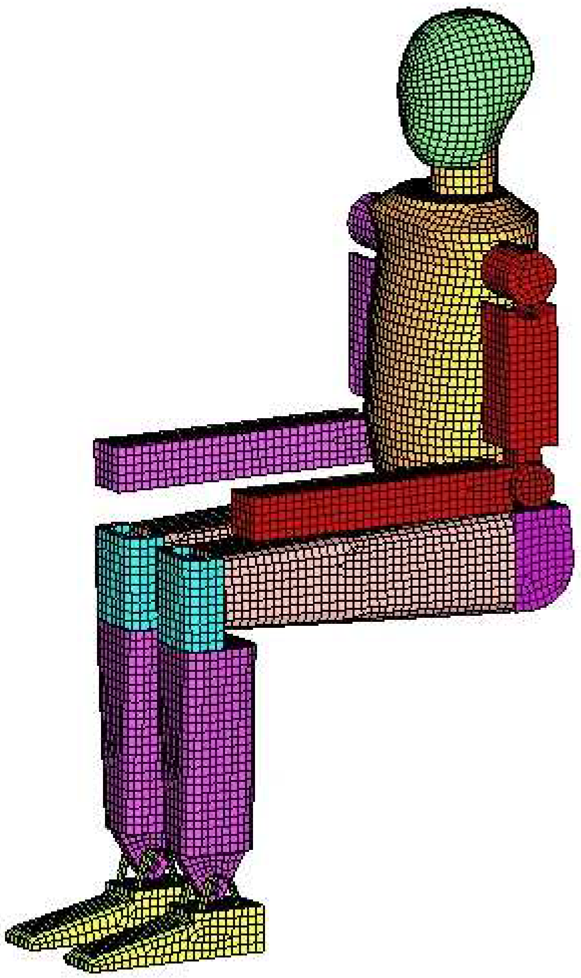


Figure 1.47 Manikin According to ECE R29 [30]

For finite element analysis LS DYNA software and explicit method were used. The pendulum impact was taken into consideration for front side of cabin according to ECE 29 regulation. For results energy balance calculated and evaluated. The related energy types were kinetic, sliding, internal and hourglass and changes of these with respect to time was shown in Figure 1.48. As a decision criteria total energy remained nearly stationary and hourglass energy stayed under %4 of total energy. At the end some improvement suggestions were declined for deformation

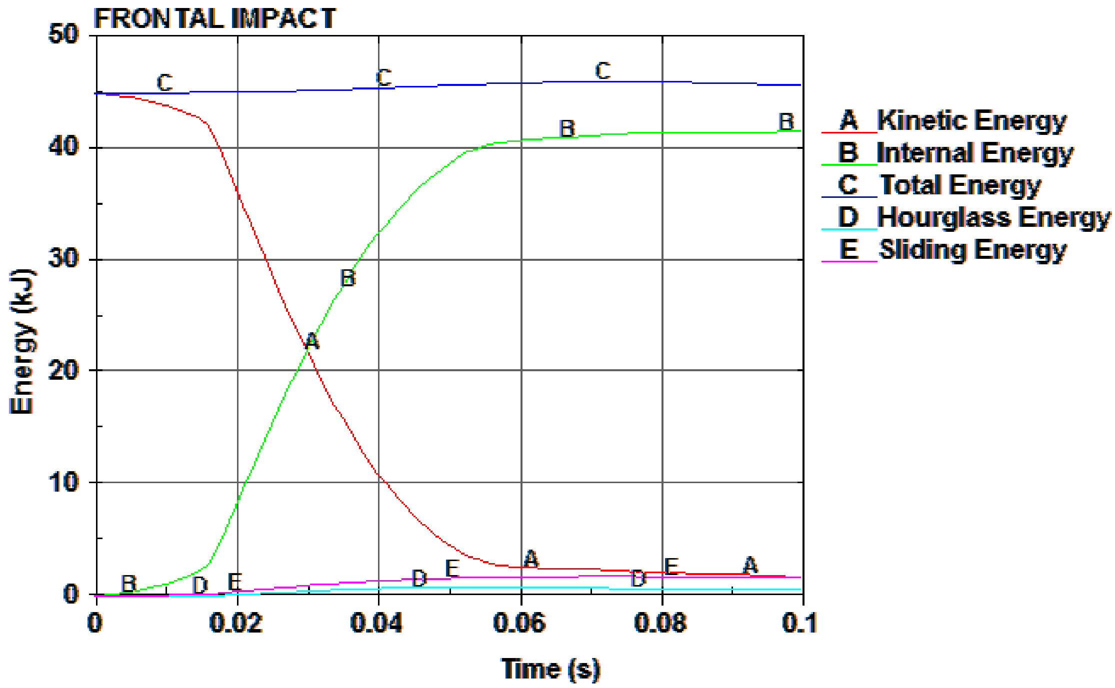


Figure 1.48 Energy Balance Graphs [30]

At a study performed by Zhang et al [31], they emphasized a different method. The product at the study was a cushion material packaged PCB. Stress values were calculated with finite element analysis by investigating the effects of different heights, different cushion material and different dropping ground. Drop heights were 1 m and 2m. Grounding surface types were marble and concrete. Cushioning material 1 has the density of 100 kg/m3 and elastic modulus of 0,003 GPa. The cushioning material 2 has the density of 200 and elastic modulus of 0,006 GPa. Results showed that drop height and grounding type have sufficient effect on stress values. The smaller elastic modulus for cushion material is better for energy absorption and impact force.

In these studies commonly strength and mechanical properties of EPS examined, FEM were used and results were compared with the drop test. For an air conditioner there is not any study for preventing such transportation caused problems until now.

In this study strain gauges were attached to deformed locations and used to measure stress on those points during drop test. Finite Element method was used and drop test of an air conditioner indoor unit was analyzed by Ansys software program. By the comparing of strain gauge measurements and FEA, validation of analysis method was carried out. Subsequently, some improvements implemented for deformed parts.

Analyzes were repeated until deciding of improvements are sufficient enough. Improvements were carried out until eliminating all deformation. When improvements are approved to eliminate deformation by analysis, drop test were made. At the next stage results were compared and accuracy of analysis and drop test validated. After validation of accuracy of numerical model, for further studies software program will be used to make structural optimization and costs at design stage will decrease.

For determining of flowchart of this study, flowcharts of previous studies [17, 18, 20, 23, 24, and 27] examined in details. Schematic representation of this study can be seen in Figure 1.49.

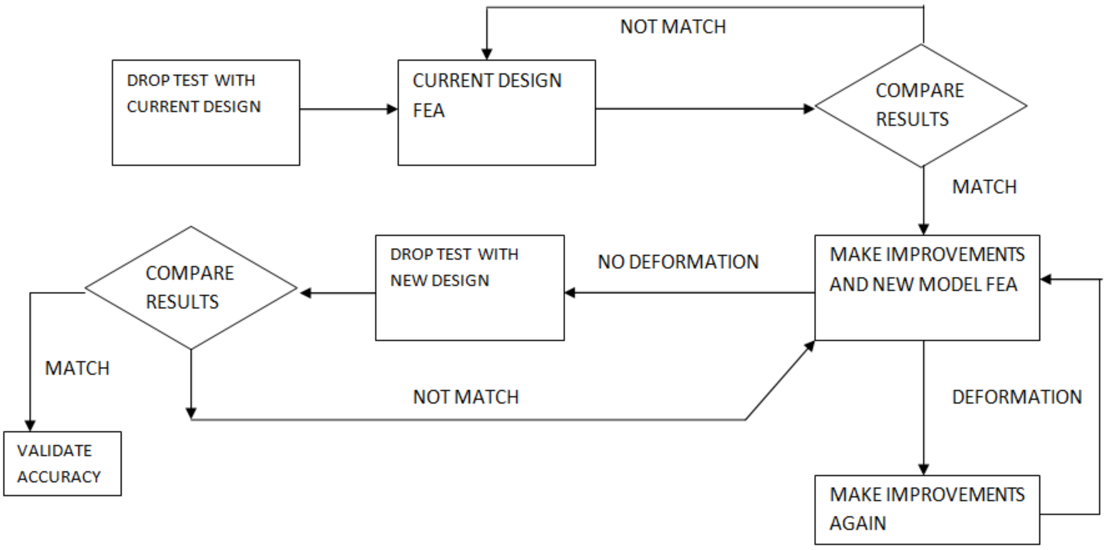


Figure 1.49 Study Cycle

2. MATERIALS AND METHODS

2.1. MATERIALS USED ON WALL-MOUNTED AIR CONDITIONERS

The bottom plate which air conditioner indoor unit strike during drop test can be considered as rigid and no deformable. Plastic parts; decor and discharge grille are made of resin Acrylonitrile Butadiene Styrene (ABS) [13] and Polypropylene (PP) [14] respectively. The properties of plastic parts are depicted in Table 2.1.

Table 2.1. Material Properties of Plastic Parts

Material Type	Density (kg/m3)	Elastic Modulus(GPa)	Poisson's Ratio
Plastic, ABS	1180	2,89	0,23
Plastic, PP	950	1,6	0,43

ABS is a widely used plastic thermoplastic material and suitable for processing. It can be seen all around the world such as cars, kitchen goods, baby toys, etc. Because of its glossy surface, toughness and strength and especially thermal stability, décor parts of air conditioners are made of ABS. Also its ability of withstanding heating and cooling, décor part was produced from it. Decor part provides easy access to power unit of product by its ergonomic design and shown in Figure 2.1.

Figure 2.1 Decor of Air Conditioner Indoor Unit

PP is another thermoplastic material which is used widely around the world. In air conditioner indoor unit discharge grille is made from it.

Some parts of air conditioner such as fan motor, control box took part in Finite Element Model as mass elements. Only weight of them was taken in consideration.

Expanded Polystyrene foams (EPS) are widely used in protective applications as a cushioning packing material for home appliances, electronic devices and so on because of its energy absorptive ability. When exposed to any impact, they are easily damaged so not suitable for repetitive impacts. So it is used for absorbing energy of air conditioner indoor unit during drop test as shown in Figure 2.2.

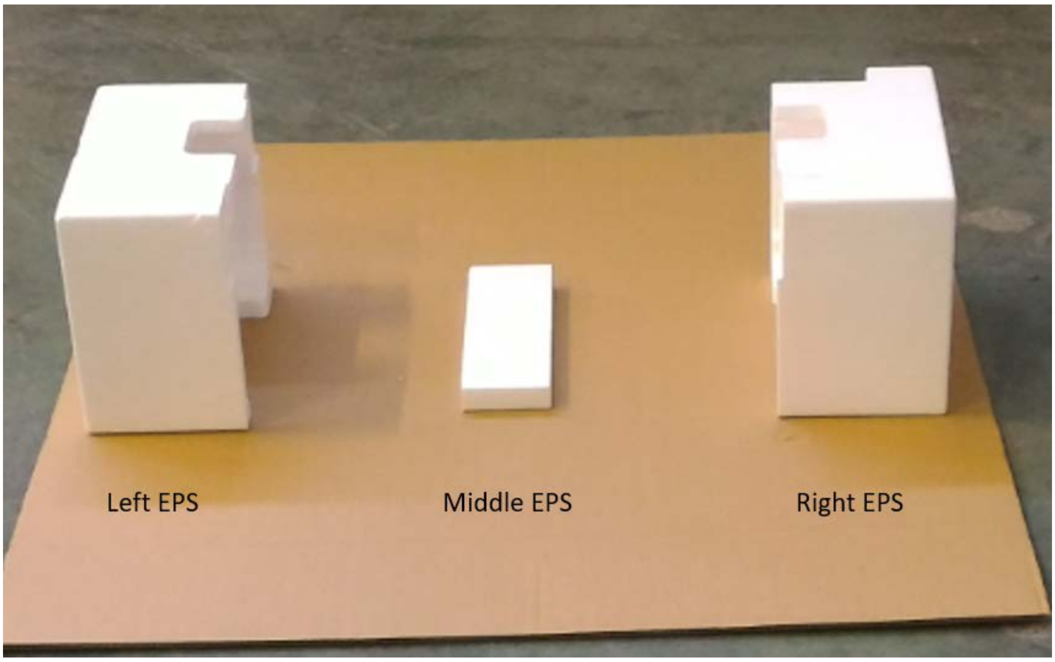


Figure 2.2 Right, Middle and Left EPS of Indoor Unit

Stress-strain curve of EPS has three zones as shown in Figure 2.3 [3]. At the first zone the relationship between stress and strain is linear. Energy absorption occurs mostly at zone 2. The relationship is also linear and deformation ends at zone 3.

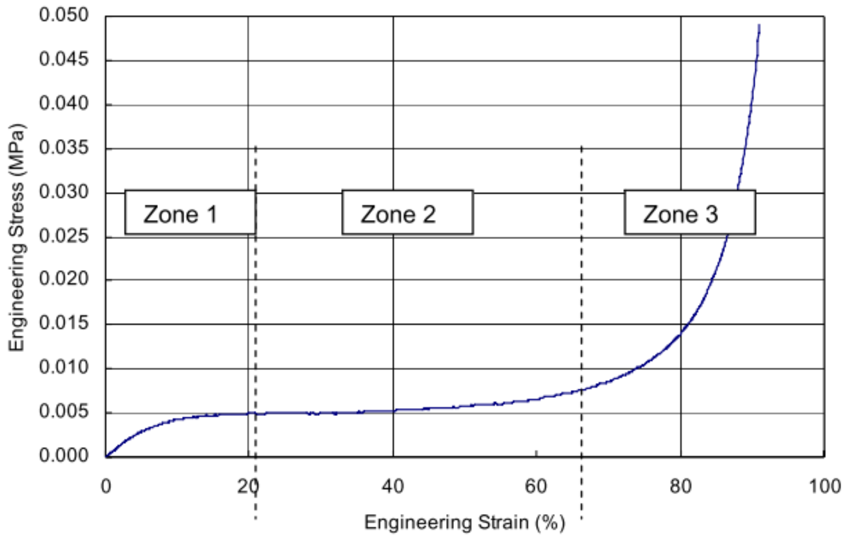


Figure 2.3 Three Deformation Zones of EPS [3]

Stress-strain of EPS curve can vary according to strain rate as shown in Figure 2.4. At the same strain value stress increases with the increasing of strain rate. Curve is also depended to density of foam and direction of impact.

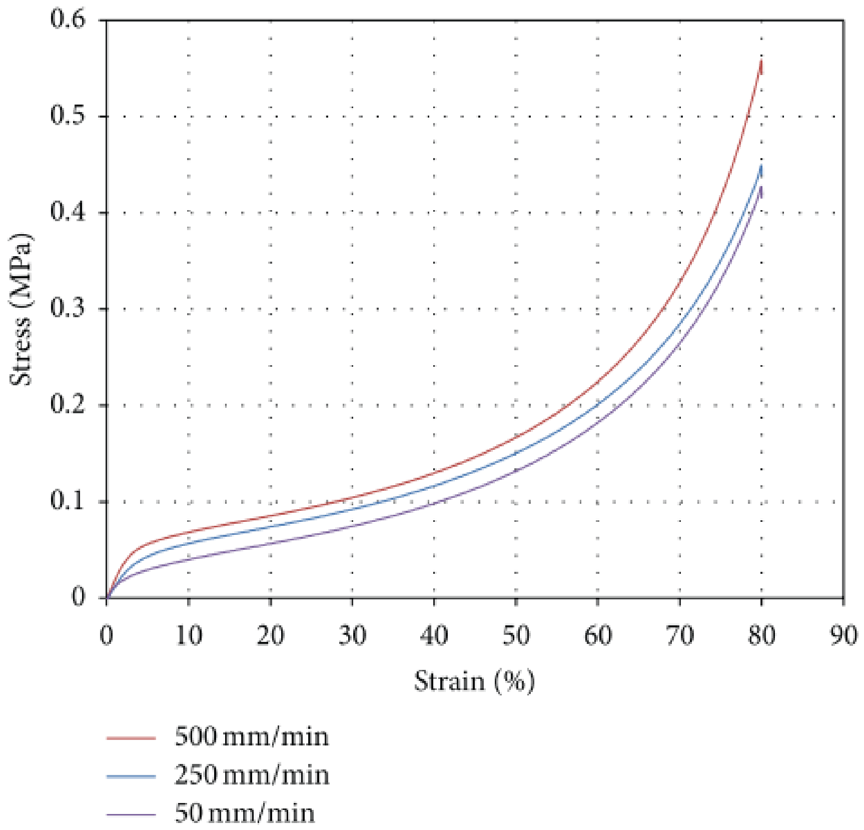


Figure 2.4 Rate Dependency of EPS Crushable Foam [15]

In this study the product drop height is 50 cm and impact velocity is 3132 mm/s. At the “Modelling and Drop Test Analysis of The Built-In Dishwasher” [7] study, experiments were conducted to detect effect of strain rate to stress-strain curve. For EPS foam which has a density of 20 kg/m^3, the curve is obtained as shown in Figure 2.5. Due to the proximity of our 3132 mm/s value, 3320 mm/s curve were taken into consideration in this study. For the other properties BASF [32] values performed on Finite Element Analysis is presented in Table 2.2.

Table 2.2 Properties of EPS [32]

PROPERTIES	**UNIT**	**VALUE**
Density	kg/m3	20
Compressive stress at 10 % compression	kPa	110-140
Modulus of elasticity	Mpa	3,5-4,5
Permitted compressive stress for packaging calculations	kPa	39
Shear strength	kPa	124-154
Tensile strength	kPa	230-330

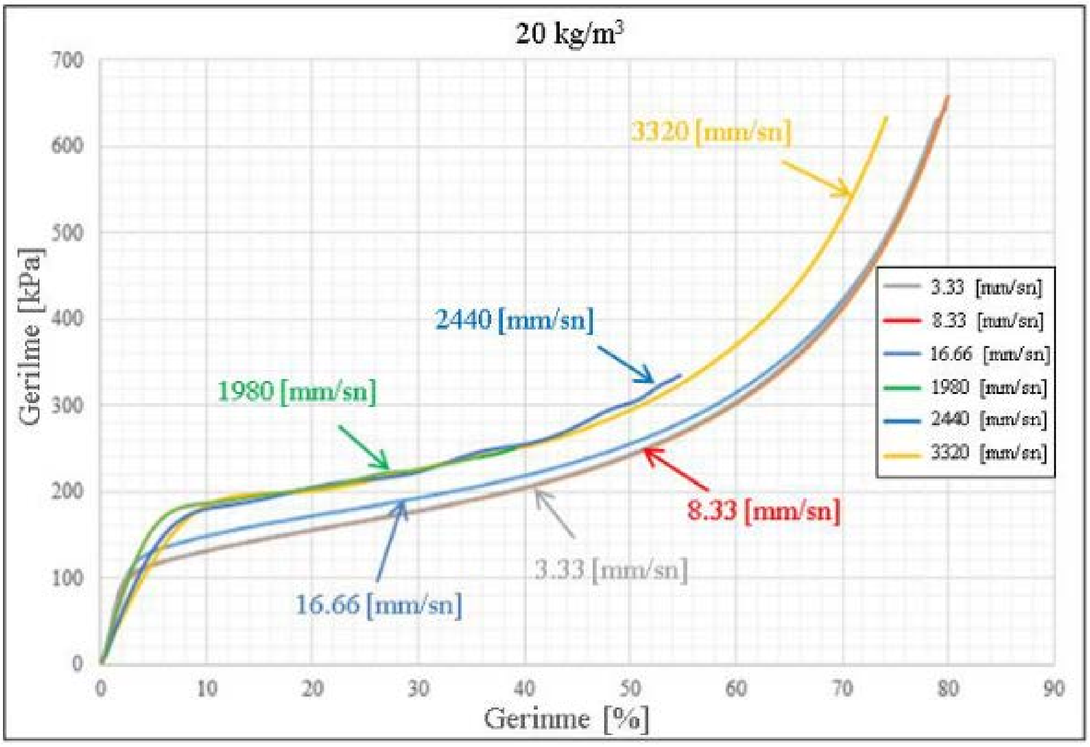


Figure 2.5 Variation of Stress-Strain Curve with the Change of Strain Rate [7]

2.2. DROP TEST

A physical drop test is the study of how well an object survives the impact resulting from being dropped in a gravitational field from a desired height onto a target surface.

Products must be able to function as designed after being subjected to this loading scenario. The drop may be due to either standard use of the object or to an accidental event (i.e., probable misuse of the product or unsuitable carrying conditions). Physical drop tests are often performed on just a prototype of the final product design, since the cost of the product and that of the testing equipment required to conduct the physical drop test may be quite high. It can be seen different types of lifting product by drop test platform in Figure 2.6.

Back Edge Left Edge Front Edge Bottom Side Top Side

Figure 2.6 Lifting Types of Product by Drop Test Machine

Drop test in Arçelik-Lg Company are made according to standards of ASTM D5276 (1998) [1] and ASTM D880 (2002) [2]. The ASTM D5276 gives details about impact strength of packaged products when exposed to sudden loads. It also provides comparison of different types of packaging performances. There are some other standards for drop test such as JEDEC. But drop test of electronic boards are generally performed according to this standard [35]. According to this standard product must be ready as delivering it to customer during drop test. Another requirement of the test is an approval test set up shown in Figure 2.7.

Figure 2.7 Drop Test Setup

This test set up allows dropping product to its different sides shown in Figure 2.8. The surface 1 is top, surface 2 is right, surface 3 is bottom, surface 4 is left, surface 5 is front and surface 6 is back. Leaving mechanism of set up must not apply any load to product and crash surface must be rigid enough to not expose to any deformation.

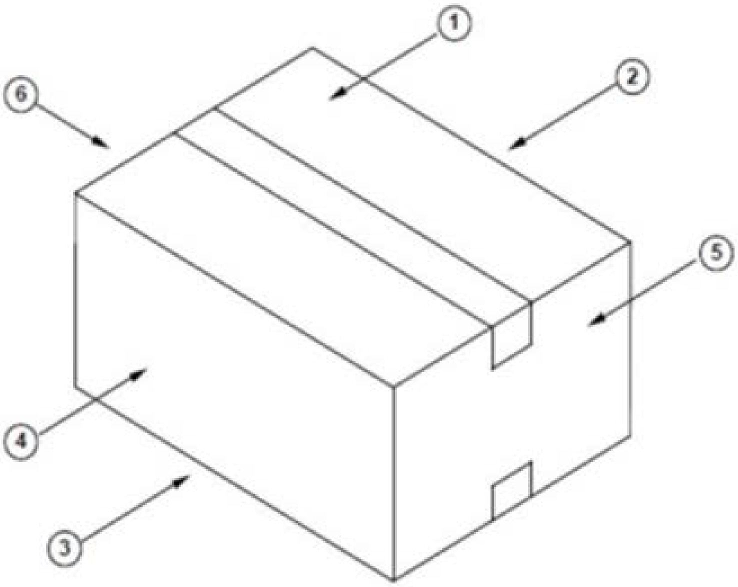


Figure 2.8 Different Dropping Locations of Product [1]

Before test determining an approval criterion of damaged location is very important. There must not be any easy realized deformation and any damage to effect performance of product. There is no information about height. So the height is decided according to its weight. Dropping sides may changes according to product's specific properties. So for an air conditioner Arçelik-LG uses its own method shown in Figure 2.6. Information about drop test setup in Arçelik-LG is given at Table 2.3.

Table 2.3 Properties of Drop Test Setup in Arçelik-LG

Properties	**Unit**	**Value**
Brand	-	Special Production
Model	-	Special Production
Height of drop range	(mm)	20-1500
Maximum sample sizes	(mm)	1200*1000*1200
Floor area dimensions	(mm)	1600*1600*200
Power	(kW)	90
External sizes	(mm)	2500*1800*1800
Net weight	(kg)	650
Applicable standards	-	ASTM D5276

2.3. STRAIN GAUGES MEASUREMENT METHOD

A Strain gauge is a sensor and it converts force, pressure, tension, weight, etc., into a change in electrical resistance. This resistance value can be measured after that. Sometimes this device is named as strain gage. Its resistance varies with applied force. Stress and strain are obtained when any force is applied to sample. The definition of the stress is sample's internal resistance forces and strain is explained as displacement and deformation.

If a conductive part is loaded mechanically, its electrical resistance is changed. Resistance of a conductive part is calculated by the formula;

$$R= \rho \frac{L}{A}$$

Where $\boldsymbol{\rho}$ is the specific conductivity, $\boldsymbol{L}$ is the length of specimen and $\boldsymbol{A}$ is section area. $\boldsymbol{R}$ is increases by the increasing of length and decreasing of section area.

For the measurement of mechanical quantities, strain gauges can be considered as one of the most effective sensor. This device provides this goal by making electrical measurement. Strain is a technical term and means both tensile and compressive displacement regardless of direction. So strain gauges can be used for enlargement and shortening.

Either an external force or internal effect can cause strain. Forces, increasing of heat, moment and high pressure structural changes of the material can be the reason of strain. If all the condition is known, measured strain value can be used to determine the amount or the value of the external effects.

This property of strain gauge is widely used on experiments to make stress analysis. The stress value which is measured on the surface of sample is used to detect safety level and strength. For the measurement of following quantities; accelerations, displacements, vibrations, moments, pressures some special transducers are used. These devices have a diaphragm which is sensitive to pressure and bonded to strain gauge.

Stress and strain are obtained when an external force is applied to a sample. Stress is defined as the object's internal resisting forces, and strain is defined as the displacement and deformation that occur. For a uniform distribution of internal resisting forces, stress can be calculated by dividing the force (***F***) applied by the unit area (***A***):

Stress (σ) = F/A

Strain is defined as the amount of deformation per unit length of an object when a load is applied. Strain is calculated by dividing the total deformation of the original length by the original length (***L***):

Strain (ε) = (∆L)/L

Maximum principal stresses are calculated by the formula;

$$\sigma_{1,2} = E\left(\frac{\varepsilon_x + \varepsilon_y}{2(1+v)} \pm \frac{1}{2(1+v)}\sqrt{(\varepsilon_x - \varepsilon_z)^2 + \left(2\varepsilon_y + (\varepsilon_x + \varepsilon_z)\right)^2}\right)$$

Where the E is the elastic modulus, $\boldsymbol{v}$ is the Poisson's ratio, $\boldsymbol{\varepsilon_x}$ is the strain in x direction, $\boldsymbol{\varepsilon_y}$ is the strain in y direction and $\boldsymbol{\varepsilon_z}$ is the strain in z direction.

Von Mises is calculated with strain gauges by the below formula;

$$\sigma_{VonMises} = \left|\sqrt{(\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2)}\right|$$

An important parameter for strain gauge is the gauge factor (GF). This factor is determined as 2 from manufacturer and calculated by the below formula;

$$\boldsymbol{GF} = \frac{\Delta \boldsymbol{R}/\boldsymbol{R}}{\boldsymbol{\varepsilon}}$$

2.3.1. Bonded Resistance Gauges

These devices use a popular way for measuring strain. The gauge has a metallic wire or semiconductor material which is bonded to surface of experiment sample or carrier matrix. This matrix is bonded with epoxy by a thin insulated layer and when it is strained this epoxy layer transmits the strain to the grid material. So some changes occur variations in the electrical resistance and this shows that there is strain. The grid has the properties that provide maximum gauge resistance. During process dimensions of gauge both vertical and horizontal change minimum by the help of grid shape. It can be seen schematically in Figure 2.9 of the bonded resistance strain gauge.

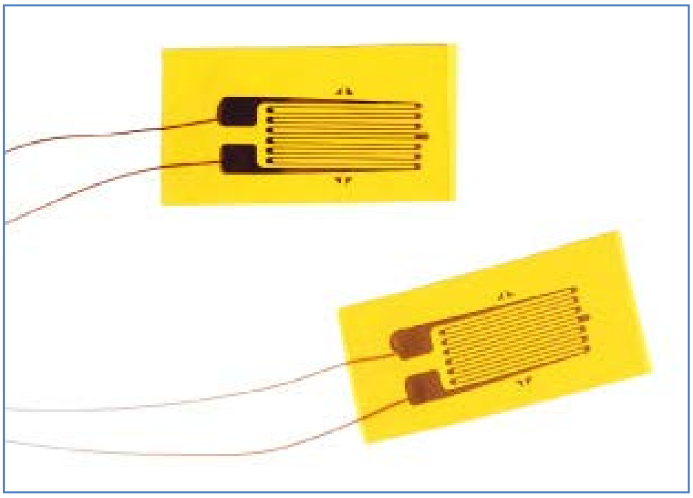


Figure 2.9 Bonded Resistance Gauges

These type gauge are known of their fine properties. They are cheap according to other gauges and their measurement accuracy is better than +/- 0.10%. They have good resistance to temperature variations, there are short types of them commercially, weight is low enough, make perfect measurement. During most of experiment bonded gauges are used to determine dynamic or static strain value. General details of bonded strain gauge are shown in Figure 2.10.

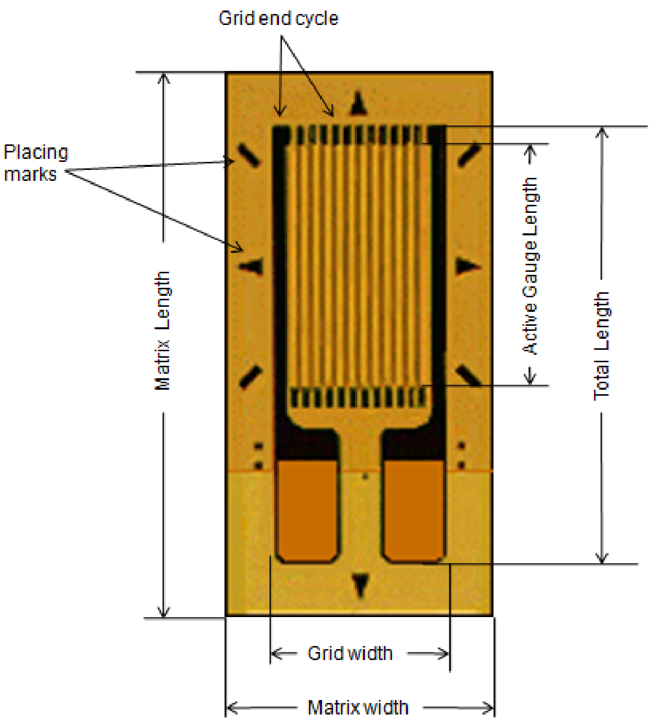


Figure 2.10 Details of Bonded Strain Gauge

It is very important for the gauge and surface are exposed to same strain during experiment. Most of time insulation layer that is the adhesive material between gauge and sample surface is exposed to creep which occurs because of degradation of bond, effects of temperature. So selecting adhesive material is a very important step of getting accurate result.

The bonded resistance strain gauge is used on very different conditions. It can measure strain in jet engine turbines operating at very high temperatures and in cryogenic fluid applications at temperatures as low as -269^{0}C. It has low mass and size, high sensitivity, and is suitable for static and dynamic applications. Foil elements are available with unit resistances from 120 to 5,000 ohms. Gauge lengths from 0.008 in. to 4 in. are available commercially. The three primary considerations in gauge selection are:

- Operating temperature,
- The nature of the strain to be detected,
- Stability requirements.

In addition, selecting the right carrier material, grid alloy, adhesive, and protective coating will guarantee the success of the application.

2.3.2 Selection of Strain Gauge and Its Measurement Position

In order to make compliance with requirements of previous section "Kyowa" strain gauges were selected. Properties of Kyowa gauges are presented in Table 2.4

Table 2.4 Properties of Kyowa Strain Gauges

Properties	**Unit**	**Value**
Brand	-	Kyowa
Model	-	KFG-5-120-C1-11L3M3R
Gage Factor	(24^{0}C, 50%RH)	2,09 ±1,0%
Gage Length	(mm)	5
Gage Resistance	(24^{0}C, 50%RH)	120,4 ± 4 ohm
Adoptable thermal expance	PPM/^{0}C	11,7
Temperature coefficient	%/^{0}C	0,008

Also photography of Kyowa strain gauges can be seen in Figure 2.11.

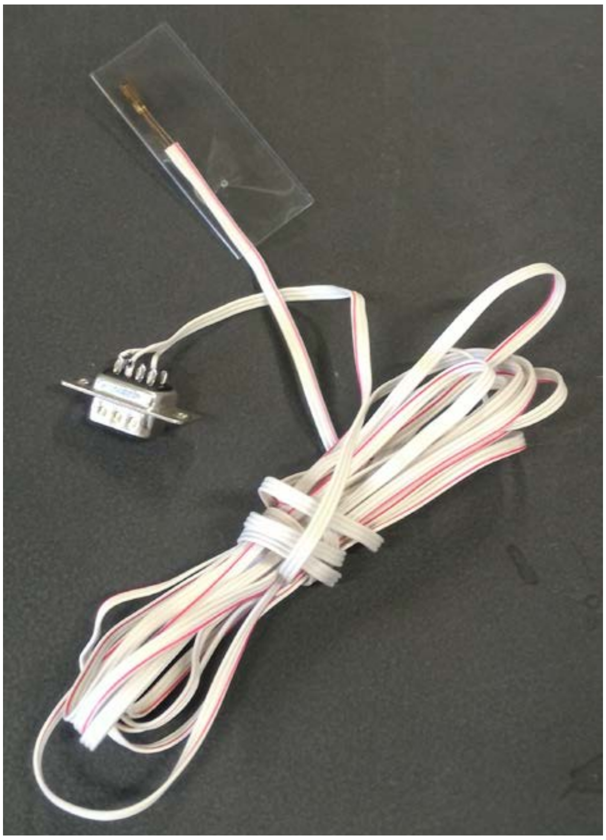


Figure 2.11 Kyowa Strain Gauge

In this study the indoor unit was just dropped to bottom side and front side. First of all pre-wired type strain gauges were attached the right hook of decor part as shown in Figure 2.12 and the left hook of discharge grille as shown in Figure 2.13. These strain gauge attachment locations of product were selected after a while drop tests which were damaged every trial. Strain gauges were attached to hook of décor perpendicular to the direction of fracture because of getting more sensitive results. The second strain gauge was also attached to hook of discharge grille in most suitable position to supply accuracy at results. By the help of this attaching position, total contact area of strain gauge reached to maximum.

Figure 2.12 Decor Hook Strain Gauge Attachment

Figure 2.113 Discharge Grille Hook Strain Gauge Attachment

After attaching of strain gauges right and left EPS foam were inserted and cartoon box closed by tape as shown in Figure 2.14.

Figure 2.124 Assembling of Product after Attachment of Strain Gauges

By the help of below equipment shown in Figure 2.15 we created a network between indoor unit and computer.

Figure 2.135 Strain Gauge Network Equipment

For different locations of the product we made connection with separate cables the Brigde Box shown in Figure 2.16. The brand of this bridge bow is “LG” and manufacturer is “İREA System Industry”

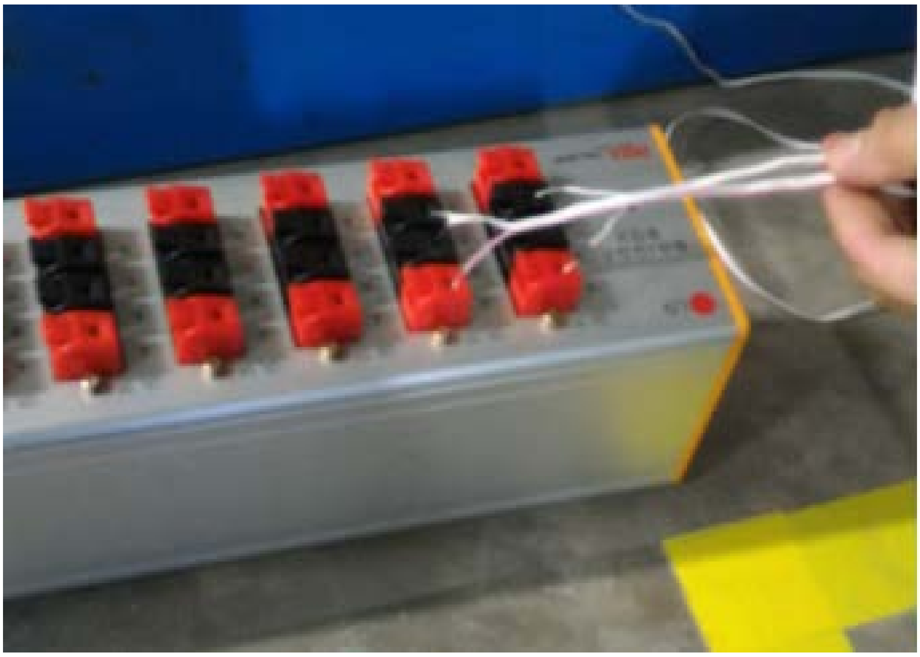


Figure 2.146 Different Cable Connections for Different Strain Gauges

Finally the product became ready to make drop test to measure stress values by strain gauges shown in Figure 2.17.

Figure 2.157 Ready Product for Drop Test

A universal recorder is used to record strain values and transmit to software as shown in Figure 2.18. Its brand is also “Kyowa” and model is EDX-200A.

Figure 2.18 Universal Recorder

After that, by the help of software program we measured stress values on the gauge attached locations as shown in Figure 2.19.

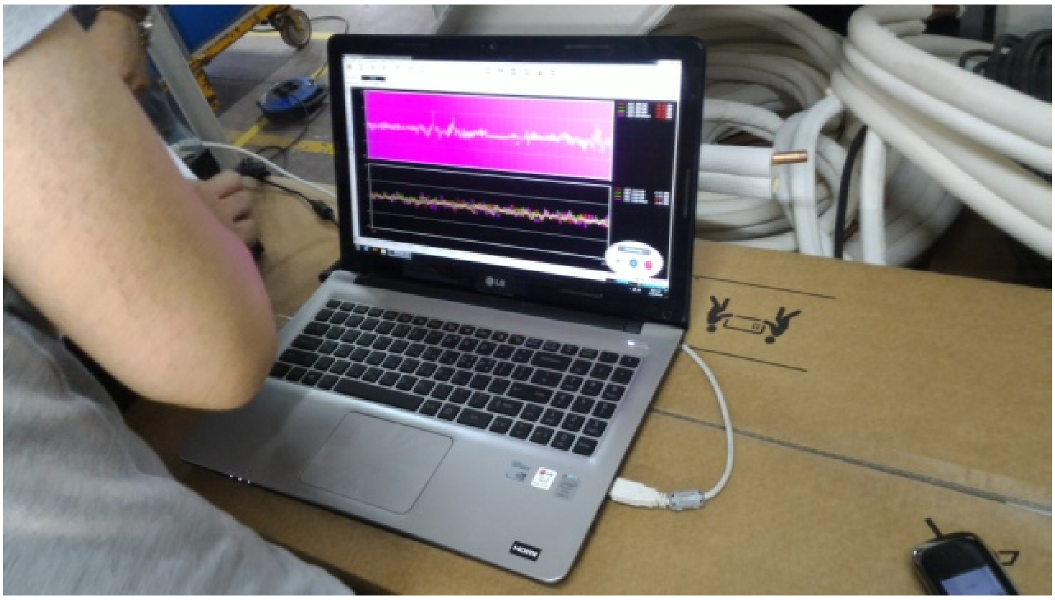


Figure 2.169 Strain Gauge Software Program

Schematic representation of this strain gauge measurement method is shown in Figure 2.20

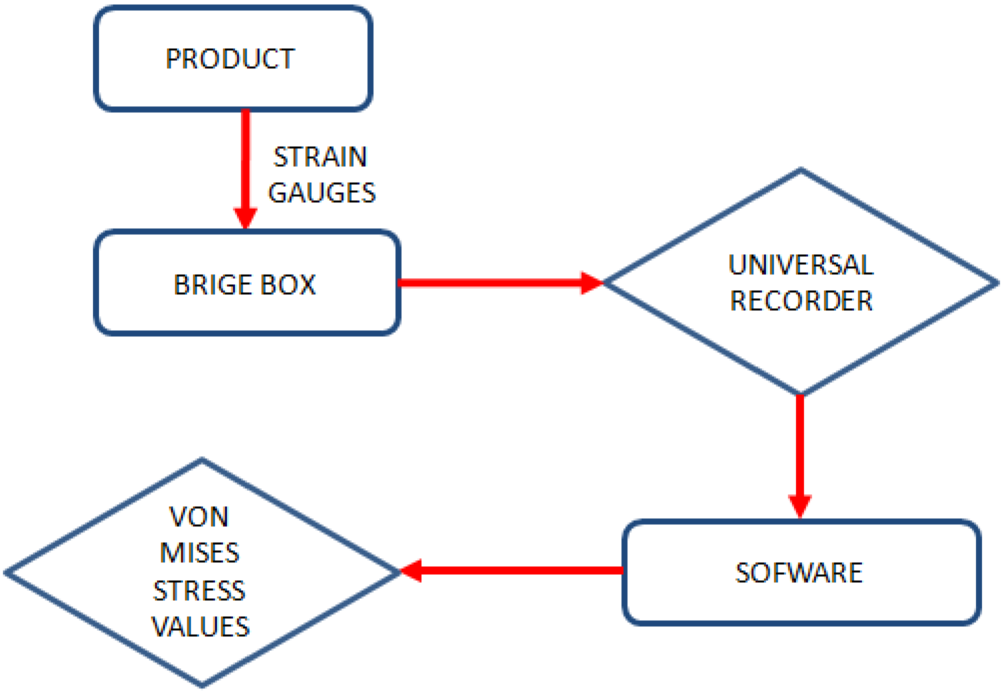


Figure 2.20 Schematic Representation of This Strain Gauge Measurement Method

A high speed camera Sony a6300 which can record 120 frame per second was employed to record drop test, special attention is paid to detect contact duration between the product and rigid ground. Duration is detected as 0,040 sec from recorded video. This duration was used as an import value at Finite Element analysis.

2.4. FINITE ELEMENT METHOD

The Finite element method is a numerical solution that seeks solutions to various engineering problems with an acceptable approach.

The solution area of the engineering problem is disaggregated to the sub-regions and statement of the function sought in each sub-region is selected to be polynomial. Within certain processes, the coefficients of the solution considered as polynomial in each sub-region are tried to be determined [33].

2.4.1. Advantages of Finite Element Method

Advantages of finite element method are;

- The Finite element method (FEM) allows the study of complex shapes. The solution zone can be divided into sub-regions and different finite elements can be used. More accurate calculations can be made in some sub-regions if required.
- FEM can be easily applied in systems with different and complex material properties. For example, material properties such as anisotropy, nonlinear, time dependent material properties can be considered
- Boundary conditions can be included in the system of equations by simple column operations after the basic equations of the system have been established
- FEM can be generalized mathematically and the same model can be used to solve many problems
- The method has both physical meaning and mathematical basis

2.4.2. Disadvantages of Finite Element Method

Finite element method has some disadvantages such as;

- There are some difficulties in applying some problems
- The accuracy of the result depends on the accuracy of the data
- There is a need of computer

- Disaggregation of the region requires experience to obtain an acceptable accurate result.
- As with other approximate methods, attention should be paid to the accuracy of the result obtained with FEM and the physical problem should be examined well. The result should be predicted and should be tested accordingly.

2.4.3. Steps of Process

Steps of process can be ranked as;

- Mathematical model of physical problem is established
- Variation Expression (Formulation) of the problem is established
- The solution zone is disaggregated to the sub-regions called finite elements
- The expression of the function sought in each finite element is considered polynomial. These functions are written in the variation expression and the basic equations for each finite element are converted into algebraic equations. For example; these algebraic equations for finite element e;

$$\boldsymbol{K}^{(e)}\,\boldsymbol{u}^{(e)} = \boldsymbol{F}^{(e)}$$

Where ***K*** is the stiffness matrix, ***u*** is the vector including unknowns and ***F*** is the force vector.

- The equations for each finite element are combined in a suitable way to obtain the corresponding set of algebraic equations. This system includes the reduced system by including the boundary conditions with the appropriate row/column operations.
- By deconstructing the reduced system, required quantities are obtained at every node
- Finally, the solution is presented to the user in the form of graphics, tables or photographs

There are two options for algorithm choice in finite element method. The first one is implicit, which always requires a repetitive solution for the step, and the second is the explicit algorithm, which avoids the repetitive step as much as possible. In the explicit solution, the model is solved for small time steps and the result of the next step is by means of known data from the previous step. Implicit algorithm is solved with a model repetitive approach and the result is approached.

For high-speed analyzes such as impact etc., it is necessary to use an explicit solvent because a small time step is required. For static analyzes, the implicit algorithm is advantageous. Therefore, it will use a solvent that uses explicit algorithm to solve the finite element model prepared within the scope of the study. The most important disadvantage of the explicit solution is that it takes a long time to achieve the final result because of the small time steps [33].

2.5. ANSYS SOFTWARE PROGRAM

Finite Element Analysis is a way to simulate loading conditions on a design and determine the design's response to those conditions.

The design is modeled using discrete building blocks called elements. Each element has exact equations that describe how it responds to a certain load. The sum of the response of all elements in the model gives the total response of the design. The elements have a finite number of unknowns, hence the name finite elements.

FEA is needed to reduce the amount of prototype testing and to simulate designs that are not suitable for prototype testing.

Among many software program ANSYS is a complete FEA software package used by engineers worldwide in virtually all fields of engineering:

- Structural
- Thermal
- Fluid, including CFD (Computational Fluid Dynamics)
- Electrical / Electrostatics
- Electromagnetic

A partial list of industries in which ANSYS is used:

- Aerospace
- Automotive
- Biomedical

- Bridges & Buildings
- Electronics & Appliances
- Heavy Equipment & Machinery
- MEMS - Micro Electromechanical Systems
- Sporting Goods

Ansys has 3 of the top explicit dynamic solutions;

- ANSYS Explicit/STR
- ANSYS/LS-DYNA
- ANSYS Autodyn

Among these solutions we used explicit nonlinear finite element software program "ANSYS Autodyn". Because it is easy to use for multiphysics and sophisticated material response and well suited for designers and analysts who use Ansys Workbench to easily solve complex problems. It greatly simplifies the tasks associated with conducting a drop test simulation [34]:

- Dropped objects easily oriented
- Gravitational field quickly established
- Rigid target surface automatically constructed and restrained
- Entering drop height straightforward
- Impacting velocity conveniently calculated
- The DTM was designed to allow inexperienced users to quickly set-up a complicated drop test simulation, solve it, and review the results

Additionally Ansys describes the complexity of drop test as shown in Figure 2.21.

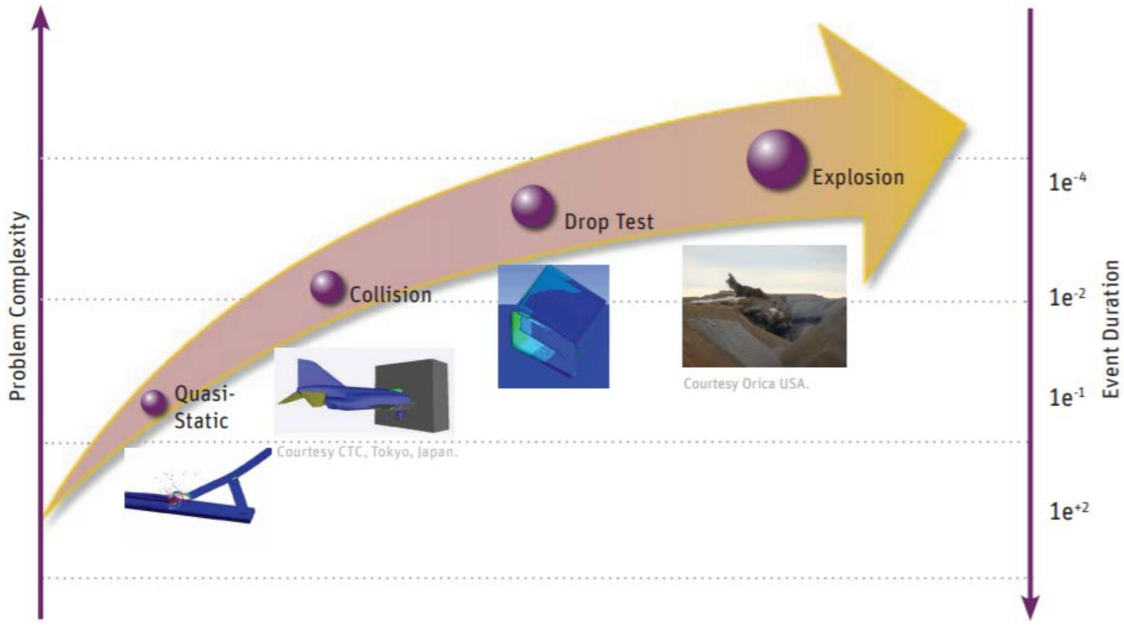


Figure 2.21 17 Complexity of Problems [34]

2.6. FINITE ELEMENT ANALYSIS

Making drop test on the software program analysis requires a step-by-step procedure. A typical test would involve dropping an object from some height in a gravitational field onto a flat, rigid surface (target), neglecting surface friction. The basic procedure outlined here assumes that the object has an initial velocity, and the object is being dropped onto a target that lies in a plane which is normal to the direction of the acceleration due to gravity. For the analysis, below units are used to indicate the result shown at Table 2.5.

Table 2.5 Units at Analysis

Unit System	Metric (m, kg, N, s, V, A)
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

According to the ANSYS Explicit Dynamics Analysis Guide tutorials [33] workflow steps for explicit dynamic analysis are;

- Introduction
- Create the Analysis System
- Define Engineering Data

- Attach Geometry
- Define Part Behavior
- Define Connections
- Setting Up Symmetry
- Define Remote Points
- Apply Mesh Controls/Preview Mesh
- Establish Analysis Settings
- Define Initial Conditions
- Apply Loads and Supports
- Solve
- Post processing

2.6.1 Creating and Assembling the Model

Firsts of all, all the parts of indoor unit were created separately at creo parametric 3D design program. Then the assembly file was made by these parts. It can be seen décor, discharge grille and full assembly data in Figure 2.22.

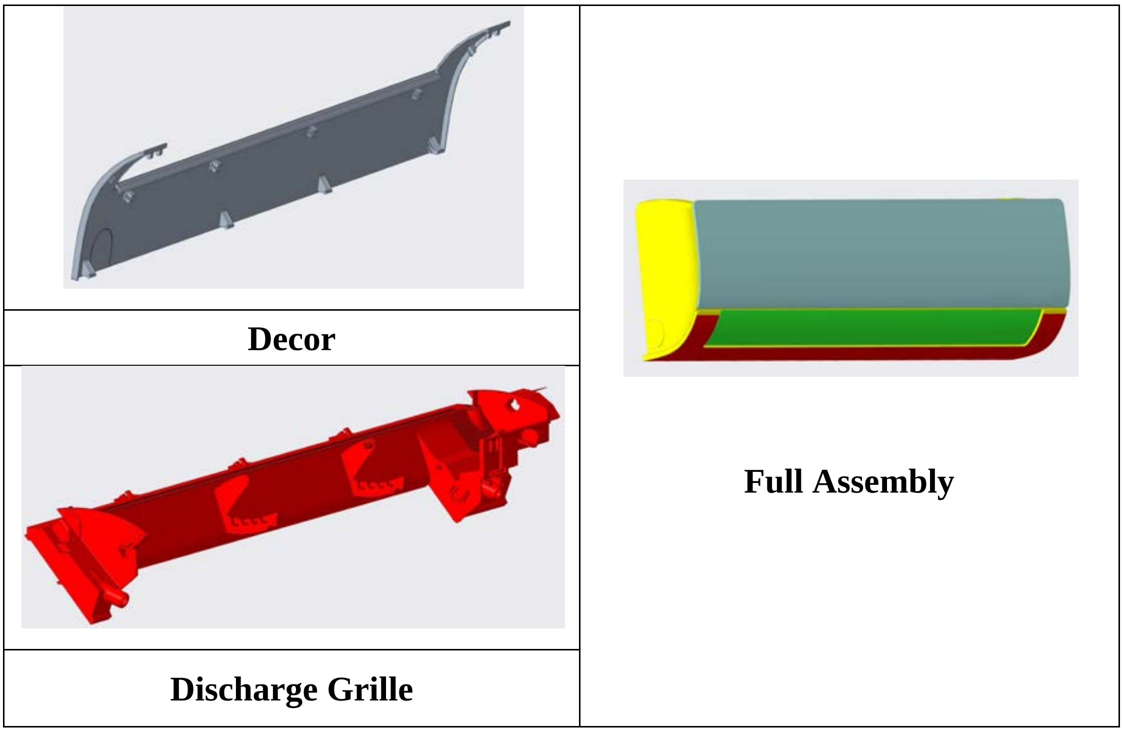


Figure 2.2218 3D Data of Decor, Discharge Grille and Full Assembly

2.6.2. Opening a New Explicit Dynamic Analysis on Ansys Workbench

Firstly Ansys Workbench was opened and an explicit dynamic file was created. Second step is determining materials from "Engineering Data" section. For decor part ABS, for discharge grille PP and for cushioning parts EPS materials must be selected. But Ansys Library includes none of them. So we introduced ABS to library by getting properties from [13], PP from [14] and EPS foam from [7] and [32].

2.6.3. Importing 3D Data

Ansys provides user to create 3D files by its sub designing and drawing program. But at this study 3D assembly file was created at Creo parametric program. This assembly data was saved as step format in order to open in Ansys program and imported as shown in Figure 2.23.

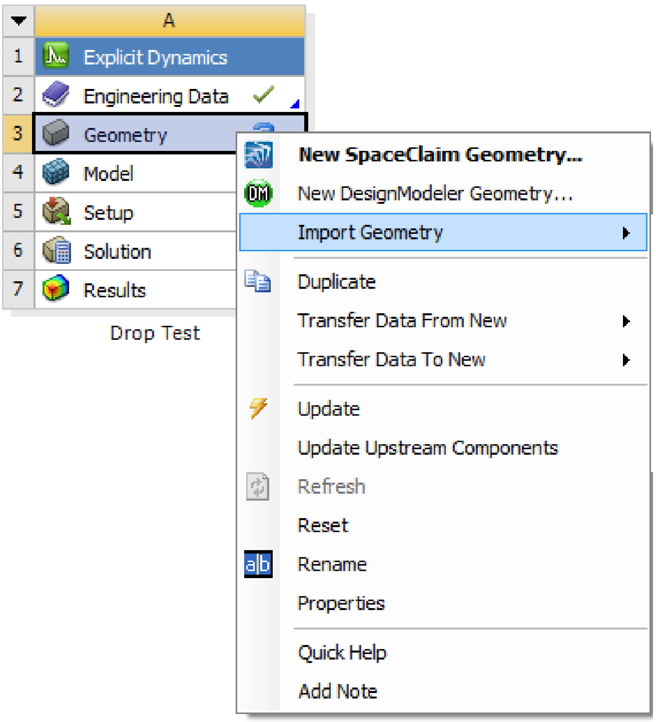


Figure 2.193 Importing Step File

2.6.4. Connections of Parts

All parts connections were defined automatically by Ansys. Hooks of décor were connected to inserts of base panel as shown in Figure 2.24.

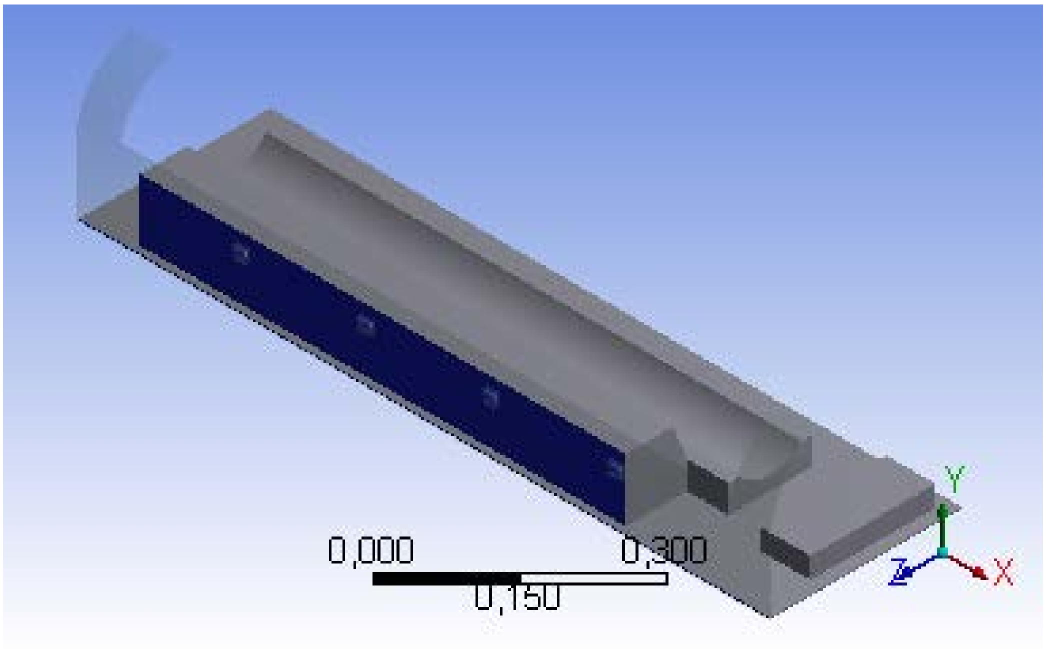


Figure 2.204 Connections of Decor Hooks

Also hooks of discharge grille were connected to inserts of vane horizontal as shown in Figure 2.25.

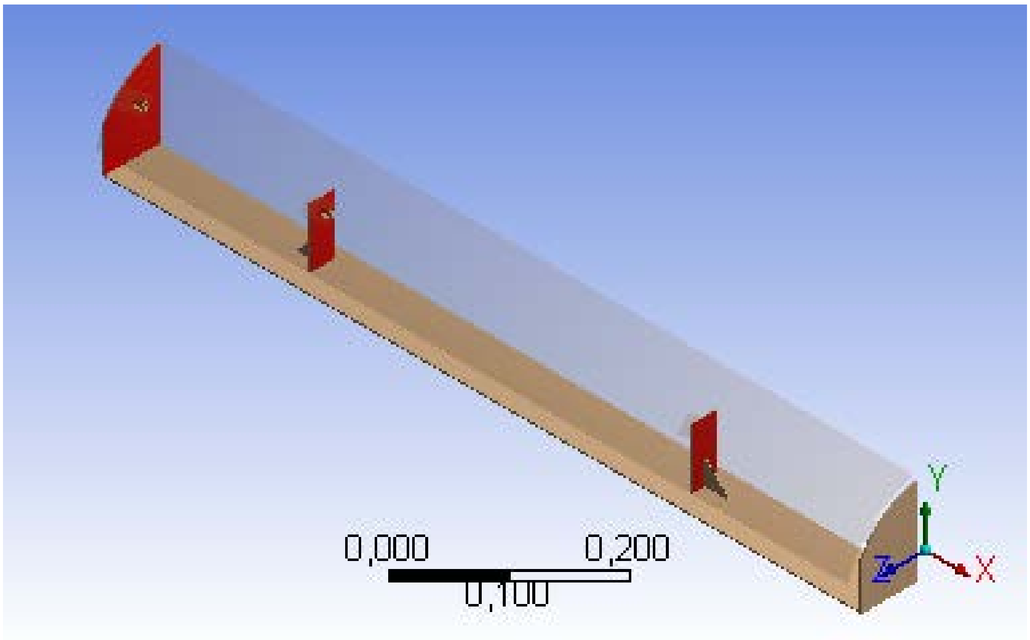


Figure 2.215 Connections of Discharge Grille Hooks

2.6.5. Generating Mesh

After importing 3D file to Ansys, by double clicking we opened AUTODYN PrepPost in order to set steps of analysis. Firstly materials were assigned to all parts one by one. After that connections of each part to another were defined automatically. Connection types used in this study are below;

- Bonded
- Frictional

By using generate mesh property of Ansysmesh, mesh was created for all assembly. Totally 711823 nodes and 658715 elements were generated as shown in Figure 2.26.

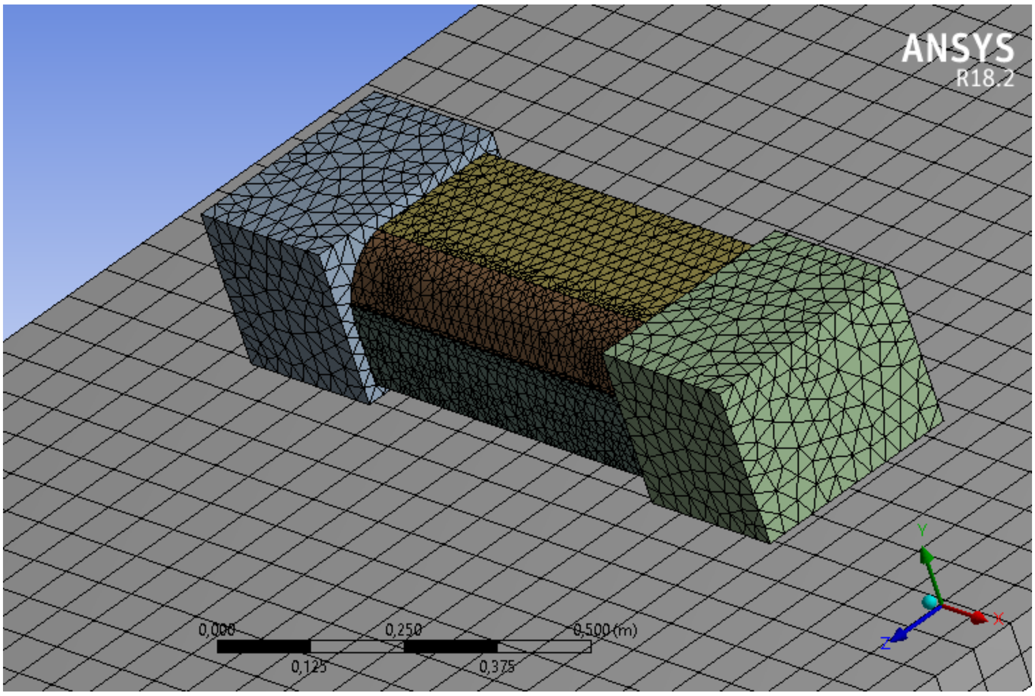


Figure 2.226 Mesh Generated Assembly

2.6.6. Defining Drop Height

Thanks to its outstanding feature of Ansys, defining of drop height, initial conditions were created as shown in Figure 2.27. This height is 50 cm for our indoor unit air conditioner.

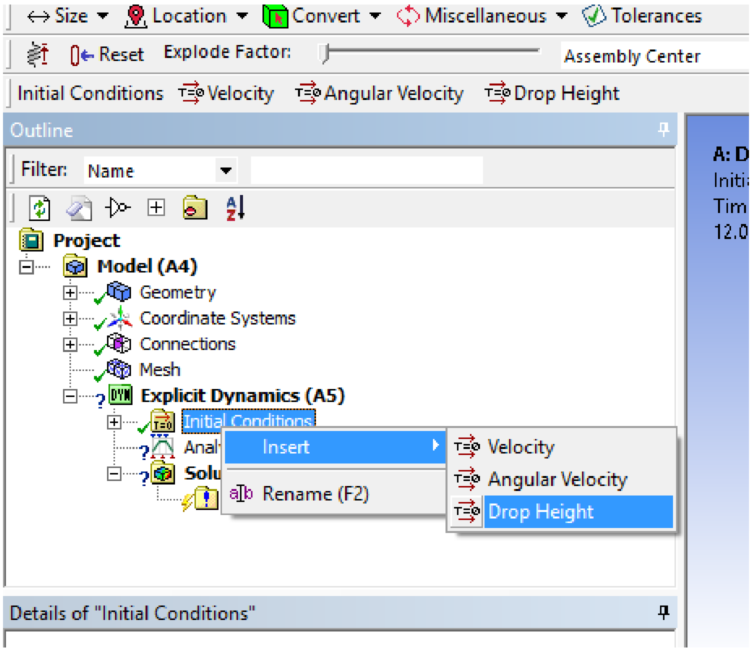


Figure 2.237 Defining Drop Height

On the drop test, indoor unit had a velocity when touched the rigid ground. This initial velocity value was calculated automatically by the software program with the below formula;

$$Vo = \sqrt{2gh}$$

Where $\boldsymbol{V_0}$ is the initial velocity, $\boldsymbol{h}$ is the height of indoor unit dropped on test and $\boldsymbol{g}$ is the acceleration of gravity.

$$Vo = \sqrt{2x\left(\frac{9{,}8066\text{m}}{\text{s}2}\right)\text{x}0{,}5\text{ m}}$$

$$Vo = 3{,}1315\ m/s$$

2.6.7. Defining Standard Earth Gravity

In order to perform a drop test analysis it is an obligation to define the direction and values of gravity. By the help of below function shown in Figure 2.28 we defined gravity in –Y direction and enter the value of 9,8066 m/s^2. Bottom of rigid ground was defined as fixed support area at analysis.

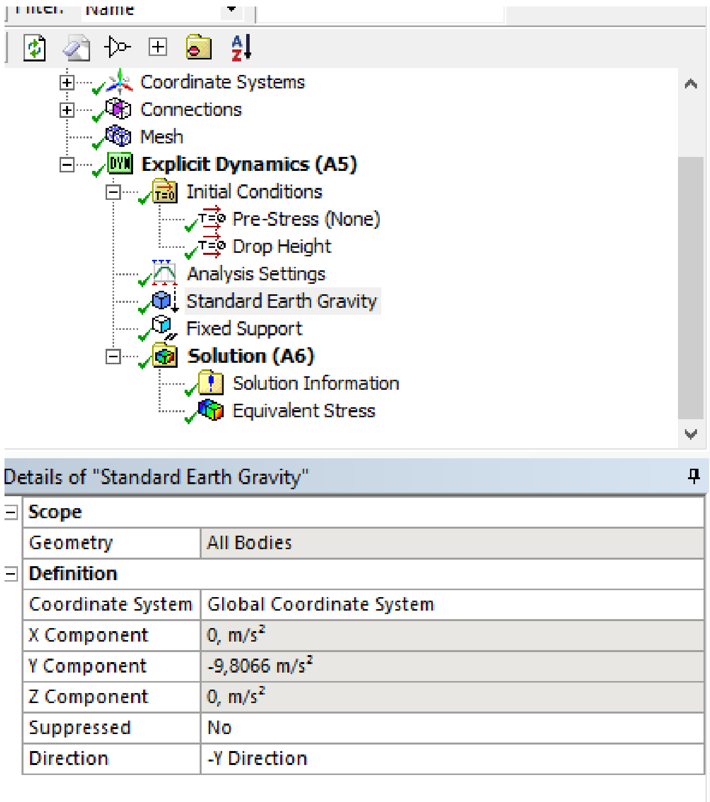


Figure 2.28 Defining Gravity

2.6.8. Specifying Solution Controls

At the end of the analysis equivalent von Mises stress values were obtained in order to compare with the ones of strain-gauges. So this solution controls was created as Figure 2.29.

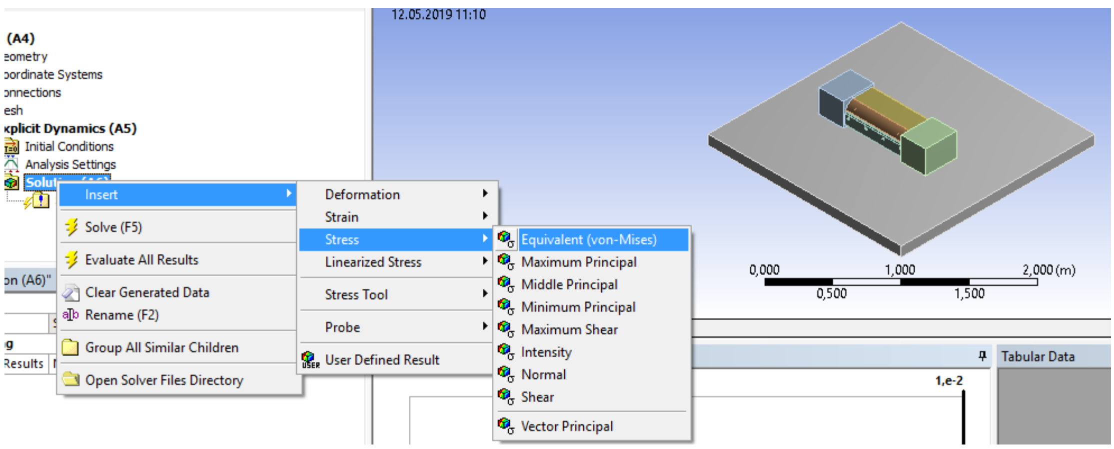


Figure 2.249 Equivalent Von Mises

2.6.9. Getting and Animation of Results

By using the solving option, below animation image was obtained as shown in Figure 2.30.

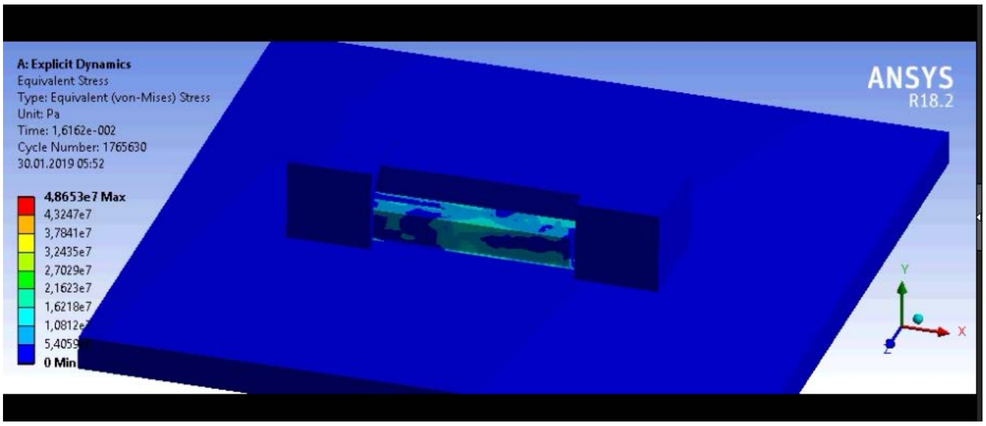


Figure 2.30 Animation Image

3. RESULTS AND DISCUSSION

3.1. RESULTS AND DISCUSSION

In this study only two types drop test were conducted. The air conditioner indoor unit dropped to its front side and bottom side and then the finite element analysis were performed according to these two types. When the product was dropped to its front side hook of discharge grille was deformed both attest and analysis as shown in Figure 3.1 and hook of décor was deformed when dropped to bottom side as shown in Figure 3.2.

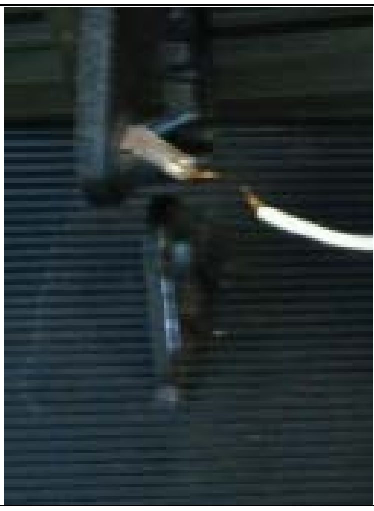
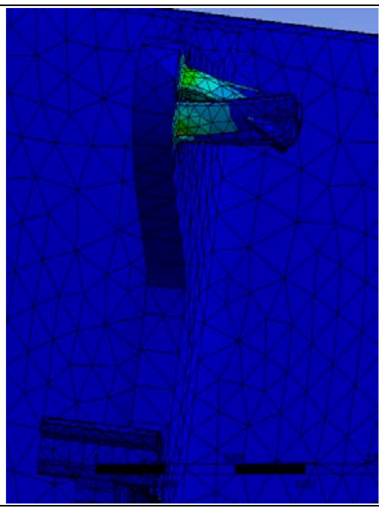
	
Drop Test with Strain Gauges	**Ansys Analysis Results**

Figure 3.1 Deformation of Hook of Discharge Grille Part

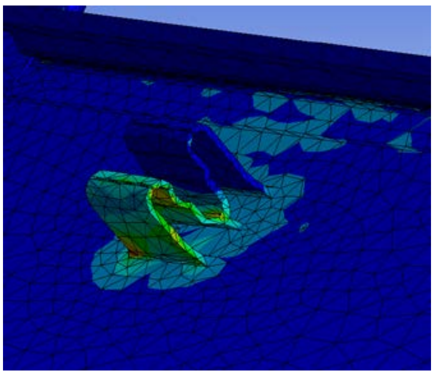
	
Drop Test with Strain Gauges	**Ansys Analysis Results**

Figure 3.2 Deformation of Hook of Decor Part

The results we measured for hooks of the decor and discharge grille are tabulated in Tables 3.1 and 3.2, respectively.

Table 3.1 Stress Values of Decor Hook Measured by Strain Gauge and Ansys

CH NAME	TIME	STRAIN GAUGE	ANSYS
CH No.	**CH1**	**STRESS (MPa)**	**STRESS (MPa)**
1	0	0,2	0,20
2	0,04	0,3	0,29
3	0,08	0,1	0,11
4	0,12	0,4	0,41
5	0,16	0,3	0,29
6	0,2	255,2	245,00
7	0,24	108,3	95,00
8	0,28	0,2	0,24
9	0,32	0,4	0,39
10	0,36	0,1	0,12
11	0,4	0,3	0,31

Table 3.2 Stress Values of Discharge Grille Hook Measured by Strain Gauge

CH NAME	TIME	STRAIN GAUGE	ANSYS
CH No.	**CH1**	**STRESS (MPa)**	**STRESS (MPa)**
1	0	0,2	0,21
2	0,04	0,3	0,32
3	0,08	0,1	0,098
4	0,12	0,4	0,389
5	0,16	0,3	0,31
6	0,2	97,1	92
7	0,24	9,9	16,5
8	0,28	0,2	0,25
9	0,32	0,4	0,43
10	0,36	0,1	0,17
11	0,4	0,3	0,28

The stress results of the strain gauge attached locations obtained from the drop test are compared with the analysis results to verify the reliability. As seen from Figure 3.3 and 3.4, diversity of von Mises Stress values of drop test and analysis is negligible and validation of finite element analysis was performed. Similar to previous studies for example washing machine and refrigerator (respectively [5] and [8]) total average difference is under the value of 10%. Small differences between von Mises stress values are thought to be due to measurement accuracy of strain gauges and simplicity of assembly file in order to reduce analysis time. Using more than one strain gauge for one area and a detailed assembly file will increase the accuracy of results.

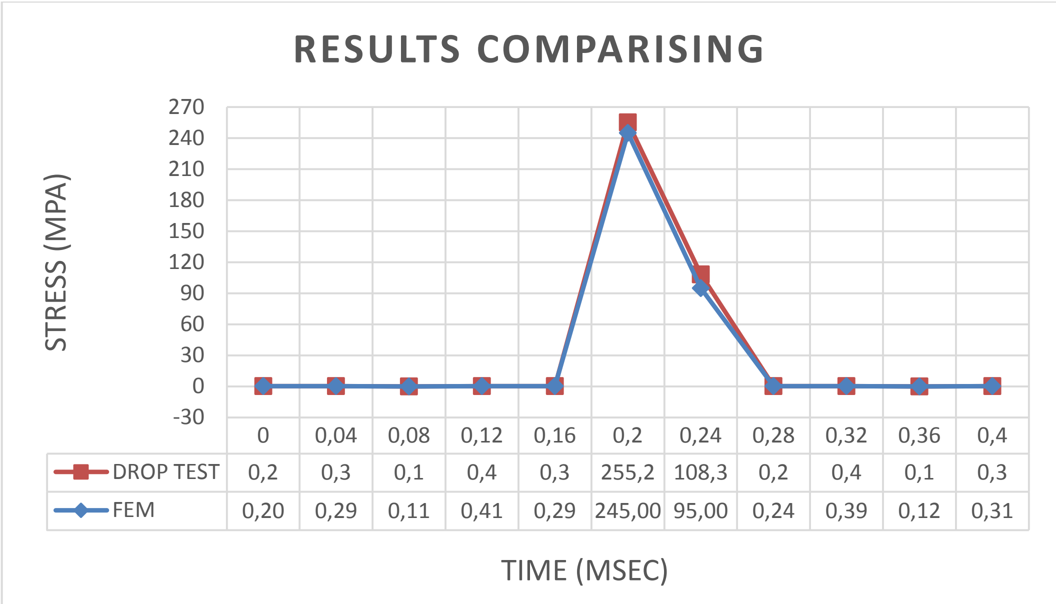


Figure 3.3 Comparison of von Mises Stresses of Experiment and Simulation for Decor Hook

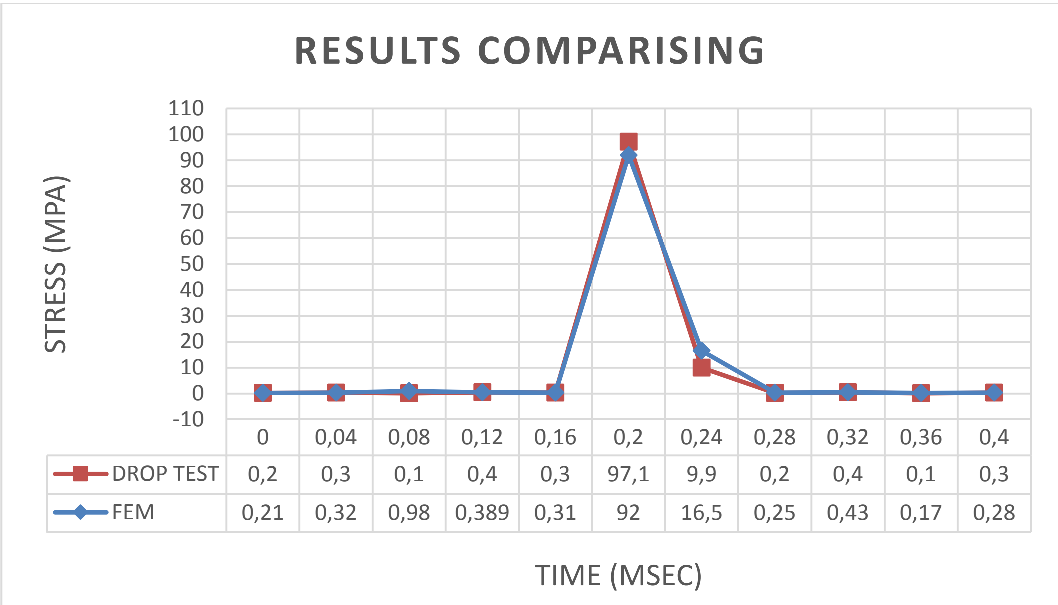


Figure 3.4 Comparison of von Mises Stresses of Experiment and Simulation for Discharge Grille Hook

3.2. IMPROVEMENTS FOR DAMAGES

After the validation of analysis, improvements were made in order to eliminate deformations occurred drop test. A 1 mm round was added to bottom of decor hook rib Figure 3.5. Additional EPS was used in order to eliminate deformation of discharge grille hook as shown in Figure 3.6.

Figure 3.5 Round at the Bottom of Decor Hook

Figure 3.6 Additional EPS Preventing Deformation of Discharge Grille Hook

3.3. REPEATING OF ANALYSIS WITH THE IMPROVED PARTS

When improvements were implemented on 3D design data, analysis was performed again. Comparison of décor part images are shown in Figure 3.7.

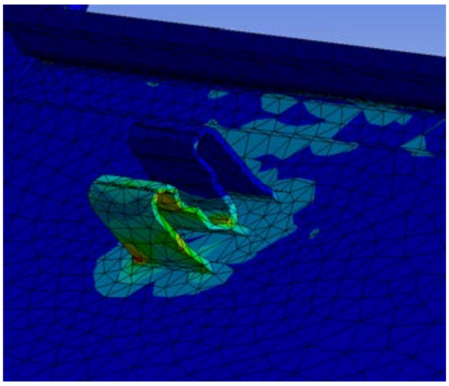
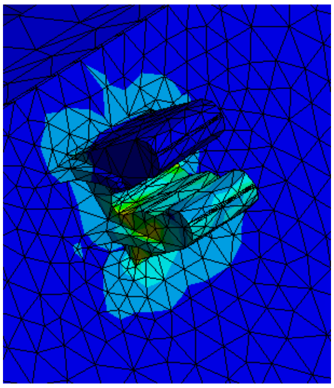
	
Décor Hook Before Improvement	**Decor Hook After Improvement**

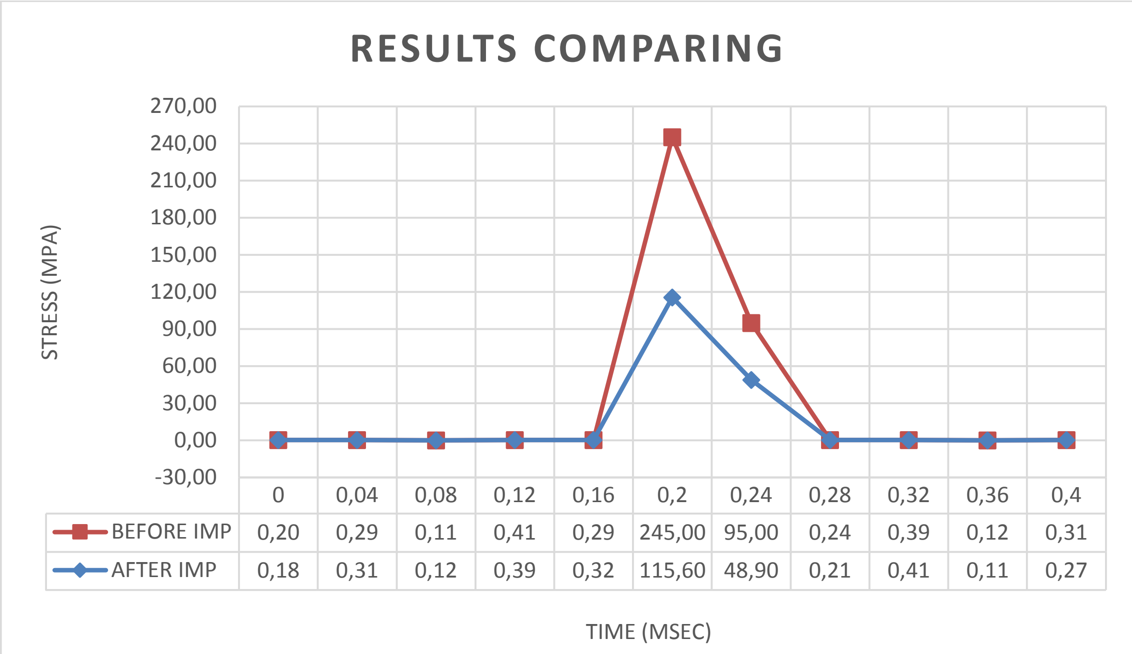
Figure 3.7 Deformation of Hook of Decor Part Before and After Improvement

Von Mises stress results which were measured on analysis are shown at the Table 3.3 for comparing improvement design situation with before.

Table 3.3 Comparison of Stress Values Before and After Improvement

CH NAME	TIME	ANSYS STRESS	ANSYS STRESS
CH No.	CH1	Before Imp. (MPa)	After Imp.(MPa)
1	0	0,20	0,18
2	0,04	0,29	0,31
3	0,08	0,11	0,12
4	0,12	0,41	0,39
5	0,16	0,29	0,32
6	0,2	245,00	115,60
7	0,24	95,00	48,90
8	0,28	0,24	0,21
9	0,32	0,39	0,41
10	0,36	0,12	0,11
11	0,4	0,31	0,27

And comparison of results is shown graphically in Figure 3.8.



	0	0,04	0,08	0,12	0,16	0,2	0,24	0,28	0,32	0,36	0,4
BEFORE IMP	0,20	0,29	0,11	0,41	0,29	245,00	95,00	0,24	0,39	0,12	0,31
AFTER IMP	0,18	0,31	0,12	0,39	0,32	115,60	48,90	0,21	0,41	0,11	0,27

Figure 3.8 Comparison of von Mises Stresses of Decor Part Before and After Improvement Measured from Analysis

According to analysis result stress values decreased nearly 51 % with respect to unimproved design data. New analysis results show that improvement is good enough. According to these analysis results drop test was repeated by attaching strain gauges. At this time hook of décor part did not deformed as shown in Figure 3.9.

Figure 3.9 Drop Tested and Unbroken Hook of Decor Part

Comparison of discharge grille part's images is shown in Figure 3.10.

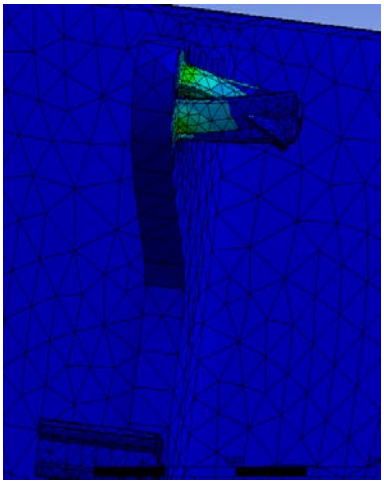
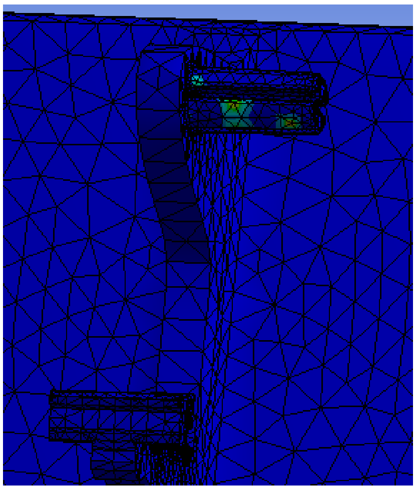
	
Discharge Grille Before Improvement	**Discharge Grille After Improvement**

Figure 3.10 Deformation of Hook of Discharge Grille Before and After Improvement

Von Mises stress results which were measured on analysis are shown at the Table 3.4 for comparing improvement design situation with before.

Table 3.4 Comparison of Stress Values Before and After Improvement

CH NAME	TIME	ANSYS STRESS	ANSYS STRESS
CH No.	CH1	Before Imp. (MPa)	After Imp.(MPa)
1	0	0,21	0,19
2	0,04	0,32	0,27
3	0,08	0,98	1,1
4	0,12	0,389	0,41
5	0,16	0,31	0,28
6	0,2	92	7,2
7	0,24	16,5	1,3
8	0,28	0,25	0,21
9	0,32	0,43	0,39
10	0,36	0,17	0,21
11	0,4	0,28	0,25

And comparison of results is shown graphically in Figure 3.11.

Figure 3.11 Comparison of von Mises Stresses of Decor Part Before and After Improvement

According to analysis result stress values decreased nearly 89 % with respect to unimproved design data. New analysis results show that improvement is good enough. According these analysis results drop test was repeated by attaching strain gauges. At this time hook of discharge grille part did not deformed as shown in Figure 3.12.

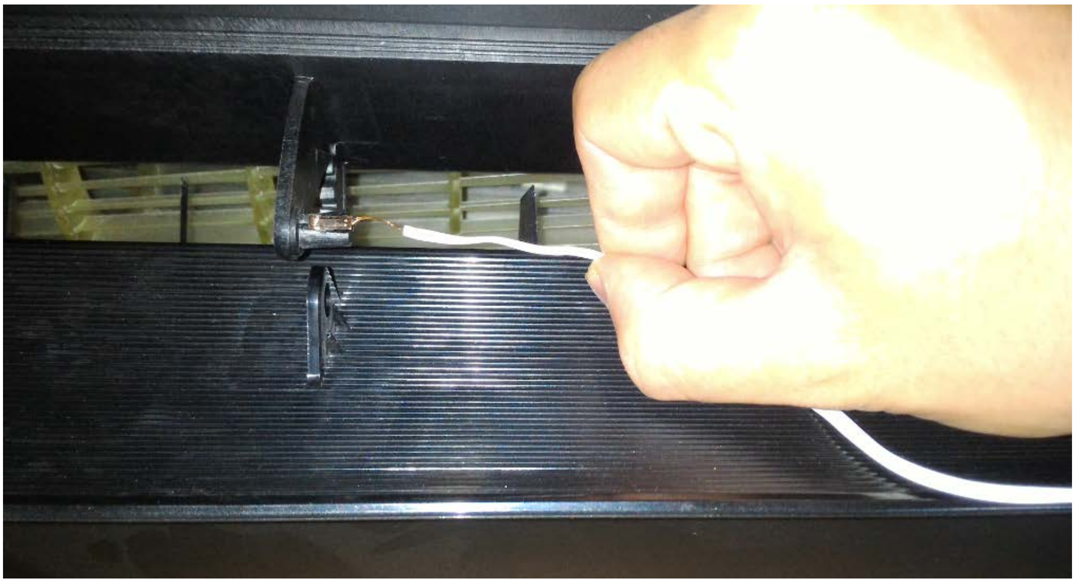


Figure 3.12 Drop Tested and Undeformed Hook of Discharge Part

4. CONCLUSION

4.1. CONCLUSION OF THE WORK

Home appliances and some electronic devices may be exposed to some accidents such as dropping to floor, striking to some or crushing during transportation. These undesirable events may cause some plastic and glass parts to break and some sheet metal parts to bend. This situation may result in visible damage to the product or the product may not be able to perform its expected functions. Furthermore customer dissatisfaction and complaints can damage the company brand also loses money. To ensure this type of risk is not the case, drop test is conducted to detect weak points of product before mass production. After the test product is opened and checked if there is there any damaged part or not. If damages are detected in these tests, some improvements are performed and drop test is repeated. This cycle continues until all damages are eliminated. At these destructive drop tests, whether any damage is encountered or not the product is discarded. So the lead time and design costs increase as a result of these tests.

In this study drop tests were performed on wall-mounted air conditioner indoor unit by attaching strain gauges to most damaged areas. These potential risk zones are hook of décor part which usually cracked and hook of discharge grille which usually damaged. By the help of stress convert software program, von Mises stress values were measured from these areas during drop test. Test duration was recorded by a high speed camera which has a capability of 120 frame per second. Impact duration is detected as 0,40 msec and this value is used as an input value in finite element analysis. Finite element analyses were performed with the ANSYS Autodyn program. By the help of sub-program, “Drop Test Module”, setting up a drop test scenario is very easy. Defining drop height and gravity are very straight forward. Floor is set as rigid body automatically. At the end of simulation again von Mises stress values were obtained and compared with the ones obtained from strain gauges. Approximately 6% difference occurred for décor part and 2% for discharge grille part. At the previous studies such as

“Drop analysis of a package and cushion performance of drum washing machine” [5] similar von Mises stress vales were measured from strain gauges and compared with the ones from finite element analysis. Between two methods nearly 4% difference occurred and considered as reasonable. In this study some improvements were performed for damaged areas and the analysis repeated. 1 mm round was added to the bottom of décor hook and additional EPS foam was used for the damage of discharge grille. At the end of second analyses 89% improvements obtained for discharge grille and 51% for décor hook. According to these results real drop test were performed and no damage was observed for both parts.

Drop tests can be done in the early product design stages, eliminating the costs associated with developing an inadequate product and last minute “band-aid” corrections to a poor design.

After an early design is analyzed, the proposed design modifications can be evaluated before committing to the new design. Simulating the drop test of air-conditioner indoor unit with FEM will have the following advantages;

- Lead time will decrease.
- Time and money saving
- Taking precautions in advance

In this study, it has been found that the stresses and extensions obtained by the finite element method are compatible with the values obtained in experimental methods, thus it can be concluded that the damages resulting from the impact can be accurately analyzed by simulation.

4.2. RECOMMENDATION FOR FURTHER WORK

With the help of current study, a wall mounted air conditioner passed drop the test successfully and entered to mass product stage. Considering this study, some suggestions may be made in terms of triggering further research and development studies.

Possible future works could include:

- By examining mechanical properties of EPS foam in detail, an optimization study can be performed in order to decrease volume of EPS foam used for preventing the damage of discharge grille.
- Using more than one strain gauges for one damaged location in each direction x, y, and z will be increase accuracy of results.
- Number of element mesh can be increased in order to get more accurate results from finite element analyses.
- Different plastic materials can be tried for décor and discharge grille part for further improvement.
- This method may be used for other types of air conditioners such as floor standing and cassette.
- In this study von Mises stress values were used for comparing results of two methods. Von Mises stresses give good results for sheet metal parts but may not give precise results for plastics. So another failure criterion can be considered for plastic parts.
- Small cameras can be inserted to inside of air conditioner and all drop process can be recorded and compared with finite element analysis record.

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CURRICULUM VITAE

Mehmet Fazlı TEKNECİ was born in 9th December 1987, in Trabzon, Turkey. He graduated from Istanbul Technical University, Faculty of Mechanical Engineering, and Mechanical Engineering Department in June 2011 with Bachelor of Science degree. At the spring semester of 2014-2015 season, he started his Master of Science degree education in Mechanical Engineering Department at Marmara University, Institute for Graduate Studies in Pure and Applied Sciences. After several works and internship experiences, he has been working as an R&D engineer at a company in private sector. He is married and has a kid.