DOKUZ EYLÜL UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MULTISCALE STRUCTURAL OPTIMIZATION OF REFRIGERATOR UNDER STATIC AND DYNAMIC LOADS

by

İlhan TABER

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İZMİR

MULTISCALE STRUCTURAL OPTIMIZATION OF REFRIGERATOR UNDER STATIC AND DYNAMIC LOADS

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İlhan TABER

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"MULTISCALE STRUCTURAL OPTIMIZATION OF REFRIGERATOR UNDER STATIC AND DYNAMIC LOADS"** completed by **İLHAN TABER** under supervision of **PROF.DR. RAMAZAN KARAKUZU** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

.....

Prof.Dr. Ramazan KARAKUZU

Supervisor

.....

Prof.Dr. Yusuf ARMAN

Jury Member

.....

Asst.Prof.Dr. Hamza TAŞ

Jury Member

Prof. Dr. Okan FISTIKOĞLU

Director

Graduate School of Natural and Applied Sciences

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MULTISCALE STRUCTURAL OPTIMIZATION OF REFRIGERATOR UNDER STATIC AND DYNAMIC LOADS

ABSTRACT

This study investigates the impact resistance of bottom-freezer refrigerators during transportation, focusing on drop impact testing and damage analysis. Utilizing industry standards (ASTM D5276, ASTM D880) and LS-DYNA simulations, the research examines how packaging solutions and design modifications can enhance refrigerator durability.

The finite element model incorporates various material models, such as MAT_PIECEWISE_LINEAR_PLASTICITY (MAT24) for DC04 steel, MAT_ELASTIC for other steel components, MAT_SOIL_AND_FOAM for foam components, to simulate realistic impact scenarios. AUTOMATIC_SINGLE_SURFACE is used for initial contact definitions and enhances the model with TIED_NODES_TO_SURFACE and TIED_SURFACE_TO_SURFACE to manage interactions within the model.

The test rig ensured precise drops from a height of 250 mm at a 10° angle to the ground. The finite element analysis utilized 1,646,795 meshed elements with an impact velocity of approximately 2.215 m/s. Computational efficiency is achieved with Massively Parallel Processing (MPP), the MPP_IO_BINOUTONLY keyword, and precise output management techniques. For the baseline design, plastic strain findings in the compressor section and hinges showed deformation with strains ranging from 0.12 to 0.21, with maximum values reaching up to 0.27. This suggests a requirement for design enhancements to improve durability, as such levels of deformation could affect the functionality and performance of the refrigerator door, emphasizing the necessity for design upgrades in these areas.

As a result of the design changes made based on the test and simulation results obtained from the basic reference product, it was observed in the repeated FEA simulation that the maximum deformation at the critical points of the improved design

decreased. The plastic strain analysis for the improved design revealed strains ranging from 0.12 to 0.20, with peak values at 0.26 near the compressor and hinge areas, indicating that the material in these zones has undergone shaping and requires further strengthening for improved longevity. These improvements resulted in more stable door distances, reduced peak Von Mises stress values, and enhanced overall impact resistance and structural strength of the product, making the mechanical function of the refrigerator door more reliable.

Keywords: Drop impact testing, white goods, refrigerators, finite element analysis, LS-DYNA

STATİK VE DİNAMİK YÜKLER ALTINDA BUZDOLABININ ÇOK ÖLÇEKLİ YAPISAL OPTİMİZASYONU

ÖZ

Paketli buzdolaplarının taşınması sırasında düşme etkisi direnci üzerine yapılan araştırmada, darbe testleri ve hasar analizi üzerinde durulmuştur. Endüstri standartlarına (ASTM D5276, ASTM D880) ve LS-DYNA simülasyonlarına dayanarak, ambalaj çözümlerinde tasarım değişiklikleriyle buzdolaplarının dayanıklılığını artırmanın yolları incelenmiştir.

Gerçekçi darbe senaryolarını simüle etmek için DC04 çeliği MAT_PIECEWISE_LINEAR_PLASTICITY (MAT24), DC01 çeliği MAT_ELASTIC ve köpük bileşenler MAT_SOIL_AND_FOAM kullanılarak sonlu eleman analizi oluşturulmuştur. Analizde, temas noktaları AUTOMATIC_SINGLE_SURFACE ile tanımlanmış ve modelin etkileşimleri TIED_NODES_TO_SURFACE ve TIED_SURFACE_TO_SURFACE ile iyileştirilmiştir.

Simülasyon ve fiziksel düşme testleri, yerden 250 mm yükseklikten 10° açılı hassas bir şekilde gerçekleştirilmiştir. Sonlu elemanlar düşme simülasyonu 1,646,795 eleman içeren model ile yaklaşık 2,215 m/s başlangıç hızı ile gerçekleştirilmiştir. Hesaplama verimliliği Massively Parallel Processing (MPP), MPP_IO_BINOUTONLY anahtarıyla sağlanmıştır. Temel tasarımda, kompresör bölümü ve menteşe noktalarındaki plastik deformasyonlar, 0,12 ile 0,21 arasında değişen gerilme değerleri gösterdi ve en yüksek değerler 0,27'ye kadar çıktı. Bu durum, dayanıklılığı artırmak için tasarım iyileştirmelerine ihtiyaç duyulduğunu göstermektedir, zira bu tür deformasyon seviyeleri buzdolabı kapısının işlevselliğini ve performansını etkileyebilmektedir.

Bu nedenle ürünün belirlenen bölgelerinde tasarım geliştirmelerinin gerekliliği çalışmanın odak noktasını oluşturmaktadır. Temel referans üründen elde edilen test ve simülasyon sonuçlarına dayanarak yapılan tasarım değişiklikleri sonucunda tekrar edilen FEA simülasyonunda, geliştirilmiş tasarımın kritik noktalarında maksimum

deformasyonun azaldığı görüldü. İyileştirilmiş tasarım analiz sonuçlarında plastik gerilme değerleri kompresör ve menteşe bölgelerinde değişkenlik göstererek genel olarak 0,12 to 0,20 aralığında, tepe değeri olarak ise 0,26 değeri görülmüştür. Düşme testleri ile doğrulanan simülasyon sonrası yapılan geliştirilmiş tasarım iyileştirmeleri sayesinde kapı mesafelerinin daha istikrarlı hale geldiği, maksimum Von Mises gerilme değerlerinin azaldığı ve buzdolabının genel darbe direncinin ve yapısal gücünün arttığı kanıtlandığı için buzdolabının mekanik işlevselliğini daha güvenilir hale getirdiği ortaya konmuştur.

Anahtar kelimeler: Düşme darbe testi, beyaz eşya, buzdolabı, sonlu elemanlar analizi, LS-DYNA

CONTENTS

Page

M.Sc THESIS EXAMINATION RESULT FORM ii
ACKNOWLEDGMENT iii
ABSTRACT iv
ÖZ vi
CONTENTS viii
LIST OF FIGURES x
LIST OF TABLES xv

CHAPTER ONE - INTRODUCTION 1

1.1 Background 1
1.2 Problem, Tests, Improvements and Scope of the Study 3
1.2.1 Problem Statement 3
1.2.2 Tests 5
1.2.3 Scope of the Study 7
1.2.4 Improvements 8

CHAPTER TWO - LITERATURE REVIEW 10

2.1 Refrigeration Systems Packaging for Transition Safety 10
2.2 Historical Development of Impact Testing 11
2.3 Finite Element Analysis in Drop Test Simulations 13
2.4 LS-DYNA in Drop Impact Simulations 15
2.5 Simulation and Testing Correlation 17
2.6 Gaps in Current Research 18

CHAPTER THREE - METHODOLOGY AND ANALYSIS OF DATA 21

3.1 Overview of Methodological Approach 21
3.1.1 Experimental Validation Framework 24
3.2 Drop Test Process and Procedure 25
3.2.1 Focus of the Drop Scenario 28

3.2.2 Performed Drop Test Setup 29
3.2.3 Measurements after Drop Tests 31
3.2.4 Materials Used in Refrigerators 35
3.3 Refrigerator Packaging Materials and Protective Methods 41
3.3.1 Styrofoam Components 41
3.3.2 Carton Box Component 43
3.4 Finite Element Method Principles 44
3.4.1 Finite Element Model Setup 45
3.4.2 Numerical Methods in Finite Element Analysis 45
3.4.3 Central Difference Method 46
3.4.4 LS-DYNA Simulation Model Development 47
3.4.5 Mesh Generation and Optimization 50

CHAPTER FOUR - RESULTS 72

4.1 Baseline Design FEA Results 72
4.1.1 Baseline Design FEA Simulation Door Distance Measurements 75
4.2 Implementation and Validation of Design Improvements 81
4.3 Post-Improved Design FEA Results 84
4.4 Comparison between Baseline FEA Results and Improved FEA Results 91
4.4.1 Peak Values Comparison 92
4.4.2 Change in Length Values Comparison 93
4.5 Drop Test Results 94
4.5.1 Base Design Drop Test Analysis 94
4.5.2 Post-Improved Design Drop Test Results 96
4.5.3 Drop Test Comparative Analysis 98

CHAPTER FIVE - CONCLUSION 101

5.1 Discussion and Summary 101
5.2 Future Studies and Recommendations 102

REFERENCES 104

LIST OF FIGURES

Page

Figure 1.1 Simplified diagram of refrigerating process 1
Figure 1.2 Bottom-freezer model 2
Figure 1.3 Product stowing and transfer view in factory storage (Personal Archive, 2022) 3
Figure 1.4 Shipment transportation (Safe Load Testing Technologies, 2024) 3
Figure 1.5 Possible consequences of drop impacts on refrigerator 4
Figure 1.6 Packaging for white goods (Mondi Group, 2024) 5
Figure 1.7 Vibration testing (LABTONE, 2024) 6
Figure 1.8 Drop test simulation (Labotech, 2024) 6
Figure 2.1 Refrigerator packaging view 10
Figure 2.2 FEA Model of product with EPS assembly (Wang et al., 2005) 13
Figure 2.3 FEA model mesh optimization (Mülkoğlu et al., 2017) 14
Figure 2.4 Drop test condition's experimental view (Lengas et al., 2023) 16
Figure 2.5 Taylor impact test schematic view (Pantalé & Ming, 2022) 19
Figure 3.1 Drop impact simulation of electronic equipment packed with cushioning material 22
Figure 3.2 Study methodology flowchart 23
Figure 3.3 Free fall drop test (Topa Institute, 2024) 25
Figure 3.4 Plane surface drop test and edge drop test experimental concept figure 26
Figure 3.5 Concentrated drop test experimental concept, corner drop test view with 100mm drop height and 10° ramp 26
Figure 3.6 ISTA 6-AMAZON.COM 2018 – Concentrated impact drop test concept figure for hazard box 27
Figure 3.7 Design improvements added model view 28
Figure 3.8 Overview of the fridge free fall (Blanco et al., 2015) 29
Figure 3.9 Drop scenario of the product 30
Figure 3.10 Edge drop test experimental concept view with 250 mm drop height and 10° ramp 31
Figure 3.11 2D Measurement areas view after drop test performed 32

Figure 3.12 3D view of measurement points after drop test performed 33
Figure 3.13 Door distance measurement method view 33
Figure 3.14 3D View of refrigerator door rotation axis and measurement points 1, 2, and 3 34
Figure 3.15 3D View of refrigerator door rotation and axis 35
Figure 3.16 Stress-strain curve of reference DC04 EN 10130, cold-rolled steel (Kaplan et al., 2022) 36
Figure 3.17 Stress-strain curve of reference DC01 EN 10130, cold-rolled steel (Kumar & Digavalli, 2020) 37
Figure 3.18 Stress-strain curve of reference ABS, Acrylonitrile Butadiene Styrene (Sabah & Wahid, 2019) 38
Figure 3.19 Stress-strain curve of reference PP, Polypropylene (Khlif, Masmoudi, & Bradai, 2012) 38
Figure 3.20 Stress-strain curve of reference HIPS, High Impact Polystyrene (Antich et al., 2006) 39
Figure 3.21 Stress-strain curve of reference POM, Polyoxymethylene (Bedoui & Fayolle, 2014) 39
Figure 3.22 Stress-strain curve of reference PU, Polyurethane in FEA simulation (Croop & Lobo, 2009) 41
Figure 3.23 Styrofoam designs with the product packaging 42
Figure 3.24 Refrigerator packaging view 42
Figure 3.25 Stress-strain curve of reference EPS used in FEA simulation (Shah & Topa, 2015) 42
Figure 3.26 FEA simulation carton box modeling 43
Figure 3.27 Strap design usage on packaged refrigerators 44
Figure 3.28 FEA model explicit analysis methodology flowchart 47
Figure 3.29 FEA simulation model development view 49
Figure 3.30 Refrigerator assembly FEA model 51
Figure 3.31 Simplification View of the Reference Study Model (Blanco et al., 2015) 53
Figure 3.32 FEA Model compressor area mesh generation 53
Figure 3.33 Generated FEA model EPS assembly 54

Figure 3.34 FEA model element mesh types 55
Figure 3.35 FEA model generation element formulation 55
Figure 3.36 FEA model meshed eps components 56
Figure 3.37 FEA model shell elements' formulation setting 57
Figure 3.38 Upper hinge meshed model 57
Figure 3.39 Middle hinge meshed model and shell element midplane view 58
Figure 3.40 Bottom hinge meshed model 58
Figure 3.41 Material LS-DYNA keywords 61
Figure 3.42 Contact and interaction definitions AUTOMATIC_SINGLE_SURFACE selection in simulation 63
Figure 3.43 Contact and interaction definitions NODAL_RIGID_BODY selection in simulation 64
Figure 3.44 Gravity definition shown in the simulation 65
Figure 3.45 FEA simulation drop impact velocity setting 66
Figure 3.46 Compressor position in refrigerator 67
Figure 3.47 Compressor weight in simulation 67
Figure 3.48 FEA strap modeling representation with beam load, 2.5 N·m torque 68
Figure 3.49 MPP working methodology example (Simware, 2017) 69
Figure 3.50 FEA Drop simulation computational setting "MPP_IO_BINOUTONLY'' keyword 70
Figure 3.51 Improved design final FEA model and drop condition 71
Figure 3.52 Improved design final FEA model and drop condition with EPS components 71
Figure 4.1 Baseline design assembly model Von Mises stress results 72
Figure 4.2 Baseline design assembly model plastic strain results 73
Figure 4.3 Baseline design door hinges Von Mises stress results 74
Figure 4.4 Middle hinge shell model stress dissipation 74
Figure 4.5 Bottom Styrofoam von mises stress and strain examination results 75
Figure 4.6 FEA model door distance measurement points 76
Figure 4.7 Baseline design FEA simulation point 1 change in length at contact duration 76

Figure 4.8 Baseline design FEA simulation point 2 change in length at contact duration 77
Figure 4.9 Baseline design FEA simulation point 3 change in length at contact duration 77
Figure 4.10 Baseline design FEA simulation point 4 change in length at contact duration 78
Figure 4.11 Baseline design FEA simulation point 5 change in length at contact duration 78
Figure 4.12 Baseline design FEA simulation point 6 change in length at contact duration 79
Figure 4.13 Baseline design FEA simulation point 7 change in length at contact duration 79
Figure 4.14 Baseline design FEA simulation point 8 change in length at contact duration 80
Figure 4.15 Baseline design FEA simulation point 9 change in length at contact duration 80
Figure 4.16 Baseline design FEA simulation point 10 change in length at contact duration 81
Figure 4.17 Design improvements 82
Figure 4.18 Design improved model: reinforcement added view 83
Figure 4.19 Final FEA model and simulation 84
Figure 4.20 Post-improvement Von Mises stress results 85
Figure 4.21 Post-improvement plastic strain results 86
Figure 4.22 Post-improvement design FEA simulation point 1 change in length at contact duration 86
Figure 4.23 Post-improvement design FEA simulation point 2 change in length at contact duration 87
Figure 4.24 Post-improvement design FEA simulation point 3 change in length at contact duration 87
Figure 4.25 Post-improvement design FEA simulation point 4 change in length at contact duration 88

Figure 4.26 Post-improvement design FEA simulation point 5 change in length at contact duration 88
Figure 4.27 Post-improvement design FEA simulation point 6 change in length at contact duration 89
Figure 4.28 Post-improvement design FEA simulation point 7 change in length at contact duration 89
Figure 4.29 Post-improvement design FEA simulation point 8 change in length at contact duration 90
Figure 4.30 Post-improvement design FEA simulation point 9 change in length at contact duration 90
Figure 4.31 Post-improvement design FEA simulation point 10 change in length at contact duration 91
Figure 4.32 Peak value comparison between baseline FEA results and improved FEA results 93
Figure 4.33 Change in length comparison between baseline FEA results and improved FEA results 94
Figure 4.34 Baseline design drop test door distance measurement results in chart ... 96
Figure 4.35 Post-improved design drop test door distance measurement results in chart 98
Figure 4.36 Baseline design and post-improved design drop test door distance measurement result comparison in chart 99
Figure 4.37 Baseline design and post-improved design drop test door distance measurement average results comparison in chart 100

LIST OF TABLES

Page

Table 3.1 Drop test conditions for average household usage conditions standards and selected product specifications..... 30
Table 3.2 Drop Polyurethane Wall Theoretical and Practical Thickness 40
Table 3.3 The material properties of the analyzed model..... 59
Table 4.1 FEA analysis door distance peak value and change in length measurements 91
Table 4.2 Baseline design drop test door distance measurement results 1 95
Table 4.3 Post-improved design drop test door distance measurement results 1 97

ABBREVIATIONS

FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Method
3D	Three-dimensional
CPU	Central Processing Unit
MPP	Massive Parallel Processing
LCID	Load Curve ID for gravitational force
SF	Scale Factor for gravitational acceleration
NSID	Node Set ID For initial velocity
VY	Initial Velocity in the Y-direction
MAT24	MAT_PIECEWISE_LINEAR_PLASTICITY keyword
MAT01	MAT_ELASTIC keyword
HIPS	High Impact Polystyrene
ABS	Acrylonitrile Butadiene Styrene
PP	Polypropylene
PU	Polyurethane
EPDM	Ethylene Propylene Diene Monomer
CDTI	Central Difference Time Integration
EPS	Expanded Polystyrene
PET	Polyethylene Terephthalate

DC04/DC01	Cold Rolled Steel
POM	Polyoxymethylene
Hex	Hexahedral Elements
SECID	Solid section ID
ELFORM	Element Formulation
JC	Johnson Cook
T	Temperature
RH	Relative Humidity

LIST OF SYMBOLS

σ_v	Von Mises Stress (Effective Stress)
σ_{max}	Maximum Principal Stress
ϵ_p	Plastic Strain
d	Distance Measurement
ΔL	Change in Length
$d_{theoretical}$	Theoretical Default Distance
Mpa	Megapascal (Unit of Stress)
Gpa	Gigapascal (Unit of Stress)
Δ_d	Difference in Distance (between theoretical and actual measurements)
d_{point}	Distance Measurement at a Specific Point
$d_{baseline}$	Baseline Distance Measurement
d_{post}	Distance Measurement after Design Improvements
$\Delta d_{baseline}$	Baseline Design Distance
$\Delta d_{post-improvement}$	Post-Improvement Distance
Σ_v^{max}	Maximum Von Mises Stress
ϵ_p^{max}	Maximum Plastic Strain
σ_v^{top}	Von Mises Stress at the Top Hinge
σ_v^{middle}	Von Mises Stress at the Middle *Hinge*
σ_v^{bottom}	Von Mises Stress at the Bottom Hinge
σ_{max}^{top}	Maximum Principal Stress at the Top Hinge
σ_{max}^{middle}	Maximum Principal Stress at the Middle Hinge

σ_{max}^{bottom}	Maximum Principal Stress at the Bottom Hinge
$d_{point-1}$	Distance Measurement at Point 1
$d_{point-2}$	Distance Measurement at Point 2
$d_{point-3}$	Distance Measurement at Point 3
$d_{point-4}$	Distance Measurement at Point 4
$d_{point-5}$	Distance Measurement at Point 5
$d_{point-6}$	Distance Measurement at Point 6
$d_{point-7}$	Distance Measurement at Point 7
$d_{point-8}$	Distance Measurement at Point 8
$d_{point-9}$	Distance Measurement at Point 9
$d_{point-10}$	Distance Measurement at Point 10
$d_{improvement-1}$	Distance Measurement at Point 1 after Improvement
$d_{improvement-2}$	Distance Measurement at Point 2 after Improvement
$d_{improvement-3}$	Distance Measurement at Point 3 after Improvement
$d_{improvement-4}$	Distance Measurement at Point 4 after Improvement
$d_{improvement-5}$	Distance Measurement at Point 5 after Improvement
$d_{improvement-6}$	Distance Measurement at Point 6 after Improvement
$d_{improvement-7}$	Distance Measurement at Point 7 after Improvement
$d_{improvement-8}$	Distance Measurement at Point 8 after Improvement
$d_{improvement-9}$	Distance Measurement at Point 9 after Improvement
$d_{improvement-10}$	Distance Measurement at Point 10 after Improvement

CHAPTER ONE
INTRODUCTION

1.1 Background

Refrigerators have become vital household, commercial, and industrial appliances that are used to preserve and keep cool perishable goods. Since their invention, refrigerators have evolved significantly. They integrate advanced thermodynamic principles to improve efficiency and convenience. Thermodynamics is the study of heat transfer, and the key components of this system include compressors, which increase the pressure and temperature of the refrigerant gas; condensers, where the refrigerant releases heat and turns into a liquid; and expansion valves, which reduce the refrigerant's pressure and temperature before it enters the evaporator (see Figure 1.1).

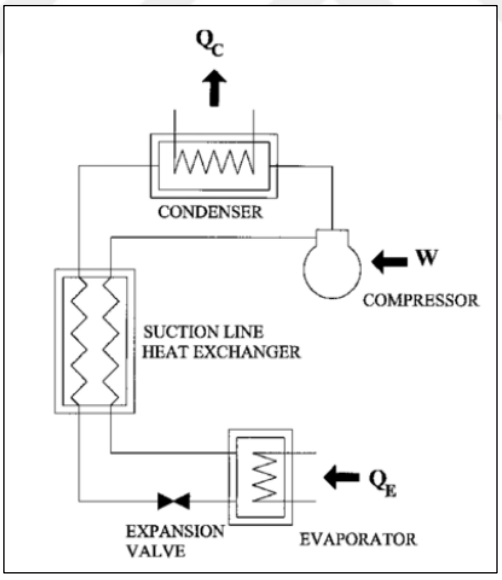


Figure 1.1 Simplified diagram of refrigerating process

While there are different types of refrigerators each designed to suit the specific space in which they will be used, be it commercial settings, specialized industrial settings, and/or recreational settings, this study focuses exclusively on household refrigerators due to their widespread use and the unique challenges they face in terms of packaging and transportation.

Household refrigerators are designed for domestic use and come in various designs, including traditional models such as top-freezer and bottom-freezer, as well as modern variations like French doors and side-by-side models. Compared to top-freezer and side-by-side models, the bottom-freezer design (see Figure 1.2), which is a popular model in Türkiye/Europe, was chosen for this study due to its ergonomic advantages. What makes this model ergonomic is its refrigerator compartment that is situated at eye level which makes frequently used items more accessible. Additionally, the bottom-freezer configuration places the freezer drawer at the base of the unit and provides an organized and convenient access to frozen goods. This design minimizes the need for constantly bending down to reach the goods, hence, it is also user convenient.



Figure 1.2 Bottom-freezer model

This study analyzes the drop impact resistance of a packaged bottom freezer model and aims to identify weaknesses as well as to propose design improvements. By enhancing packaging durability, the study seeks to ensure that refrigerators are delivered to consumers in optimal condition, thereby improving overall product reliability and customer satisfaction. The findings will contribute to advancing packaging technologies and methodologies and improving product reliability and customer satisfaction.

1.2 Problem, Tests, Improvements and Scope of the Study

1.2.1 Problem Statement

Similar to other white goods, the bottom-freezer refrigerator model is susceptible to drop impacts during transportation. Given their large size and weight, these appliances can be damaged if not handled properly during loading and unloading (see Figure 1.3, 1.4). Furthermore, they are often transported over long distances and stored in warehouses for extended periods of time. Hence, this prolonged handling and storage can raise the risk of damage to the appliance.



Figure 1.3 Product stowing and transfer view in factory storage (Personal Archive, 2022)



Figure 1.4 Shipment transportation (Safe Load Testing Technologies, 2024)

This damage may include dents and deformation in refrigerator’s sheet metal parts or cracks in its plastic components (see Figure 1.5). Some damage can be particularly observed in the corner areas and structural components like hinges and fasteners. However, some damage caused by drop impacts may not be immediately detectable by the naked eye. For example, internal damage to components such as the compressor may not be visible but can affect the appliance's performance or safety. This suggests a need for improvements in both the design and packaging to enhance the durability and protection of the appliance during transportation.



Figure 1.5 Possible consequences of drop impacts on refrigerator

To minimize damage and ensure safety, manufacturers in the white goods industry often take steps to ensure that their products are packaged and transported safely. For

instance, the use of packaging materials that can withstand the stresses of transportation and storage is prioritized (see Figure 1.6).



Figure 1.6 Packaging for white goods (Mondi Group, 2024)

1.2.2 Tests

To avoid the aforementioned damages, besides opting for high quality packaging, manufacturers also subject their products to rigorous testing procedures that are designed to ensure durability and safety during transportation, handling, and storage. These tests simulate the effects and stresses that may occur on the packaged appliance and are essential for predicting potential damage. For instance, electrical and mechanical testing, as well as durability and impact resistance testing, are done to ensure product safety. Packaged products must be subjected to the following tests:

- Squeeze Test
- Compression Test (simulates real stacking test)
- Vibration Test (see Figure 1.7)
- Inclined Plane Impact Test
- Drop Test
- Side Drop Test
- Real Stacking Test
- Walking Test



Figure 1.7 Vibration testing (LABTONE, 2024)

Since this study focuses on drop impact tests, it is crucial to bring a short description of what these tests entail. Impact Tests involve subjecting the refrigerator to impacts from different heights and surfaces to detect any deformations or malfunctions (see Figure 1.8). These tests ensure the appliances' durability and functionality in real-world conditions and contribute significantly to product reliability. They simulate real-world conditions that the products might encounter during transportation, handling, and usage. The primary types of impact tests are the following:



Figure 1.8 Drop test simulation (Labotech, 2024)

Free-Fall Drop Test: This test involves dropping the product from various heights to evaluate its ability to withstand impacts. Different orientations, such as edge, corner, and flat drops, are tested to identify potential weak points in the design and it is the focus of this study.

Horizontal Impact Test: This test simulates horizontal impacts that might occur during transport, such as sudden stops or collisions with other objects. The product is subjected to controlled impacts using pendulums or horizontal impact testers.

Incline Impact Test: In this test, the product is placed on an inclined plane and allowed to slide into a stationary object. This simulates the impact that might occur when the product slides during transportation or handling.

Rotational Drop Test: This test involves dropping the product while it is rotating to simulate complex impacts that might occur during real-world handling. The product's response to rotational forces and its ability to absorb and distribute impact energy are evaluated.

Pendulum Impact Test**:** This test uses a pendulum to deliver controlled impacts to specific points on the product. The force and location of the impacts are varied to identify potential vulnerabilities in the product's design.

These impact tests are conducted using specialized equipment and according to industry standards to ensure the consistency and reliability of the results. By performing these tests, manufacturers can identify design flaws and make necessary improvements to enhance the durability and safety of their white goods and refrigerators.

1.2.3 Scope of the Study

The scope of this study encompasses several key aspects:

1. Drop Impact Testing: The study focuses on drop impact tests to simulate real-world transportation scenarios. This involves performing drop tests from various heights and orientations to assess the damage to both the refrigerator and its packaging. The tests follow the industry standards such as ASTM D5276 (1998) for free-fall drop impacts and ASTM D880 (2002) for shipping container impacts.

2. Damage Analysis: The study analyzes the types of damage sustained by the refrigerator, including deformation of sheet metal parts, cracks in plastic components,

and internal damage to critical components like the compressor and motor. This analysis helps to identify specific design and material weaknesses.

3. Design and Material Improvements: Based on the findings from the impact tests and damage analysis, the study proposes modifications to the refrigerator's design and packaging. These include reinforcing corner areas and redesign of EPS packaging to enhance impact resistance.

4. Evaluation of Improvements: The effectiveness of the proposed improvements is evaluated through additional drop impact testing to ensure that the modifications adequately address the identified issues. This involves comparing pre- and post-improvement test results to assess the impact on the refrigerator's durability and safety.

In conclusion, this study aims to address the identified issues with the bottom-freezer refrigerator model by enhancing its impact resistance through targeted design and material improvements. By focusing on drop impact testing and damage analysis, the study seeks to ensure that the refrigerator remains functional and safe throughout the transportation process, ultimately contributing to improved product reliability and customer satisfaction.

1.2.4 Improvements

As discussed in the previous subsections, the problem with these packaged white goods is that during transportation they can be subjected to various types of drop impacts, such as drops from forklifts during loading/unloading, drops while being transported or shipped, or drops that may happen during their prolonged storage time in warehouses. To address the damage caused by these impacts I used additional materials to reinforce the corner areas**,** as well as focused to revise and improve Styrofoam design of the packaging. To evaluate the effectiveness of these improvements, drop impact test standards and conditions were considered. These included standards set by organizations such as the American Society of Testing and Materials ASTM D5276 (1998) for free fall drop impact scenarios and, ASTM D880 (2002) for impact testing for shipping containers standards. By conducting thorough testing according to these standards, I was able to see the effectiveness of this design and bring manufacturing improvements to the performance and safety of the refrigerator.

In conclusion, the issue with the refrigerator highlights the importance of considering all aspects of the design, manufacturing, and transportation process when producing mass-produced consumer goods. Thorough testing and evaluation can help manufacturers identify potential weaknesses and develop solutions to improve the durability and performance of their products.

CHAPTER TWO
LITERATURE REVIEW

2.1 Refrigeration Systems Packaging for Transition Safety

Ensuring that refrigeration systems can safely transition through drop impact testing is vital in the field of packaging engineering. Refrigeration units are essential for operations. Widely used in the market requiring transportation to different locations without affecting their performance or structure. As in our study, the targeted packaging design processes need to include thorough drop impact-testing procedures to prevent any damage during transit (see Figure 2.1).



Figure 2.1 Refrigerator packaging view

Drop impact testing for refrigeration systems involves subjecting the packaged unit to impacts that simulate handling and transportation stresses. The packaging must protect the refrigeration system from impacts that occur from various orientations and

heights, as specified by industry standards such as those outlined by the International Safe Transit Association (ISTA, 2018) and the American Society for Testing and Materials (ASTM- D4168 Package Cushioning Material Testing). The design of packaging solutions that effectively absorb impact energy and reduce the transmission of forces is informed by both experimental testing and computational modeling.

Using models such as LS DYNA allows for an approach to studying how refrigeration systems react dynamically when subjected to impact during drops. LS DYNA serves as a tool for conducting in depth finite element analysis (FEA) enabling the simulation of real-world situations and evaluating the effectiveness of packaging in protecting the system. The reliability of these simulations heavily relies on representing the properties of the refrigeration system, packaging materials and the test conditions during drop impact analysis in explicit dynamic studies such as this one. According to the study published by Neumayer, Chatiri and Höermann (2006), who also used the same methodology for consumer products mechanical impact loading, LS- DYNA simulation for drop impact scenarios proved to be effective.

The academic research in this field delves into the methods used to create test packaging systems for cooling devices like the case in this study. Gui Kun and Wang Xi published work on how packaging materials behave and how packaging design can be optimized to increase impact resistance (Gui & Xi, 2017). Additionally, an in-depth study on packaging materials by Foad Rahimidehgolan and William Altenhof (2023) examined the sensitivity of PVC foams to strain rates between 0.005 1/s and 600 1/s in dynamic experiments.

This study will examine the current challenges of selected product in structural and packaging design for transition safety. It will also address the role of FEA in enhancing the predictive accuracy of drop impact tests and guiding the development of resilient engineering solutions.

2.2 Historical Development of Impact Testing

The historical development of drop impact testing can be systematically traced back to the foundational requirements of evaluating material resistance under dynamic loading conditions. This process is critical for understanding the behavior of materials and structures subjected to sudden forces resulting from falls or collisions. In its

essence, drop impact testing quantifies the robustness, resilience, and energy absorption characteristics of a given material or assembly when subjected to high-rate deformation, typically simulating real-world accidental drop scenarios.

In their study, Liu et al. compared drop impact test methods using strain gauge measurements (2009). Strain gauge measurement proves to be an effective method for evaluating the differences between various drop test methods. The differences that were found with these measurements are the bases for the analysis of the loading and the damage of the interconnects. In this study, however, strain gauge methods were not used; instead, we employed distance measurements, a method specialized for assessing refrigerator products, to compare with the analysis (Liu et al., 2009).

In the field of packaging drop impact testing gained significance due to the research efforts of scholars such as Zhou, Yu, and Lee who investigated the impacts of shocks on packaged items (Zhou et al., 2008). The development of this testing was significantly propelled by the release of a groundbreaking study on drop impact analysis of packaged products with cushion buffers and multilayer circuit boards by Wang Yuki (2008) offering a thorough exploration of packaging dynamics.

In the 20th century El Magd (1993) made important progress in studying how materials behave when subjected to impact, particularly in examining the connection between impact energy and how materials fail. This research played a role in creating models that can predict impact resistance, which has been vital for choosing materials and designing engineering solutions.

The field took a computational turn with the implementation of finite element analysis (FEA) in evaluating drop impacts, an approach pioneered by researchers such as Wang et al. (2005). Their methodologies enabled the simulation of complex model's impact scenarios that were difficult to replicate in physical experiments, thereby greatly expanding the potential for analyzing various material behaviors under drop impact conditions. For this study, their inferences are very essential and well examined in terms of drop impact conditions (see Figure 2.2).

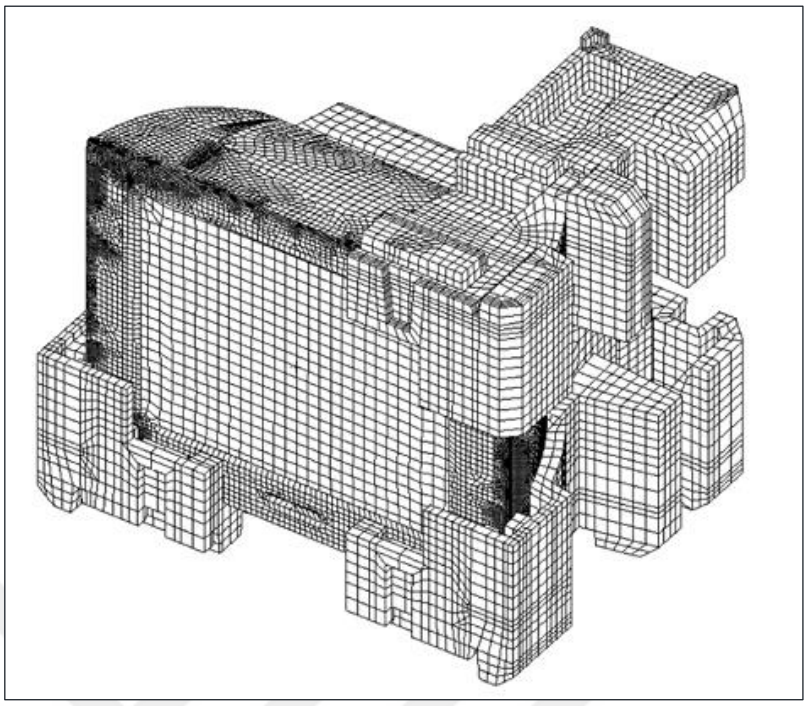


Figure 2.2 FEA Model of product with EPS assembly (Wang et al., 2005)

In the contemporary context, drop impact testing continues to be a vital area of research. As an instance, modern advancements have been spearheaded by scholars such as Abrate (1998), who investigated the impact on composite structures. In their study, findings provide insight into advanced materials.

As industries and technologies progress, the importance of drop impact testing persists, with continuous innovation required addressing the challenges posed by new materials and structures. In this research, material characteristics are examined; on the other hand, in the improvement stage, we focus on mechanical design. Current research efforts focus on enhancing test methodologies, developing more accurate predictive models, and integrating the test results into the design process for improved performance and safety of products.

2.3 Finite Element Analysis in Drop Test Simulations

Finite Element Analysis (FEA) has become an indispensable tool in packaging design, providing engineers with the ability to simulate and analyze the mechanical behavior of packaging materials under various loading conditions. The adoption of FEA in packaging design allows for the optimization of material usage, enhancement

of structural integrity, and prediction of failure modes, leading to more efficient and cost-effective packaging solutions.

The origins of FEA can be traced back to the work of scholars such as Richard Courant, who, in the early 20th century, utilized the Ritz method of numerical analysis for solving complex elasticity and structural analysis problems (as cited in Williamson, 1980). However, it was not until the latter half of the century that FEA began to be widely applied in industrial contexts, including packaging design.

The drive for sustainability in packaging has further underscored the relevance of FEA. By enabling the prediction of material behavior under various conditions, FEA aids in minimizing material waste and improving the recyclability of packaging materials, as discussed in the works by Fadiji et. al. (2018). The efficiency of FEA in reducing the need for physical testing is also directly related to reducing the environmental footprint of the design process.

The current state of FEA in packaging design is marked by the integration of sophisticated simulation software with advanced material models. This integration allows for high-fidelity simulations that can predict the behavior of packaging under real-world conditions, including impact, vibration, and thermal stresses. The work by Mülkoğlu, O., Güler, M. A., Acar, E., & Demirbağ (2017) on advanced material modeling in FEA simulations has contributed significantly to this field, providing greater accuracy in predicting the performance of packaging materials (see Figure 2.3).

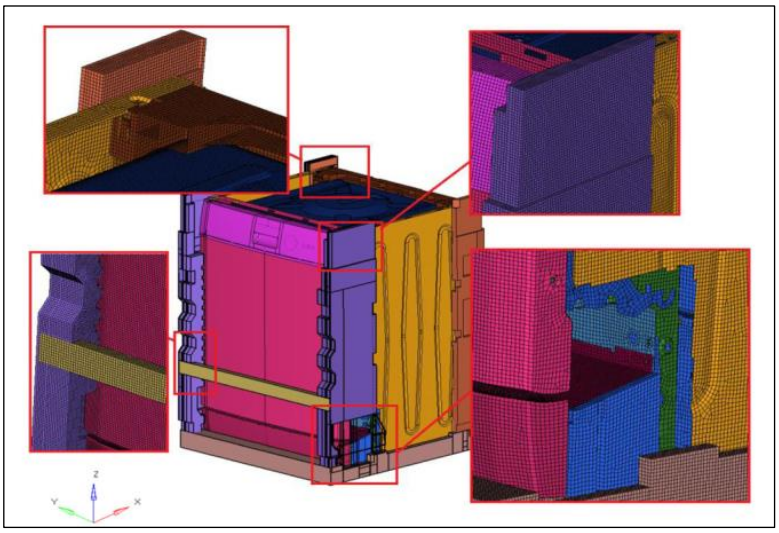


Figure 2.3 FEA model mesh optimization (Mülkoğlu et al., 2017)

As packaging technology evolves, so does the complexity of FEA models. Future research is oriented towards enhancing the computational efficiency of FEA simulations and integrating them with other simulation methods to provide a more holistic view of packaging performance. The potential for FEA to revolutionize packaging design continues to grow as computational capabilities expand, as noted by recent scholars in the field.

2.4 LS-DYNA in Drop Impact Simulations

The accurate prediction of material response to drop impacts is essential in the design and integrity assessment of various products ranging from electronic devices to packaging materials. LS-DYNA, a highly versatile explicit finite element program, has been extensively employed for simulating complex real-world drop impact scenarios. Its robust computational capabilities facilitate the analysis of transient dynamic events where high strain rates and nonlinear material behavior are prevalent. This introduction delineates the application of LS-DYNA as a tool for drop simulation, underlining its methodological foundations, practical implementations, and scholarly contributions to the field. Willford and others noted that a special advantage of LS-DYNA is its high computational speed for large and complex models by using explicit methodology that may contain millions of elements (Willford et al., 2010). In this study, the final FEA model contain 1646795 elements and 1431553 nodes.

LS-DYNA's development, initially for automotive crash simulation, has expanded its application to a wide spectrum of engineering problems. Karen E. Jackson and Edwin L. Fasanella (2004) provided a comprehensive overview of LS-DYNA's capabilities, demonstrating its ability to handle large deformation and complex contact situations—characteristics inherent to drop impact events such as crash test programs performed included military test programs, space test programs, and crash modeling with simulations.

The software's explicit time integration feature allows for the detailed capture of transient stress waves and deformation patterns that occur during a drop event. Singh and Singh (2014), in their study, performed the analysis using the software code MSC.Dytran. It is an explicit nonlinear transient dynamic finite element computer code used for analyzing solid components and structures. In their study, the impact

velocities ranged from 32 to 40 m/s. In this thesis, our velocity is calculated as 2.2147 m/s (Singh & Singh, 2014).

The fidelity of a drop simulation in LS-DYNA is dependent upon accurate material modeling, geometry, and the representation of contact interfaces. Researchers such as Hughes (1987) have contributed to the theoretical underpinnings of explicit finite element methods, which are critical for understanding the performance of LS-DYNA in drop simulations. In their research, optimization of the geometry is carried out by investigating and comparing the performance of geometrical combinations and the number of safety berms by means of numerical modeling (Hughes, 1987).

In this study, LS DYNA was used to predict and enhance the ability of packaging materials to withstand impact during drops and detailed examination was done. For example, Lengas et al. (2023) utilized LS DYNA to assess how filled fiberboard boxes packaging responds dynamically. Their research displayed the software's capability to simulate the characteristics of foam materials, such as compression and energy absorption (see Figure 2.4).

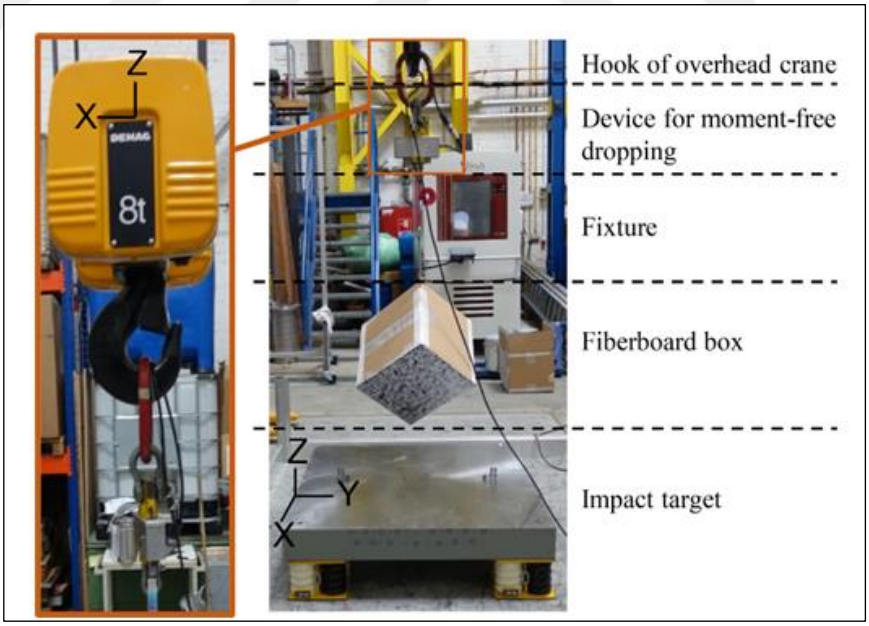


Figure 2.4 Drop test condition's experimental view (Lengas et al., 2023)

In a study conducted by Fadiji, Coetzee, Berry, Ambaw and Opara (2018), they examined how effective finite element analysis (FEA) is, as a tool for designing food packaging. They used LS DYNA along with design optimization techniques to reduce

weight and material usage in structures impacted by drops while still meeting performance standards. Their methods provide insights into enhancing products than improving designs, setting their research apart from our current investigation.

LS DYNA goes beyond materials to investigate materials and how they react in drop scenarios. The research conducted by Nichols, Cohen and Johnson (2001), on models for high strength materials laid the groundwork for studying materials in LS DYNA, such as composites and polymers like corrugated fiberboard boxes commonly employed in top tier packaging. Additionally, the laminate theory, for composite plates finds application in this context.

Recent advancements in LS-DYNA focus on enhancing its predictive accuracy and computational efficiency. Scholars such as Dørum, Hopperstad, Lademo, & Langseth (2007) have developed new constitutive models within LS-DYNA to simulate the intricate behavior of materials at the microstructural level during impact. Such detailed models contribute to a more precise prediction of failure mechanisms and the overall structural integrity of products subjected to drop events. The fracture criterion is coupled to an element wear algorithm in LS-DYNA. The constitutive model and the fracture criterion are calibrated with data from both material tests and process simulation using MAGMAsoft.

In the simulations, on the contact forces estimation during impact events in the study of Yang, Sun, Lam, & Zhang (2014), focused on dynamic compressive stiffness and they have refined the understanding of the impactor effect in drop simulations.

In essence, LS DYNA has become a tool for engineering analysis and design offering insights into the intricate scenarios seen in drop impacts. Its seamless incorporation of material databases, sophisticated contact algorithms and optimization techniques creates a user platform that empowers engineers and researchers in crafting drop resistant structures.

2.5 Simulation and Testing Correlation

The connection between simulating and testing in engineering design and validation is crucial. Simulations using methods aim to forecast how a system will behave in diverse scenarios. On the other hand, experimental testing involves evaluating a system to observe its real performance under controlled circumstances. According to

Motzev (2019) the alignment between simulation outcomes and experimental data is key in assessing the reliability and accuracy of simulation models ultimately enhancing their capabilities and usefulness, in engineering practices.

In the field of materials science, the development of constitutive models that accurately represent material behavior is crucial for achieving correlation. Studies by Johnson and Cook (1983) introduced dynamic material models that account for strain rate effects, temperature dependency, and failure, which have been widely adopted in FEA simulations, including those performed with LS-DYNA.

Moreover, advancements in experimental techniques, such as high-speed imaging and digital image correlation, have provided more detailed data for validating simulations emphasizes the role of these advanced techniques in obtaining high-resolution deformation and strain data, which can be directly compared to simulation results for validation purposes (Reu & Miller, 2008).

The purpose of this thesis is to investigate methodologies and best practices that provide a strong correlation between simulation and experimental validation to evaluate the challenges and limitations native in correlations, and to examine case studies that set a good sample for the successful application of correlated simulation and testing in engineering projects.

2.6 Gaps in Current Research

The perspective of this research, while expansive and richly detailed in numerous scientific and engineering domains, often reveals significant gaps. These gaps may contain unexplored territories, underdeveloped methodologies, insufficient data, or the need for integration between different disciplines. In the context of correlating simulation with experimental testing, several research gaps can be identified. Addressing these gaps is not only critical for knowledge but also for the practical enhancement of engineering applications where predictive modeling and validation are essential.

Various configurations, speeds of impact and variations, in impacts pose difficulties. For example, the Taylor impact examination demonstrates how different impact scenarios can influence the reactions of materials emphasizing the importance of conducting studies to fill these gaps (see Figure 2.5). Moreover, there is a

necessity for models that can anticipate performance in circumstances, like extreme temperatures or multi directional pressures (Pantalé & Ming 2022).

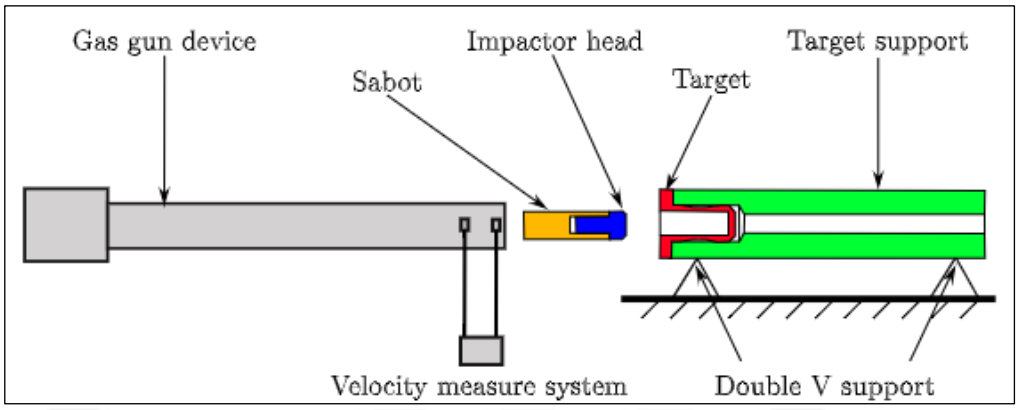


Figure 2.5 Taylor impact test schematic view (Pantalé & Ming, 2022)

Another gap is which are often constrained by computational limitations. Simulations typically focus on either macro-scale structural responses or micro-scale material behaviors, with insufficient coupling between these scales. Brancherie, Feissel, Bouvier, & Ibrahimbegovic (2017), researched on mechanical behavior of materials that are highly influenced by their microstructures. Hence, progress in material science involves understanding and modeling the link between the microstructure and the material behavior at different scales; bridging this gap would enable a more holistic understanding of material and structural performance from the microstructure up to the component level.

The issue of dealing with uncertainty, in simulations and real-world experiments poses a research gap. Uncertainties stem from factors like material characteristics, production irregularities and variations in circumstances. There is a need for enhanced methods to quantify and handle uncertainties in simulations along with establishing connections, with uncertainties through approaches. This area calls for investigation according to Grenyer et al. (2021).

Lastly, the field suffers from a degree of fragmentation, where research efforts are often siloed within specific industries or applications. A cross-pollination of insights between sectors—such as automotive, aerospace, biomedical, and consumer electronics—could bridge these gaps and foster the development of more universally applicable simulation and testing methodologies (Ghasemisahebi et al., 2017).

This thesis will explore these gaps, analyzing the current state of research, identifying potential avenues for innovation, and proposing frameworks for integrating simulation with experimental testing across various stages of product development. The ultimate goal is to offer a roadmap for future research that can lead to more reliable, efficient, and universally applicable simulation and testing practices.

In conclusion, there is some fragmentation in the field, as research tends to focus on industries or applications. Sharing knowledge across sectors, like aerospace, biomedical and consumer electronics could help connect these areas and promote the creation of simulation and testing methods that can be applied broadly (Ghasemisahebi et al., 2017).

CHAPTER THREE
METHODOLOGY AND ANALYSIS OF DATA

3.1 Overview of Methodological Approach

In the domain of mechanical engineering, the methodological approach to evaluating the structural integrity of appliances subjected to accidental drops is of paramount importance. This is particularly critical in the case of refrigerators, where the impact can compromise door connections stability and thermal insulation by the operational efficiency. The drop impact test is a standardized procedure that assesses the durability and robustness of refrigerators by simulating the effects of a fall from a specific height, as prescribed by industry standards. The adoption of computational tools such as LS-DYNA, an advanced finite element analysis (FEA) software, has been instrumental in simulating these impact events, allowing engineers to predict the consequences of drops on refrigerator structures prior to physical testing.

It is important to take precautions when performing drop weight impact tests to prevent any damage. These precautions include checking the equipment before the test, controlling test conditions, positioning the test specimen correctly using safety measures and inspecting after the test. By following these steps, we can reduce the risk of harm to goods during handling and storage while also maintaining the precision and trustworthiness of our test outcomes.

This study introduces a methodological framework that employs LS-DYNA to perform drop impact simulations on refrigerator models. The methodology is grounded in a correlation-driven approach, wherein results from numerical simulations are systematically compared and validated against experimental data. The literature provides extensive insights into the mechanics of drop impact phenomena and the computational modeling thereof. Notably, underscore the capabilities of LS-DYNA in simulating complex, transient dynamic events that are characterized by high strain rates and nonlinear material behavior, which are typical in drop tests (see Figure 3.1).

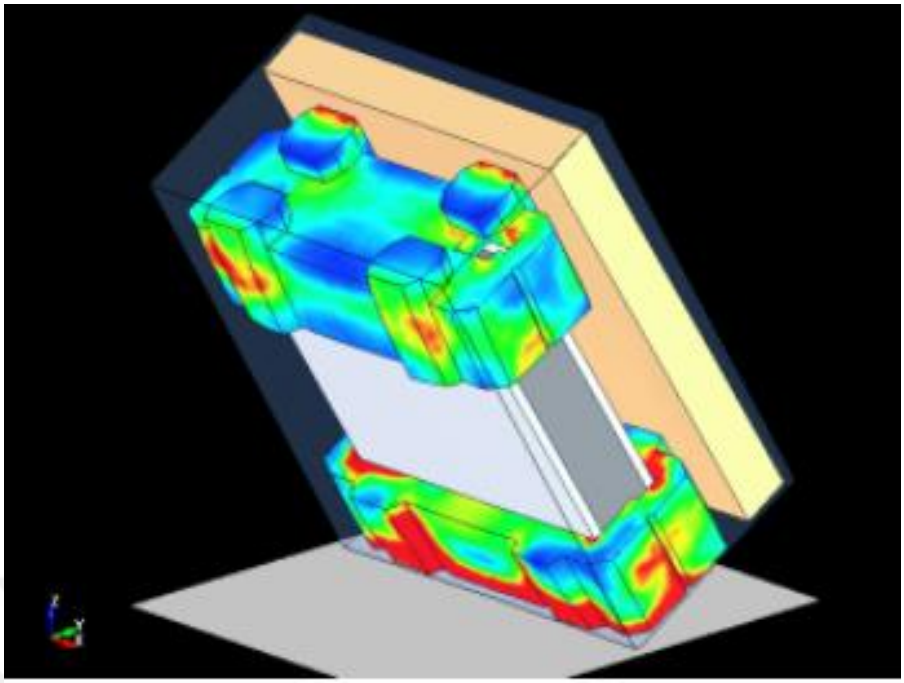


Figure 3.1 Drop impact simulation of electronic equipment packed with cushioning material

After model development, the simulation execution entails the application of appropriate boundary conditions, contact definitions, and loading parameters that replicate the experimental drop test setup. The fidelity of these simulations largely depends on the accuracy of these inputs, as discussed in the Heterogeneous Integration Roadmap (2021), Modeling and Simulation Chapter that has highlighted the importance of detailed model parameterization in achieving predictive accuracy in FEA simulations.

Once the simulation is complete, a correlation analysis is conducted to compare the numerical results with empirical data. This involves statistical assessments of energy absorption, deformation patterns, and stress distributions. The validation framework adopted from works such as those by Silvestri Dobrovolny (2006), focuses on the verification of simulation results against experimental benchmarks to ensure that the simulations can reliably predict real-world behavior.

The research methodology, as presented in Figure 3.2, aims to validate the application of LS DYNA, for simulating refrigerator drop impacts and improving the modeling process. This approach reduces the need for prototypes with specific enhancements selected. Additionally incorporating LS DYNA simulations into

product development provides a benefit by allowing engineers to pinpoint design weaknesses and make informed choices to strengthen durability.

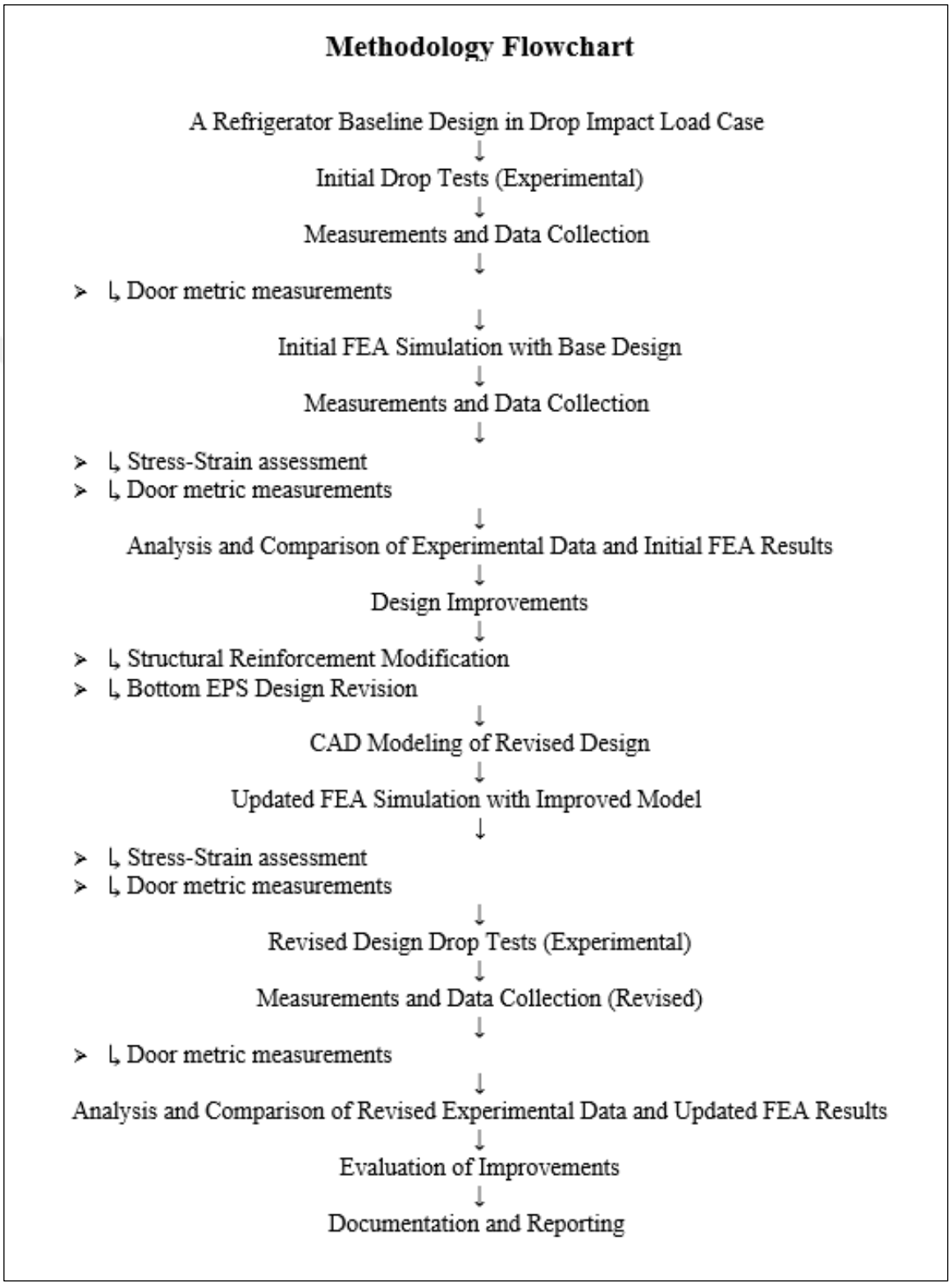


Figure 3.2 Study methodology flowchart

3.1.1 Experimental Validation Framework

Integrating experimental validation within computational drop impact analysis is crucial for verifying refrigeration unit designs in this study. This practice ensures that simulation produces empirically substantiated results, aligning theoretical predictions with real-world outcomes. Experimental validation involves comparing simulation outputs with data from controlled physical tests performed on refrigerators to validate the computational model's accuracy and predictive capabilities.

Examining the specimen both before and after conducting impact tests is crucial to detect any signs of damage or distortion. This examination plays a role in identifying problems, with the testing configuration or specimen structure guaranteeing the accuracy of test outcomes.

Ensuring the specimen is defect-free and meets dimensional and material specifications before testing is critical. Proper mounting in the fixture ensures secure alignment with the impactor, minimizing test variability.

Post-test inspection, conducted visually or with precision measurement tools, assesses damage or deformation. This analysis offers insights into the specimen's behavior under impact loading and identifies any weaknesses in design or setup.

Minimizing secondary impacts during drop weight testing involves clearing the testing area of obstructions and employing safety barriers like nets or walls. Properly designed and calibrated equipment and trained personnel equipped with safety gear further mitigate risks.

The experimental validation framework for drop impact tests integrates simulation environments with experimental conditions, replicating material properties, impact velocities, and packaging geometries (Mülkoğlu et. al. 2017). Calibration of LS-DYNA material models against experimental data ensures accurate representation of material behavior during impact events (see Figure 3.3).

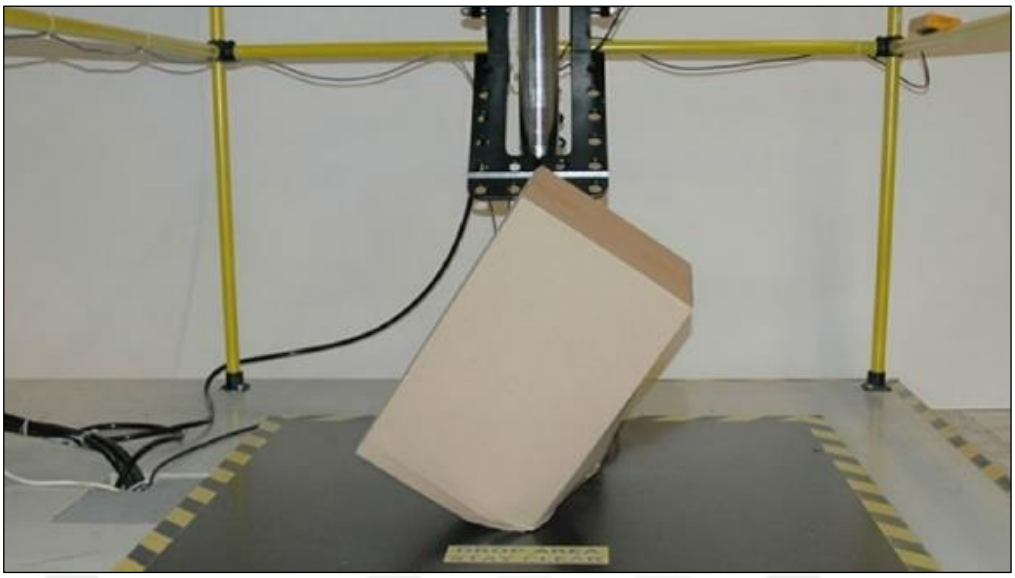


Figure 3.3 Free fall drop test (Topa Institute, 2024)

In summary, establishing a robust experimental validation framework for computational drop impact simulations ensures alignment with physical phenomena, enhancing predictive modeling accuracy for refrigerator design improvements.

3.2 Drop Test Process and Procedure

Drop testing usually includes types of drops to test how strong the packaging is, from angles. The flat drop test checks how well the bottom surface holds up when it dropped flat on its base. Edge drops focus on the front, right, back. Left edges to see how the packaging handles impacts when the product is dropped on its edges. The corner drop test, which is specific to refrigerators, evaluates how well the packaging can protect the appliance when it lands on the corner where the door hinges are situated.

Drop impact resistance and the optimization study involves assessing the type of drop impact and implementing various safety improvements to enhance the stability of refrigerator doors in three dimensions post-impact. Damage to door connections, including hinges, hinge reinforcements, fasteners, and connection holes, can misalign the door's rotation center due to displacement in connected components. Ensuring the integrity of the door connection mechanism is crucial for the refrigerator's functionality.

By incorporating standardized test protocols with practical experimentation, this study aims to evaluate the refrigerator edge drop test, ensuring it meets both regulatory standards and real-world performance criteria. If we classify generally free fall drop impact test types being applied to refrigerators (see Figure 3.4).

1. Plane (bottom surface of product)
2. Front and right edges (bottom edges of product)
3. Back and left edges (bottom edges of product)
4. Corners of product

The images below represent a real test rig for plane surface and edge drop tests refrigerators (see Figure 3.5).

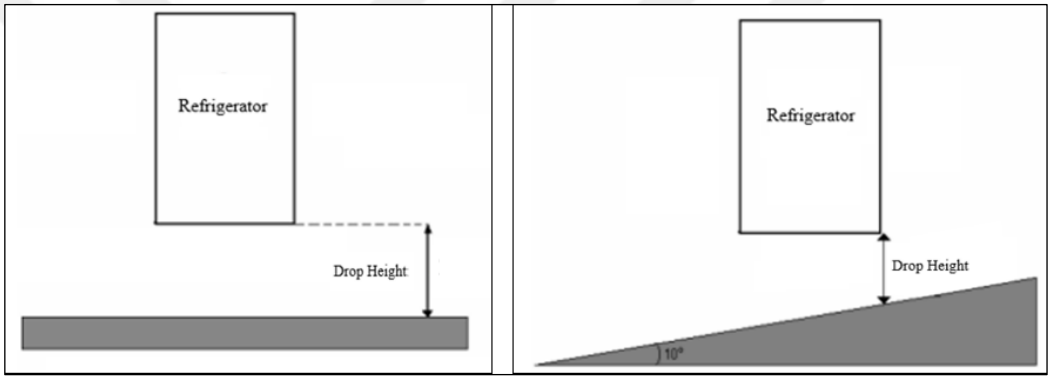


Figure 3.4 Plane surface drop test and edge drop test experimental concept figure



Figure 3.5 Concentrated drop test experimental concept, corner drop test view with 100mm drop height and 10° ramp

To verify structural improvements on the test product, ISTA 6 Amazon.com standards and "Shock - Concentrated Edge Impact" test was examined. The condition being defined for dropping a hazard box product from a height of 410 mm (16 inches)

onto a rigid surface. This part is to ensure that the packaging can protect the product during handling, transportation, and particularly focusing on the edges, corners, and the critical points of vulnerability. The focusing points suit the study methodology. However, the selected refrigerator's weight regarding the ISTA Amazon standard defines the packaging type as a hazard box. Because the selected product's packaging type is corrugated carton box, this standard is not selected as reference for drop scenarios (see Figure 3.6).

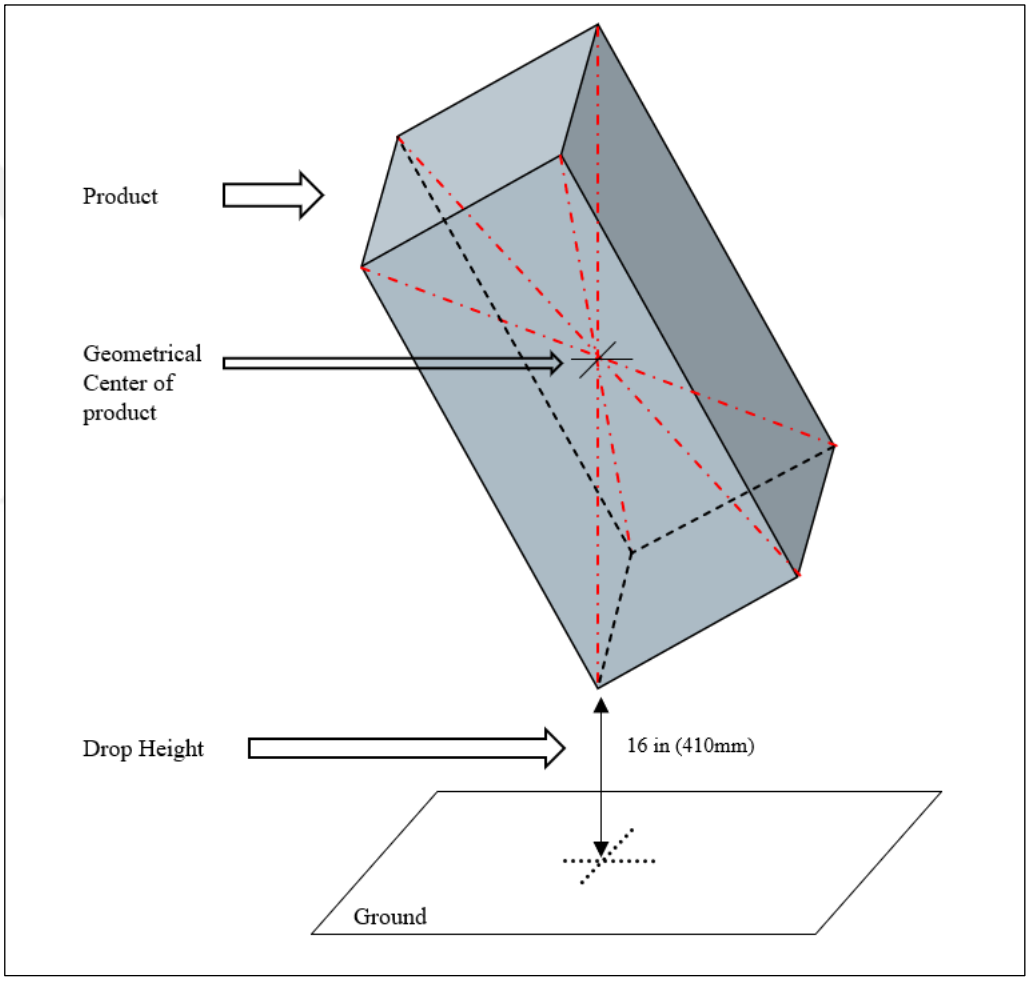


Figure 3.6 ISTA 6-AMAZON.COM 2018 – Concentrated impact drop test concept figure for hazard box

Standardized test procedures and real-life testing scenarios provide invaluable insights into the effectiveness of packaging. Various simulation setup can be arranged to the conditions outlined in the ISTA 6 Amazon.com, ASTM D5276 (1998) for free fall drop impact scenarios and, ASTM D880 (2002) for impact testing for shipping

containers standards, with a focus on assessing the packaging's ability to withstand impacts tests.

3.2.1 Focus of the Drop Scenario

The primary focus of this study is to analyze and optimize the drop impact resistance of packaged refrigerators, with particular emphasis under challenging damage conditions. In the simulation, these conditions are edge drop impact.

The optimization process will involve several strategies; selected improvements will increase the product robustness in all the details of the product first as an optimum solution for the different consequences such as improving the EPS design (Expanded Polystyrene) foam configurations to increase energy absorption during drop impacts, thereby reducing damage. Another optimization approach will involve reinforcing the product with additional components, particularly at the corners, to enhance structural strength and minimize defects in door connections. Through optimization efforts, the study aims to improve the overall drop impact resistance of refrigerators, ensuring better stability and functionality of the door mechanisms after critical drop impacts.

In the comparisons of the challenging drop type conditions, for the refrigerator, compressor weight ratio for the product total weight and the compressor positioning which is placed at back-bottom side of the refrigerator was considered as well (see Figure 3.7).

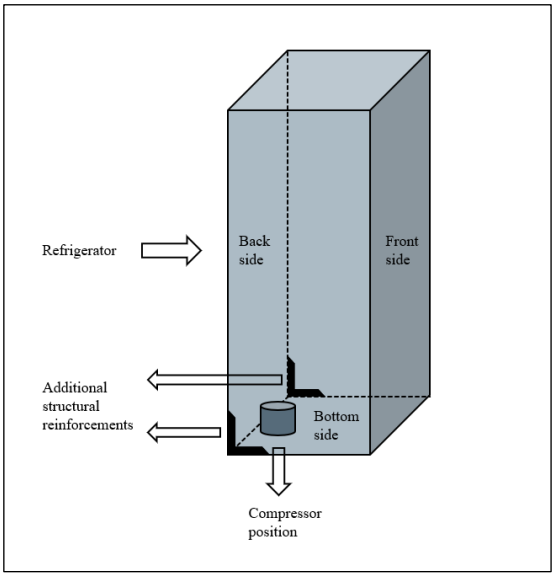


Figure 3.7 Design improvements added model view

According to the defined experience from Blanco and others (2015), for a similar type of product, in the numerical analysis, trailing edge impact, defined as the most critical scenario, was analyzed. These conditions were deemed the most critical as they tend to cause the most significant damage compared to other types of drop impacts.

Blanco, Ortalda, and Clementi (2015) found that trailing edge impact was considered the scenario, in analyzing products of a similar nature numerically. These situations were singled out as critical due to their tendency to result in substantial damage when compared to other forms of drop impacts (see Figure 3.8).

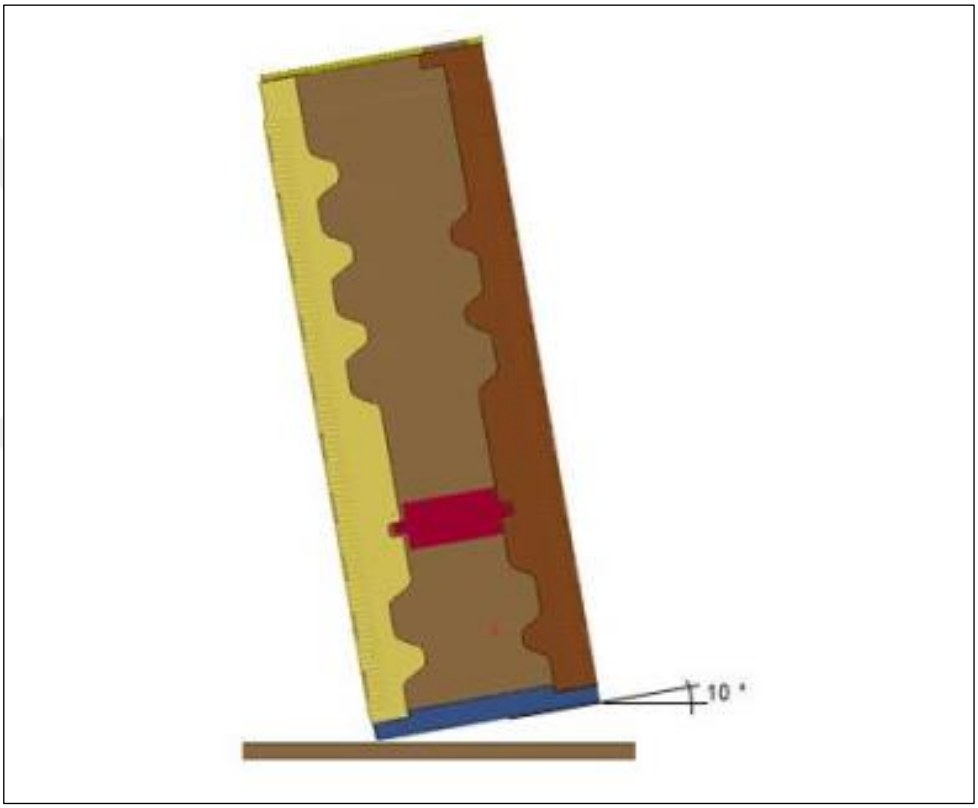


Figure 3.8 Overview of the fridge free fall (Blanco et al., 2015)

3.2.2 Performed Drop Test Setup

The test rig features a mechanism to hold and release the packaged refrigerator, ensuring a precise drop from the specified height of 250 mm with 10° to ground (see Figure 3.9) and (see Figure 3.10).

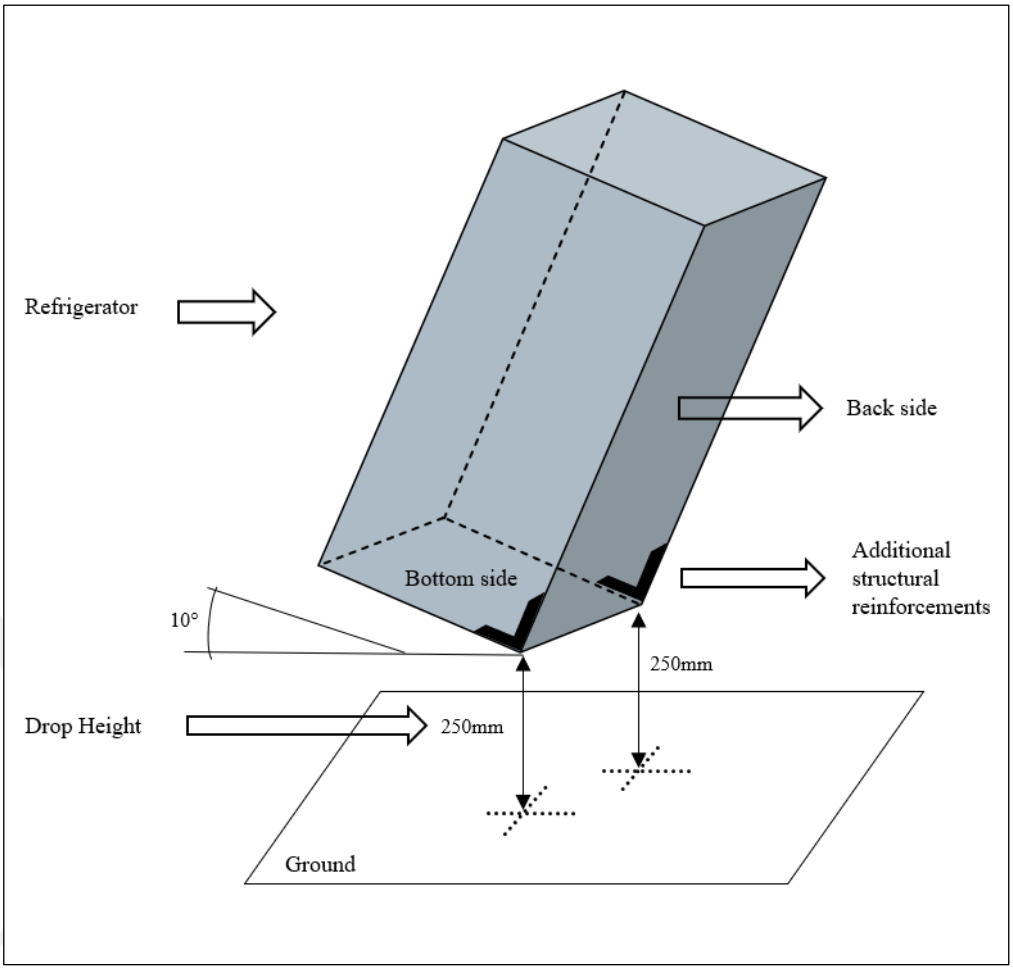


Figure 3.9 Drop scenario of the product

Refrigerator drop testing requires adherence to specific parameters and conditions to ensure accurate assessments of the test condition. These parameters encompass factors such as total refrigerator weight, external dimensions, packaging types, and environmental conditions such as temperature and relative humidity.

Ambient conditions during drop test defined as below and the selected product main parameters in drop test validation.

Table 3.1 Drop test conditions for average household usage conditions standards and selected product specifications

Gross weight:	80kg
Width x Length x Height:	677x780x1916mm
The temperature and relative humidity of the test area condition during test performance.	T= 23. 5 °C RH=% 60 ±15

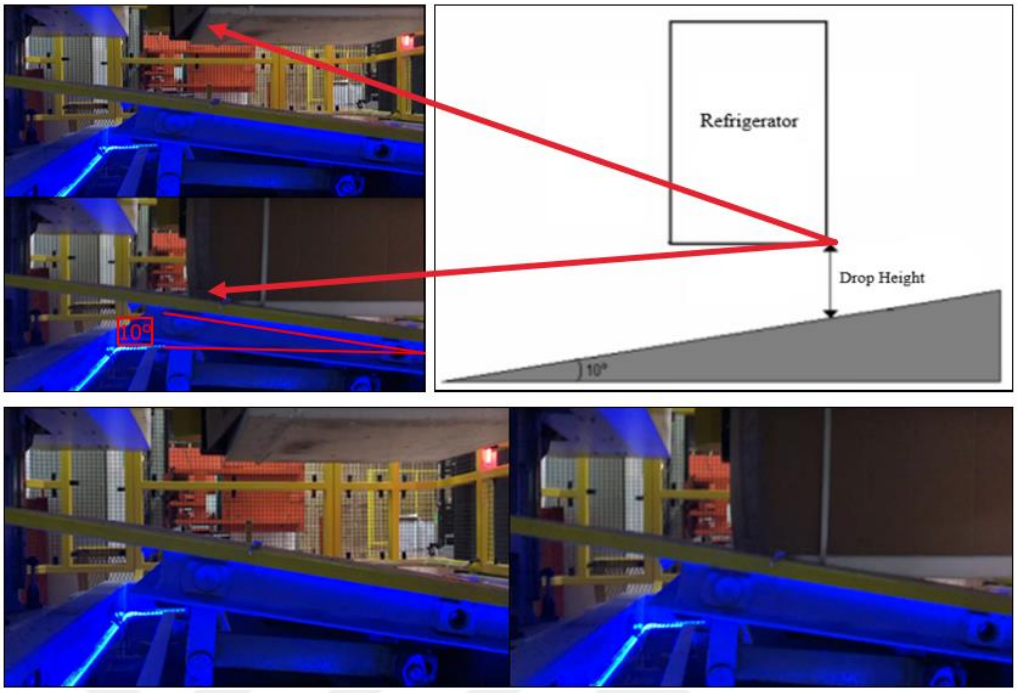


Figure 3.10 Edge drop test experimental concept view with 250 mm drop height and 10° ramp

3.2.3 Measurements after Drop Tests

After conducting drop impact tests on packaged refrigerators, the next critical step is to perform detailed measurements and analyses to evaluate the effects of these impacts on the refrigerator's structural integrity, particularly focusing on the door mechanism. The measurements to be taken include:

Following the drop impact tests, on packaged refrigerators the next important task is to measure and analyze the impact effects on the strength of the refrigerator, with special attention given to the door mechanism. The measurements to be conducted involve.

Following drop impact tests, on packaged refrigerators the next crucial phase involves conducting measurements and analyses to assess the impact of these incidents on the stability of the refrigerator with a specific emphasis on examining the functionality of the door mechanism. The measurements required for this evaluation are.

Visual Inspection: Visual inspection is performed immediately after the drop test; The refrigerator has visible damage such as cracks, deformation, or misalignment, functionality issues especially in the corners where the impacts are most severe.

Functional Impact Assessment: The impact of any observed deviations on the door's functionality (see Figure 3.14).

- Ease of opening/closing the refrigerator door
- The Door' alignment with the refrigerator body
- Assessing door sealing effectiveness in terms of cooling effectiveness

Dimensional Measurements: To measure dimensional changes in critical components such as door hinges, hinge stiffeners, fasteners, and attachment holes, measuring tools such as calipers and rulers are used to ensure accuracy (see Figure 3.13). For certain distances measurements are taken (see Figure 3.11). It can be evaluated whether the measured differences deviate from the original specifications.

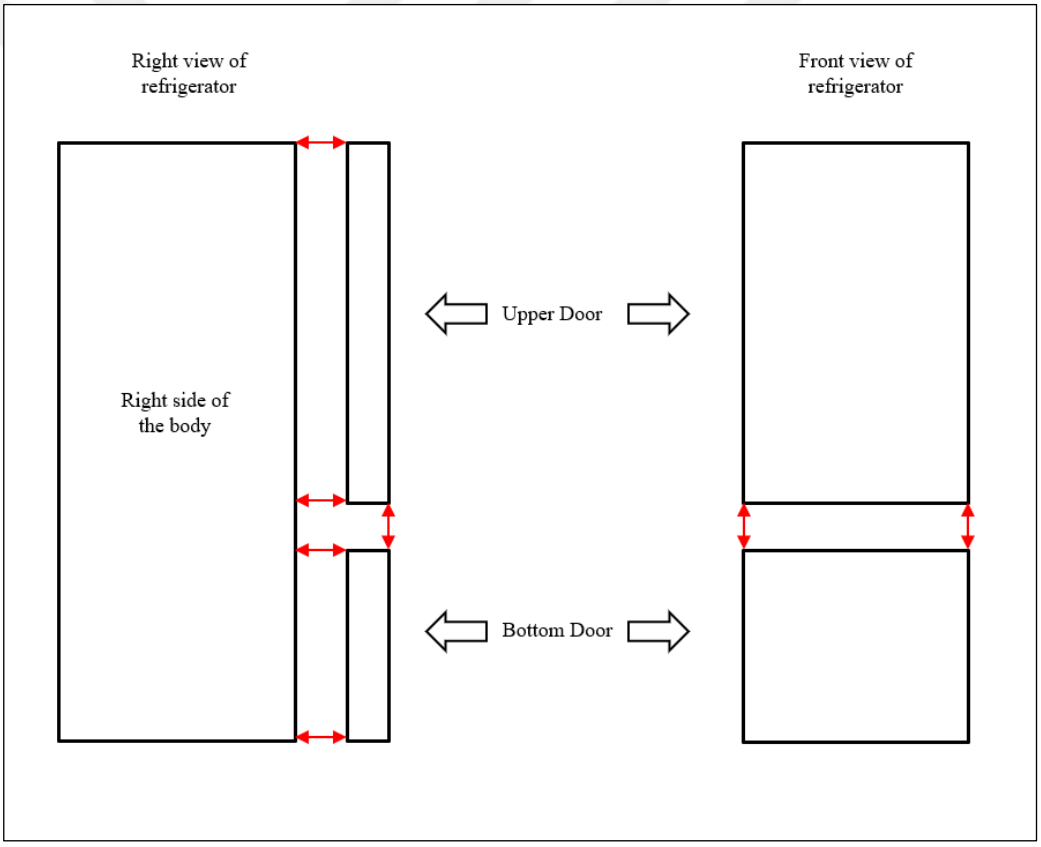


Figure 3.11 2D Measurement areas view after drop test performed

In this study, for the reference baseline design post drop test measurements are taken according to the specified dimensions below (see Figure 3.12).

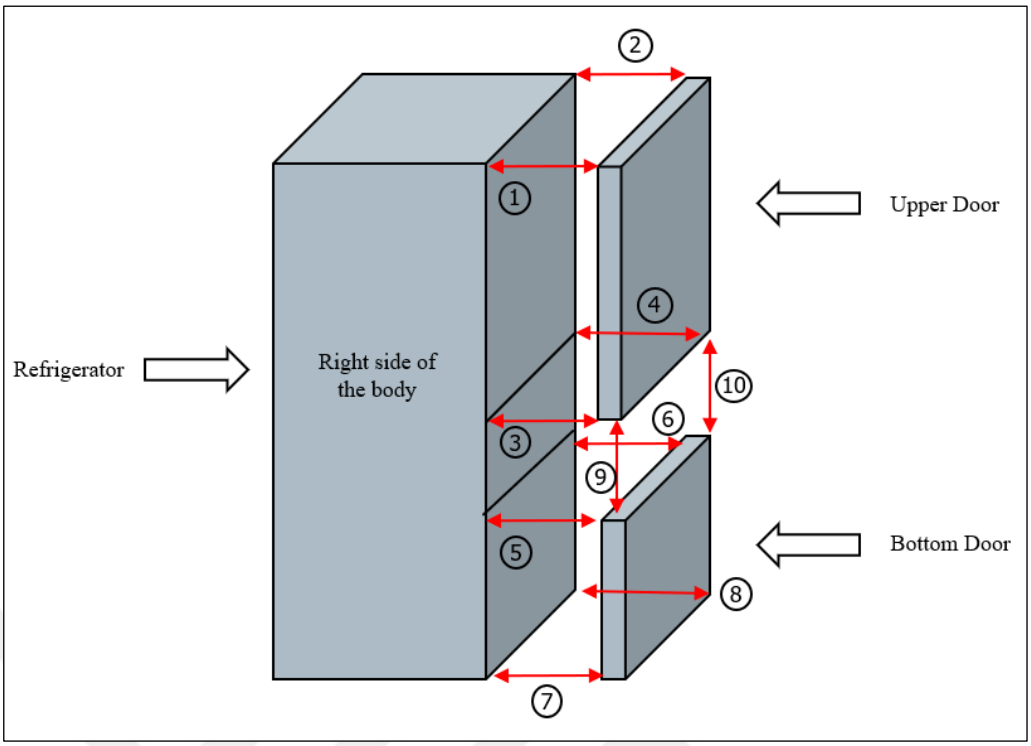


Figure 3.12 3D view of measurement points after drop test performed



Figure 3.13 Door distance measurement method view



Figure 3.14 3D View of refrigerator door rotation axis and measurement points 1, 2, and 3

Damage caused by a fall can greatly impact how the refrigerator door is positioned in three dimensions; horizontally (x) vertically (y) and, in depth (z). These impacts can cause changes in the hinge alignment and the gaps between the door and the refrigerator's body. Particularly, the door placement may shift horizontally vertically and in depth leading to irregularities in how it's spaced and positioned.

After conducting drop tests, differences in the alignment and structure of refrigerator doors were observed. These changes could lead to shifts in the hinge axis affecting the operation of the doors. Misalignments may affect the sealing, ease of use and overall functionality of the doors. This can result in difficulty closing securely or aligning with the refrigerator body ultimately affecting the efficiency of the door mechanism and potentially affecting both user experience and refrigerator performance.

The variations in distance noticed after impacts could signal issues like misalignments or distortions in the doors structure. These changes at points on the product may cause shifts in hinge positions that lead to door-related problems. Misalignment might affect how well the door seals shut, its opening and closing mechanisms and its overall functionality (see Figure 3.15). Consequently, there might be challenges in shutting the doors or aligning them correctly with the refrigerator frame influencing their functioning and potentially affecting both user satisfaction and refrigerator performance. This study focuses on enhancing design to maintain optimal door positioning.

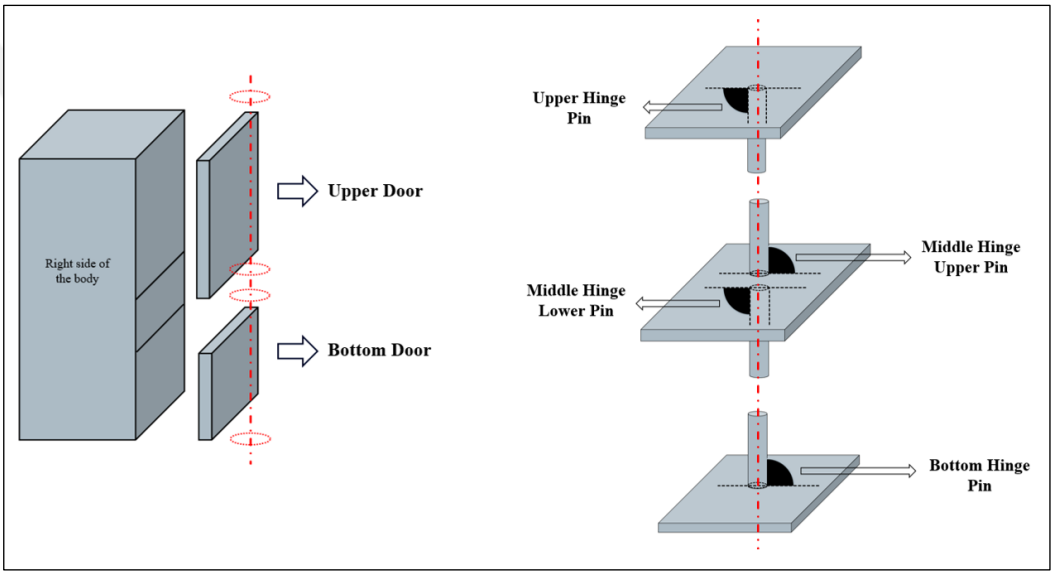


Figure 3.15 3D View of refrigerator door rotation and axis

Additionally, the FEA analysis of the product will be evaluated for the potential changes in the hinge axis and to understand how these changes might affect the door's operational performance and alignment.

3.2.4 Materials Used in Refrigerators

Household refrigerators are built using a variety of materials carefully selected for their characteristics to ensure performance, durability, efficiency, and affordability. In the refrigerator design process, the focus mechanically is on the skeleton, which includes the outer casing, internal framework, and door connections. In this study, the investigation is also on the general structure and door connections against drop impact.

Steel is the most used material for the skeleton of refrigerators. Its high strength, rigidity, and resistance to deformation make it ideal for supporting the overall structure of the appliance. The outer casing and internal support frames are typically made from galvanized or stainless steel. Galvanized steel is used for its excellent corrosion resistance, while stainless steel offers additional benefits in terms of durability and aesthetic appeal, particularly in premium models. The use of steel ensures that the refrigerator maintains its shape and integrity under various loads and stresses. Experts in materials science will be able to apply this increasingly significant method to their research and development of steel materials by learning about modeling and steels used in structural engineering (Sha, 2014).

3.2.4.1 Metal Components

The connections on the door play a role in keeping the refrigerator tightly sealed and maximizing energy efficiency. Typically, these connections are made using a mix of metals and synthetic rubber materials. This study focuses on examining the refrigerator door, specifically looking at its metal, plastic and rubber components. The hinges and latches are crafted from DC01 and DC04 steel to provide the strength needed for use (see Figure 3.16) and (see Figure 3.17). Meanwhile, synthetic rubber gaskets create a seal to keep air in and prevent warm air from seeping in which is vital for maintaining optimal temperatures and energy efficiency inside the refrigerator.

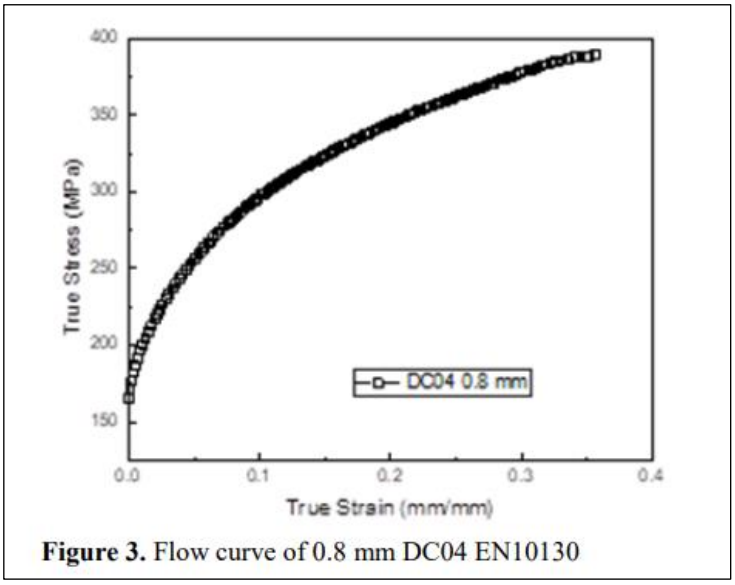


Figure 3.16 Stress-strain curve of reference DC04 EN 10130, cold-rolled steel (Kaplan et al., 2022)

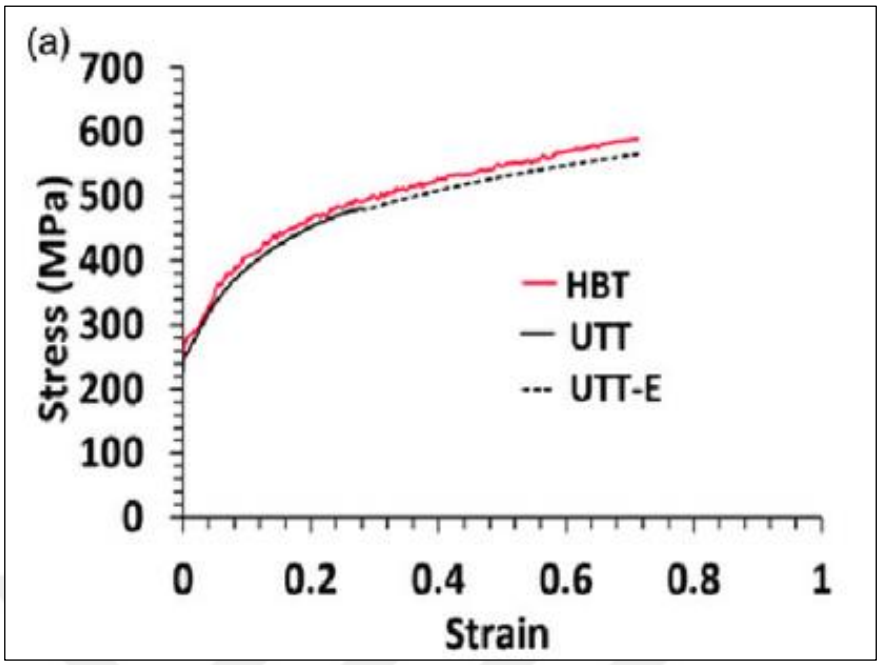


Figure 3.17 Stress-strain curve of reference DC01 EN 10130, cold-rolled steel (Kumar & Digavalli, 2020)

3.2.4.2 Plastic Components

Plastics play a significant role in the construction of refrigerators. High-impact polystyrene, polypropylene (PP) and polyethylene (PE) are commonly used for internal components like shelves, drawers, and door bins because of their durability, flexibility, and ease of molding. Acrylonitrile butadiene styrene (ABS) is often utilized for door liners and interior panels, valued for its high impact resistance and glossy finish (see Figure 3.18). These materials contribute to the overall functionality and user experience of the refrigerator and produced by different techniques such as to shape the plastic, extrusion, injection molding, thermoforming, and blow molding all use various process methods (see Figure 3.19, 2.20, 3.21). Therefore, each offers essentially distinct part geometry (Kazmer, 2011, p.31).

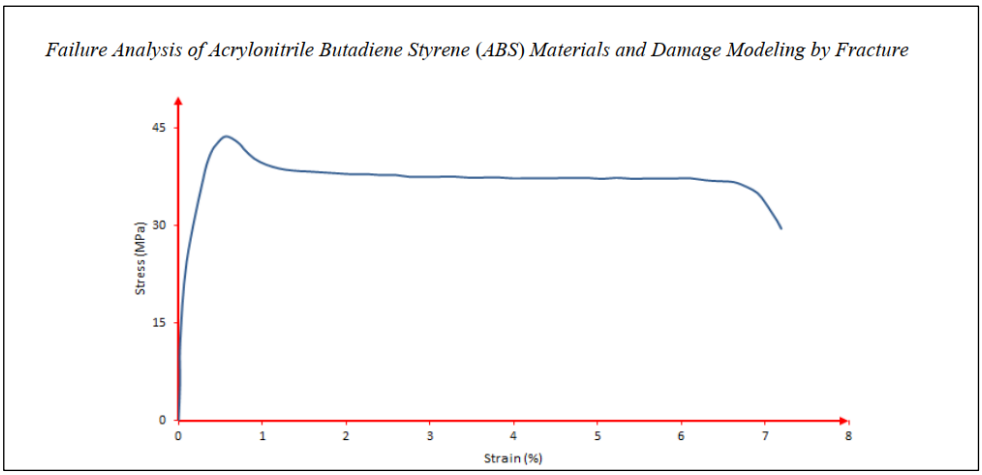


Figure 3.18 Stress-strain curve of reference ABS, Acrylonitrile Butadiene Styrene (Sabah & Wahid, 2019)

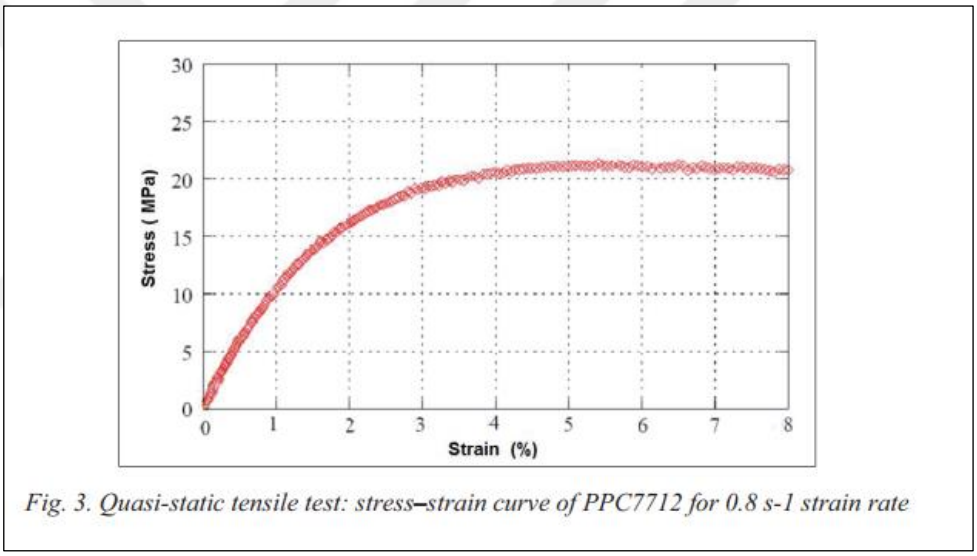


Figure 3.19 Stress-strain curve of reference PP, Polypropylene (Khlif, Masmoudi, & Bradai, 2012)

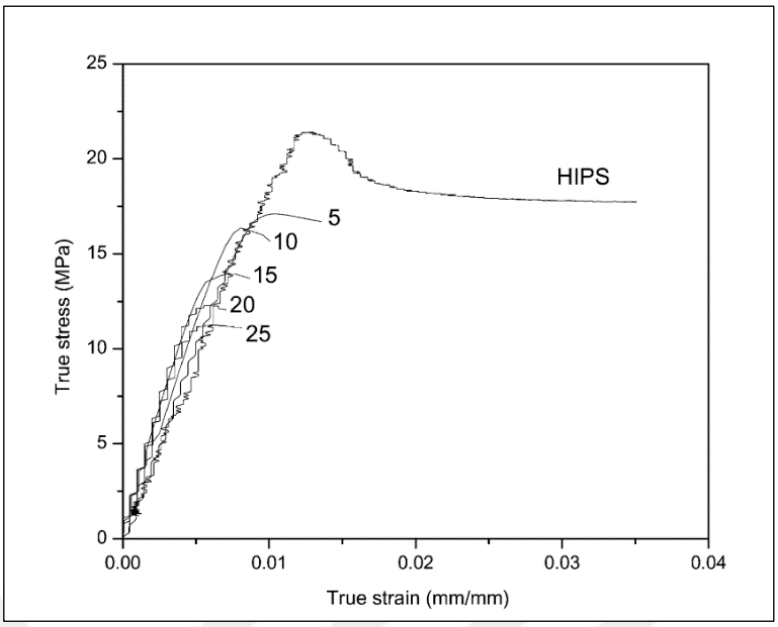


Figure 3.20 Stress-strain curve of reference HIPS, High Impact Polystyrene (Antich et al., 2006)

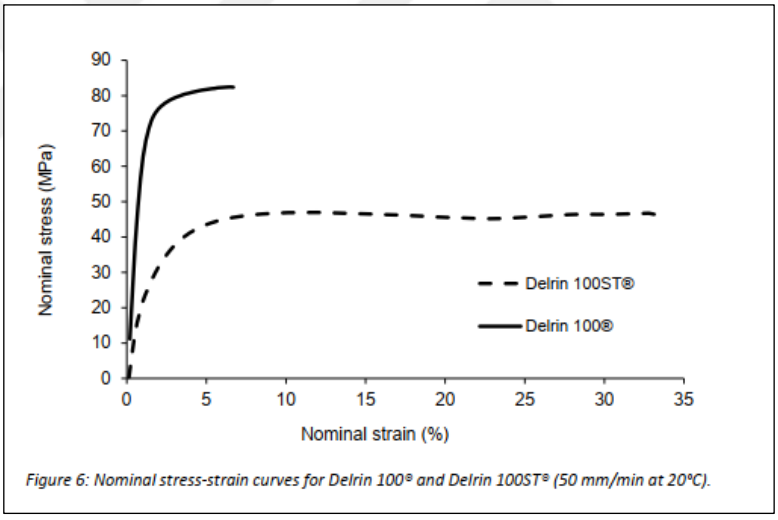
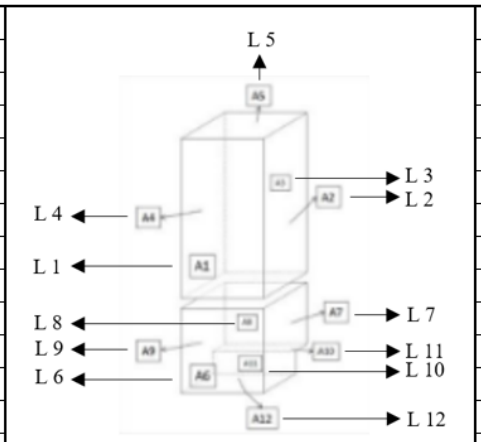


Figure 3.21 Stress-strain curve of reference POM, Polyoxymethylene (Bedoui & Fayolle, 2014)

3.2.4.3 Polyurethane Wall

Polyurethane serves as the insulating material in refrigerators filling the gap between the metal exterior and the thermoplastic interior. During manufacturing liquid polyurethane is injected into the space between these layers. Expands to fill any voids creating a barrier. While the thickness of the wall is determined based on dimensions actual measurements may vary across areas due to external influences as specified in the Table 3.2. In this study, the analysis of drop impacts the polyurethane wall thicknesses was determined using these calculations.

Table 3.2 Drop Polyurethane Wall Theoretical and Practical Thickness

Theoretical Data			Practical Results	
PU Area	Thickness(mm)		PU Area	Thickness(mm)
L1	60		L1	60
L2	43		L2	43
L3	54		L3	54
L4	43		L4	43
L5	73		L5	83
L6	80		L6	80
L7	74		L7	78
L8	74		L8	80
L9	74		L9	78
L10	50		L10	67
L11	67		L11	67
L12	63		L12	65

Recognizing differences in the thickness of polyurethane walls and properties like density and thermal conductivity is essential in acceptance. These variations are impacted by factors during palletization, such as moisture levels, additives, pressure and die temperature.

Polyurethane foam is highly valued for its ability to keep things cold and is commonly used in the walls of refrigerators. It helps maintain temperature by preventing too much heat from getting in or out. Over time, the properties of polyurethane, like its hardness, strength, and size, can change. It tends to become more brittle after being insulated for a while and may increase in size while the wall thickness changes. Therefore, it is important to study how polyurethane behaves under pressure and over time, to assess how well products will hold up and perform in real-life situations. In this research, polyurethane wall thickness was modeled based on 3D data. On the other hand, real product wall thickness always deviates from the theoretical geometry with this experimental knowledge. The FEA model and drop tested real model differ in this point because of the polyurethane wall thickness and the material behavior (see Figure 3.22).

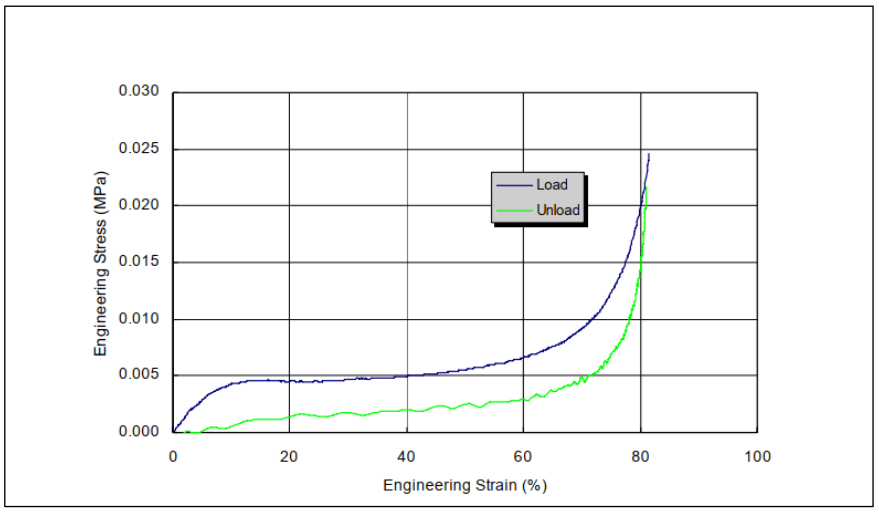


Figure 3.22 Stress-strain curve of reference PU, Polyurethane in FEA simulation (Croop & Lobo, 2009)

3.3 Refrigerator Packaging Materials and Protective Methods

3.3.1 Styrofoam Components

Manufacturers of household appliances utilize a variety of materials for packaging including cardboard, foam, polystyrene, and plastic. The selection of material is based on factors such as the weight, size, and fragility of the product as transportation methods and environmental concerns. Lighter items are typically packed in cardboard boxes while heavier or delicate items are protected with foam or polystyrene. Plastic is chosen for its strength and ability to resist water. These materials play a role in cushioning products during transit to minimize impacts like bumps or drops. Moreover, packaging may feature components like corner protectors to safeguard edges and films that prevent surface damage. The Department of the Navy Department of the Air Force and Defense Logistics Agency (2012) offers instructions on packaging and preserving materials.

Expanded Polystyrene (EPS) foam is the most used material for refrigerator packaging due to its excellent shock absorption and insulation properties (see Figure 3.23, 3.24). It is lightweight, durable, and easily molded into custom shapes to fit the refrigerator. However, it is not environmentally friendly and can be difficult to recycle. For packaging materials, additional properties such as cushioning coefficients and damping characteristics are also of significance (see Figure 3.25), (Guo, 2012).



Figure 3.23 Styrofoam designs with the product packaging



Figure 3.24 Refrigerator packaging view

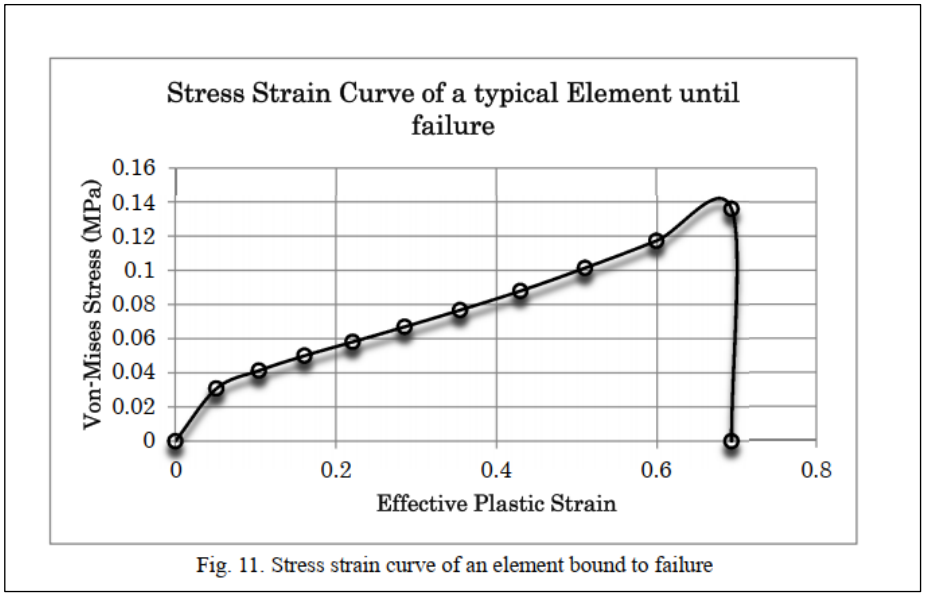


Fig. 11. Stress strain curve of an element bound to failure

Figure 3.25 Stress-strain curve of reference EPS used in FEA simulation (Shah & Topa, 2015)

Corner and edge guards are essential for safeguarding the corners and edges of a refrigerator during transit to prevent any impacts. Typically designed from foam or plastic they serve the purpose of cushioning blows. Shielding the refrigerators structure from harm. The effectiveness of this safeguard hinges on the material properties and shapes of the elements used in packaging like outer corrugated cardboard boxes, inner foam, or plastic supports, as well as additional protective features such as edge guards and anti-abrasion films (Gök & Akpınar 2020).

3.3.2 Carton Box Component

Corrugated cardboard is often used for packaging refrigerators because it is inexpensive, recyclable, and provides protection against shocks. However, during our drop test we found that its ability to absorb impact is limited for corrugated carton boxes especially for refrigerators with selected drop type. To simplify our analysis, we modeled the carton box as a liner with a thickness. This simplification is justified by the fact that the carton box plays a role in absorbing energy during the drop test conditions. Simplifying the carton box helps us streamline our computations without compromising the accuracy of the simulation.

In summary, the decided approach allows us to be efficient while still capturing the dynamics of the drop test. Additionally, due to the model complexity, modeling a carton as a corrugated board would be a waste of time instead compared to meshing and analyzing (see Figure 3.26).

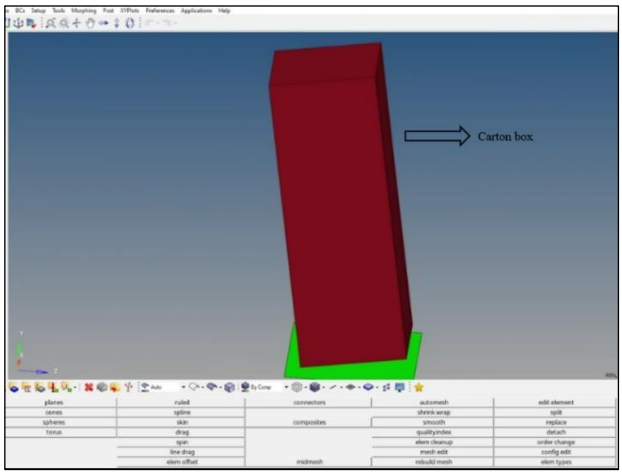


Figure 3.26 FEA simulation carton box modeling

3.3.2.1 Strap Components

One other crucial element of packaging is the strap. Typically utilized in sets, these are employed to fasten the refrigerator by linking to the pallet and keeping it stable during transport. Straps can be crafted from materials, as polyester, nylon and steel built to endure stress and strain. In this study strap designs were not modeled with its geometry and material properties. For streamlining the FEA model straps are also depicted with their installation settings. The stretching torque value is an aspect in our model. Details will take place in the part of simulation modeling (see Figure 3.27).



Figure 3.27 Strap design usage on packaged refrigerators

3.4 Finite Element Method Principles

Solving engineering issues demands solutions and the Finite Element Method (FEM) effectively offers both efficiency and precision. Originally designed to assess stress, in aircraft frameworks FEM swiftly broadened its application to engineering and practical science domains over the years. With enhancements, it has evolved into an effective technique for tackling a diverse range of engineering obstacles, in today's world (Holland, 1974).

The FEM replaces differential equations and boundary conditions with finite difference equations, enabling solutions for complex problems involving diverse geometries, boundary conditions, and loading scenarios. By dividing structures into smaller elements of various sizes and types and connecting nodes, a finite element model is constructed. This approach simplifies problem-solving to yield approximate results, with more detailed models closely approximating exact solutions.

3.4.1 Finite Element Model Setup

A detailed finite element model of the refrigerator will be created, including critical components such as the door, hinges, and corner reinforcements. This model was developed in HyperMesh2019 and LS-Prepost. For cross-validation made by using LS-dyna R13 double precision.

The drop height, orientation, and initial conditions for the drop test will be defined. Simulations will be run in LS-DYNA, incorporating the defined material model to predict the dynamic response of the refrigerator components accurately.

3.4.2 Numerical Methods in Finite Element Analysis

In the realm of nonlinear and dynamic finite element systems, numerical approaches offer more efficient and expedient solutions to equilibrium equations compared to traditional analytical methods. These numerical solutions are generally classified into two main methodologies: direct integration and modal superposition.

In integration, a step-by-step numerical approach is used where each time interval solution is based on the outcomes of the preceding step. The term "direct" indicates that the equilibrium equations are processed in their form without alteration until all steps are finished. Direct integration methods include the difference method, Hot Boult method, Wilson θ method and Newmark method (Balasubramanyam, 1999). In simulating the refrigerator drop test using LS DYNA software the choice of techniques significantly impacts the accuracy and stability of results. In this research, this particular approach was selected for its compatibility, with the nonlinear characteristics of the drop test scenario.

The equations of motion for a dynamic system in finite element analysis are generally given by:

$$Mu\ddot{}(t) + Cu\dot{}(t) + Ku(t) = F(t) \quad (3.1)$$

where:

- *M* is the mass matrix,
- *C* is the damping matrix,
- *K* is the stiffness matrix,
- $u\ddot{}(t)$ is the acceleration vector,
- $u\dot{}(t)$ is the velocity vector,
- *u(t)* is the displacement vector,
- *F(t)* is the external force vector.

3.4.3 Central Difference Method

The central difference approach is quite useful in addressing systems that deal with differential equations having constant coefficients. This method calculates the velocity and acceleration values directly at each time step. The study makes mention of the difference method. Here are the main concepts of the central difference technique.

$$u\dot{}_n = \frac{1}{2\Delta t}(u_{n+1} - u_{n-1}) \quad (3.2)$$

$$u\ddot{}_n = \frac{1}{(\Delta t)^2}(u_{n+1} - 2u_n + u_{n-1}) \quad (3.3)$$

The equation of motion for a dynamic system in the finite element analysis context can be written as:

$$(m + \frac{1}{2}\Delta tc)u_{n+1} + 1 = \Delta t^2 p_n - (\Delta t^2 k - 2m)u_n - (m - \frac{\Delta t}{2}c)u_{n-1} \quad (3.4)$$

where:

- *m* is the mass,
- *c* is the damping coefficient,
- *k* is the stiffness,
- *u* is the displacement,
- $u\dot{}$ is the velocity,

- $\ddot{u}$ is the acceleration,
- p is the external force,
- Δt is the time step size.

In this method, the solution for u_{n+1} depends on u_{n-1} and un the central difference procedure is known as an explicit integration method. Moreover, in this method, the stiffness matrix does not require that it splits.

During the simulation of a refrigerator drop test using LS DYNA, the selection of methods plays a role in determining the accuracy and stability of the outcomes. In this research, the central difference method was chosen because of its compatibility with the nonlinear characteristics of the drop test scenario. This method involves solving a set of equations at each time interval ensuring that the system reaches equilibrium conditions while effectively capturing how the refrigerator responds dynamically to impact during the drop (Chapra & Canale 2015).

3.4.4 LS-DYNA Simulation Model Development

In order to create LS DYNA model, explicit analysis methodology flowchart is generated (see Figure 3.28).

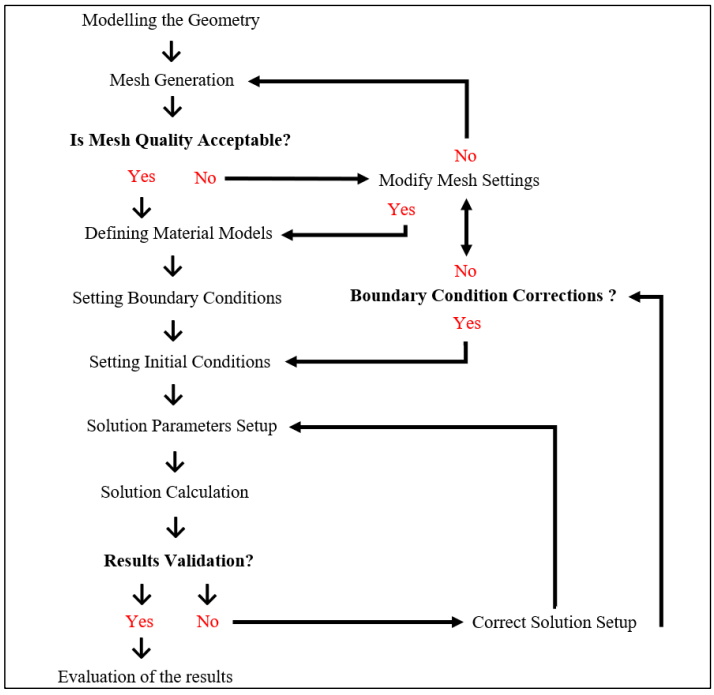


Figure 3.28 FEA model explicit analysis methodology flowchart

The flowchart outlines a step-by-step process for creating an FEA model to simulate refrigerator drop tests using LS DYNA software. It starts with creating geometry. Then moving on to creating the mesh. If the mesh quality meets the standards, the material models are defined; if not, adjustments are made to the mesh settings. After that, the next, boundary conditions are checked for correctness. Once the conditions are confirmed to be correct, the initial conditions are determined, and the solution parameters are configured. Then calculations are performed. The results obtained are then verified for correctness. If the results seem reliable at this stage, analysis will run; otherwise, adjustments need to be made to improve the solution setup until it becomes reliable. This iterative approach increases efficiency and precision by ensuring that the FEA model accurately reflects how refrigerators behave during drop tests in LS DYNA simulations.

Creating an element model is a part of simulating how refrigerators withstand drop impact tests using the simulation tools (see Figure 3.29). This involves building a version of the refrigerator to accurately predict its behavior during impact. Predictive modeling, like this, is essential for evaluating product reliability and durability without needing prototypes, which ultimately offers a cost effective and timely approach, for validating and optimizing designs.

In constructing the finite element model, meticulous attention must be paid to replicating the geometrical attributes of the refrigerator and packaging, defining the material properties, and implementing the correct boundary conditions and initial states that reflect the experimental drop test setup. The geometrical representation must capture the essential features of the refrigerator, such as dimensions, shapes, and the assembly of different components, to ensure that the model response is representative of the actual physical structure (Wang et al., 2005).

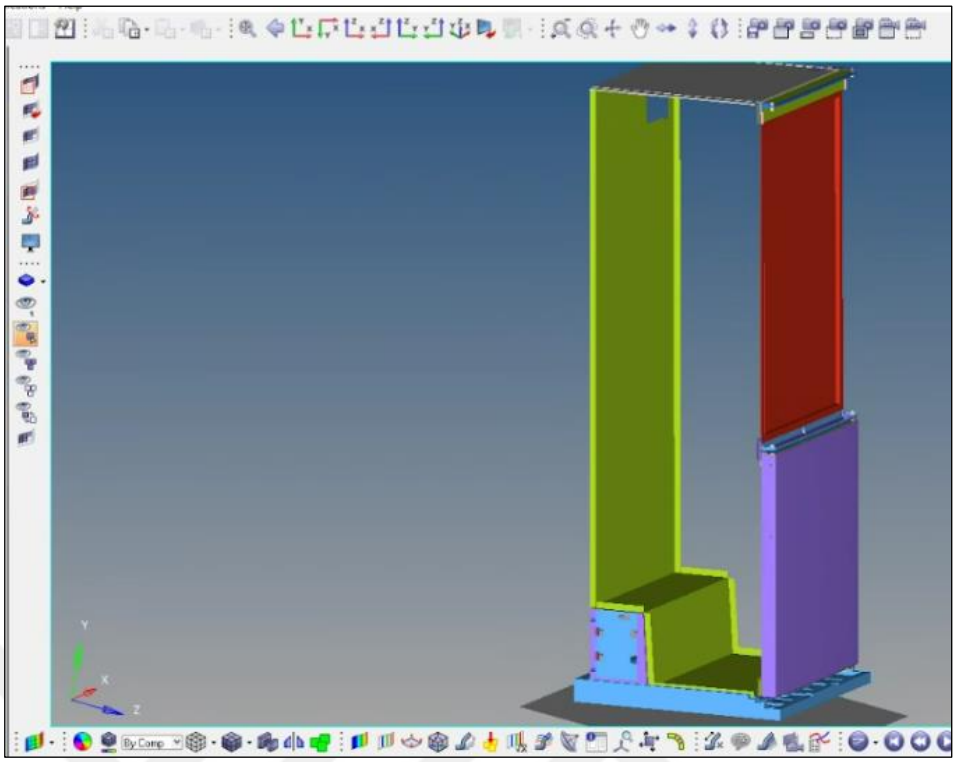


Figure 3.29 FEA simulation model development view

The material properties, derived from rigorous material characterization processes, are integrated into the model via appropriate constitutive models available within LS-DYNA. These properties may include elasticity, plasticity, density, and failure parameters, which are often a function of strain rate, particularly for materials that exhibit significant rate-dependent behavior (Nichols et al., 2001). The selection of the correct material model, such as the Johnson-Cook or Piecewise Linear Plasticity models for metals, is critical for capturing the dynamic response during the impact (Johnson & Cook, 1983). In this study, the Piecewise Linear Plasticity model was considered. Moreover, the development of the finite element model encompasses the implementation of contact interfaces between the refrigerator and packaging materials. This requires the use of sophisticated contact algorithms that can handle the complexities of impact events, including large deformations and varying contact conditions throughout the event (Hallquist, 2006).

The last step in developing the model is preparing the starting conditions and limits that match the specifications of the drop impact test including factors like the drop height, product orientation or type of drop. These factors determine the starting point

for the simulation. Are crucial for guaranteeing the precision of the simulation outcomes (Wang et al., 2005).

The peak of the element model crafted in this thesis is reached during the conduct of drop impact simulations meticulously cross referenced with test results to confirm the model's precision. This thorough comparison process guarantees that the model does not mirror real life situations but also serves as an instrument for investigating the impact performance of refrigerators under various design alterations. In essence, this model offers perspectives that guide the enhancement of both the refrigerator and its packaging system bolstering their resilience and longevity.

The study described in this thesis provides a step, by step approach for creating an element model customized for testing refrigerator drop impacts, with LS DYNA. This involves incorporating material properties ensuring geometric representation and applying boundary and initial conditions precisely. The findings of this research seek to display the benefits of utilizing element analysis of traditional testing methods contributing valuable knowledge to appliance durability simulation.

3.4.4.1 Formulation of Explicit Method

Time Integration in LS-DYNA, the explicit method utilizes central difference time integration (CDTI) to compute displacement, velocity, and acceleration at discrete time steps:

$$u(t+\Delta t) = u(t) + \dot{u}(t)\Delta t + \ddot{u}(t)\frac{(\Delta t)^2}{2} + O((\Delta t)^3) \tag{3.5}$$

Where:

- $u(t)$: Displacement vector at time t,
- $\dot{u}(t)$: Velocity vector at time t,
- $\ddot{u}(t)$: Acceleration vector at time t,
- Δt: Time increment.

3.4.5 Mesh Generation and Optimization

The development of an accurate finite element (FE) model for predicting the response of a refrigerator to drop impact events necessitates meticulous mesh

generation and optimization. This step is crucial in finite element analysis (FEA) because the mesh quality significantly influences the precision, convergence, and computational efficiency of the simulation results. In the application of LS-DYNA for impact analysis, the finite element mesh acts as a spatial discretization of the continuum domain, enabling the numerical solution of complex physical behaviors under dynamic loading conditions.

For the FE analysis, to prepare the model mainly Altair HyperMesh2019 and LS-Prepost software have been used because of the complexity of the assembly model for the provided simplification features. To solve the analysis LS-Dyna R13 double precision was used.

First, assembly parts had been created regarding the required components of study focused. Targeted parts were created through Creo Parametric 3D software and all the components were mounted to generate assembly 3D models. For the simplification of the model Creo Parametric is used in general. Additionally, for the surface modeling to prepare 3D data for analysis SolidWorks software being used (see Figure 3.30).

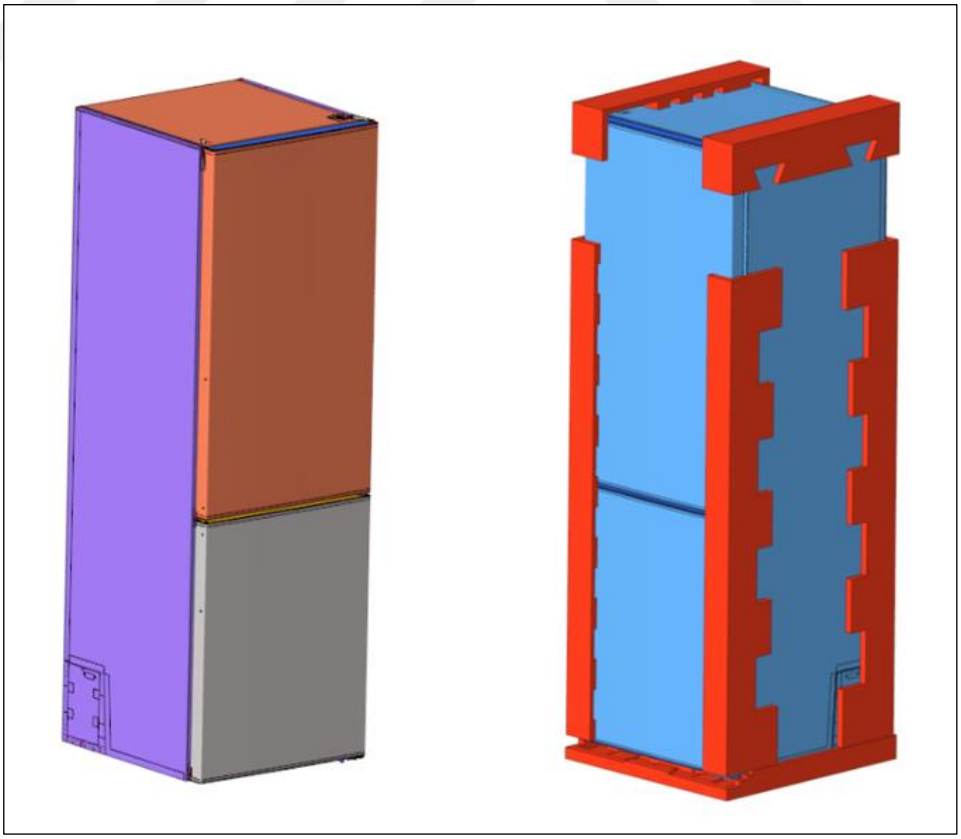


Figure 3.30 Refrigerator assembly FEA model

The finite element model of the refrigerator is composed of a discrete set of elements that can be processed by the LS-DYNA solver. The quality of this discretization is paramount; elements must be refined enough to capture stress gradients and deformation patterns accurately, particularly in critical regions where stress concentrations or complex contact interactions are expected for geometry dependent studies (Nichols et al., 2001). For instance, the mesh density is increased around areas where the impact is likely to induce high stress, such as corners and edges.

Optimization of the mesh becomes a balancing act between resolution and computational resource management. This process is informed by the principle of convergence—that the solution becomes independent of the mesh as it is refined—and by the need for a mesh that is adapted to capture the physics of the problem without unnecessary computational overhead (Wang et al., 2005). Techniques such as adaptive remeshing, where the mesh evolves based on the solution to focus computational effort where it is most needed, and sensitivity analysis, to determine the influence of mesh density on the simulation outcomes, are critical tools in this optimization process (ANSYS Advantage, 2013).

3.4.5.1 Simplifications and Modeling Challenges

The plastic components inside the body were made simpler to make the calculations easier without compromising the model's strength. This simplification involved:

1. Curved Edges and Smooth Transitions; of corners we used rounded edges with a small radius to prevent the need for detailed meshing and potential numerical challenges.

2. Simplified Design; We left out interferences and complex details that don't have an impact on the overall performance of the model to streamline the mesh and decrease element count.

In order to keep the model solvable, in a manner and ensure results, for the drop test analysis these adjustments were essential. We used meshing methods to uphold element quality, preventing skewed or distorted elements that might compromise solution accuracy.

However, overly refined meshes can lead to prohibitively long computation times and may introduce numerical difficulties, such as ill-conditioning in the system of

equations to be solved (Wang et al., 2005). To balance accuracy and computational efficiency, simplifications were made in the meshing of certain components. Specifically, the inner body plastic parts of the refrigerator were simplified as shown in Figure 3.31. This involved approximating complex geometries with less intricate shapes that still accurately represent the overall structural behavior (see Figure 3.32).

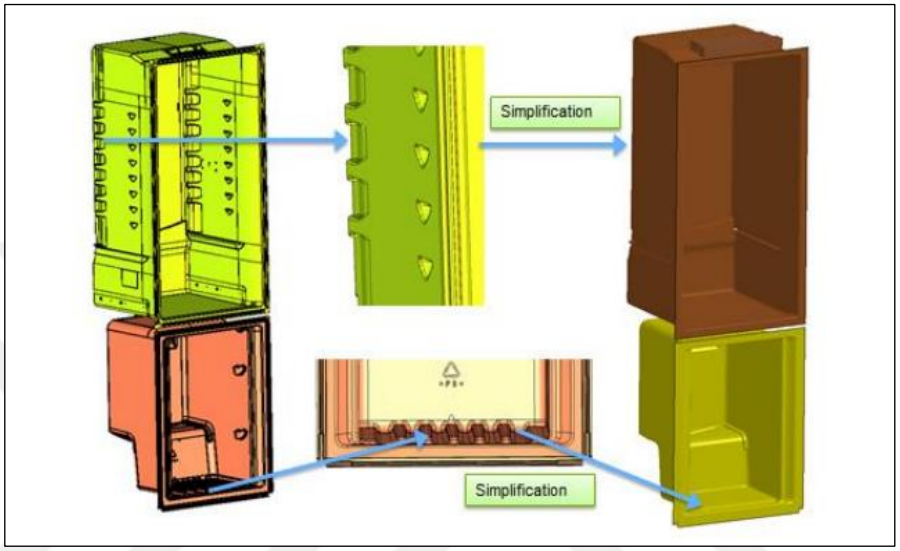


Figure 3.31 Simplification View of the Reference Study Model (Blanco et al., 2015)

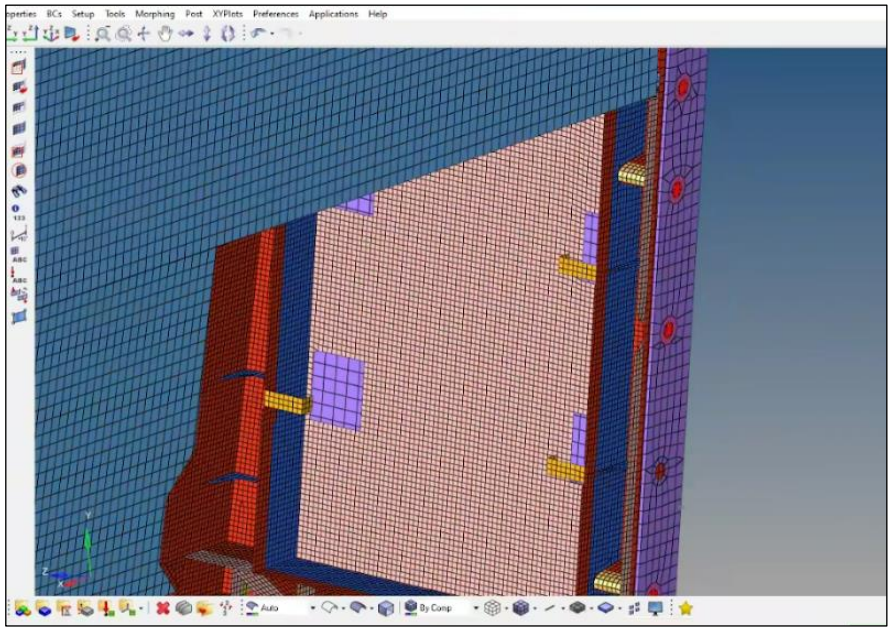


Figure 3.32 FEA Model compressor area mesh generation

The LS-DYNA environment provides a range of functionalities to support mesh generation and optimization for drop impact simulations. It offers various element formulations and types to suit different materials and loading conditions. Besides, including the ability to model complex contact between bodies (Nichols et al., 2001). Additionally, LS-DYNA facilitates the implementation of adaptive meshing strategies that can automatically refine the mesh in areas of high gradient during the simulation, ensuring that the mesh resolution is aligned with the evolving solution requirements (ANSYS Advantage, 2013).

For the most important damping component for the selected drop type, it is the bottom EPS (see Figure 3.33). The tetrahedral element form was selected applied to the bottom EPS part, utilizing ELFORM 13 formulation and solid section ID 105 (see Figure 3.34). This configuration featured 1-point constant stress with nodal pressure averaging in LS-Prepost.

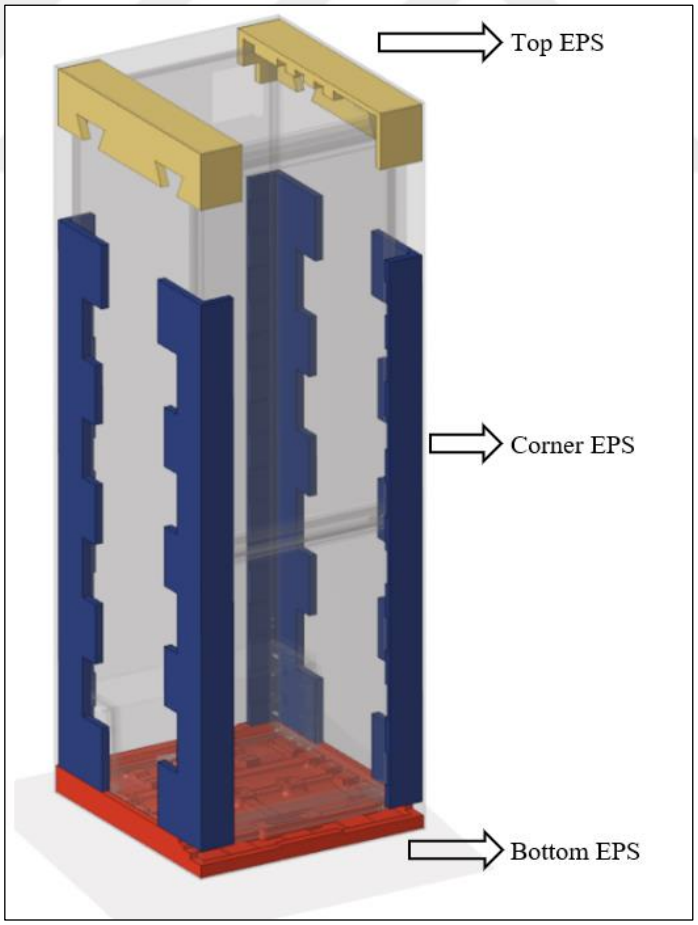


Figure 3.33 Generated FEA model EPS assembly

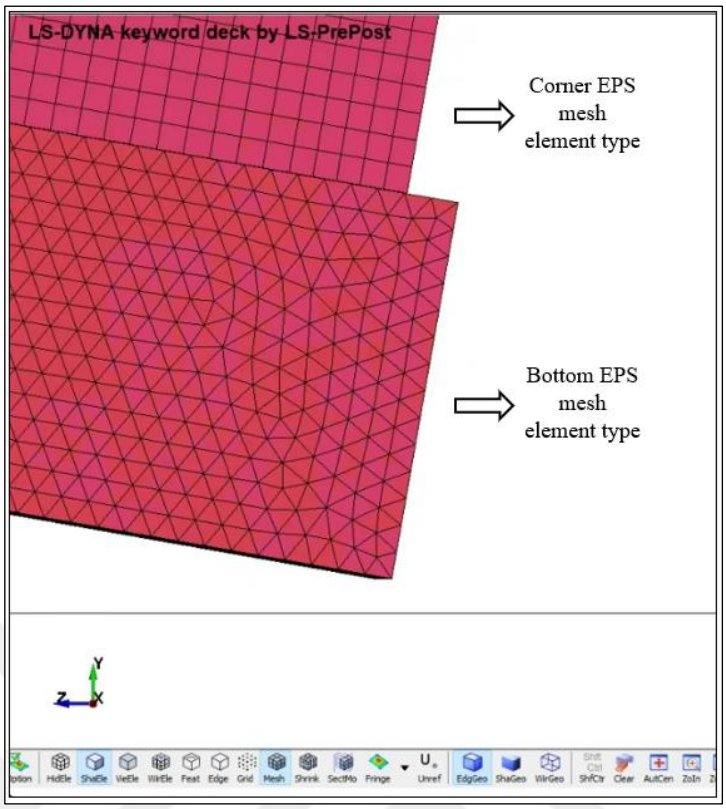


Figure 3.34 FEA model element mesh types

Hexahedral elements (Hex) were strategically utilized for sheet metal parts, specific plastic components, top and corner Styrofoam. These elements employed ELFORM 1 formulation and solid section ID (SECID) 38, chosen for their capability to provide high accuracy and computational efficiency in simulations (see Figure 3.35, 3.36).

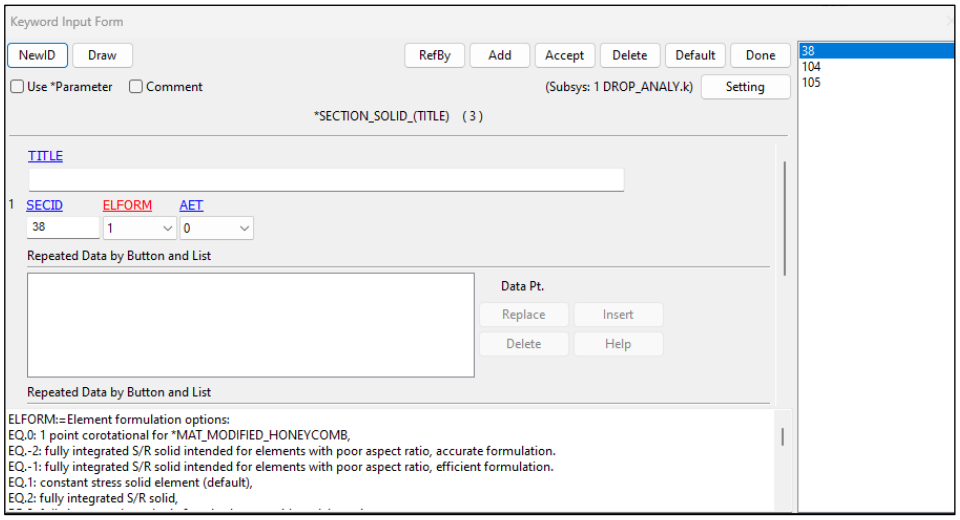


Figure 3.35 FEA model generation element formulation

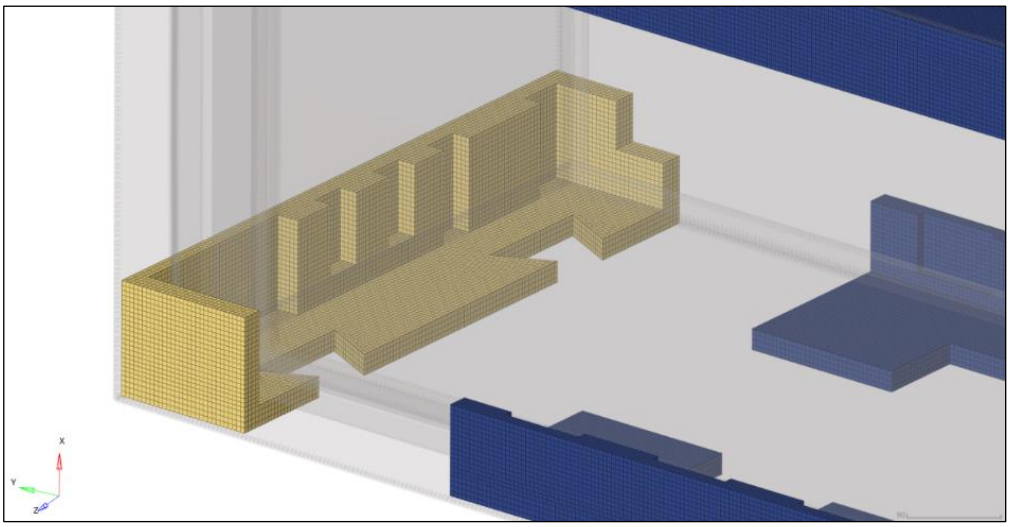


Figure 3.36 FEA model meshed eps components

Additionally, shell elements were defined using the ELFORM 2 formulation, specifically employing the formulation, as indicated by the SECTION_SHELL keyword settings in the simulation input (Belytschko & Tsay, 1984). The formulation is renowned for its computational efficiency and effectiveness in handling large-scale, nonlinear dynamic problems (see Figure 3.37).

This formulation utilizes reduced integration with hourglass control to mitigate numerical issues such as hourglass modes, ensuring accurate results in the simulation of thin-walled structures. Its application in the LS-DYNA environment allows for the accurate modeling of the refrigerator's structural response during the drop test, capturing essential behaviors such as bending, buckling, and complex contact interactions (see Figures 3.38, 3.39, 3.40). The selection of this formulation underscores the importance of choosing appropriate numerical methods to balance accuracy and computational cost in finite element analysis (Belytschko & Tsay, 1984).

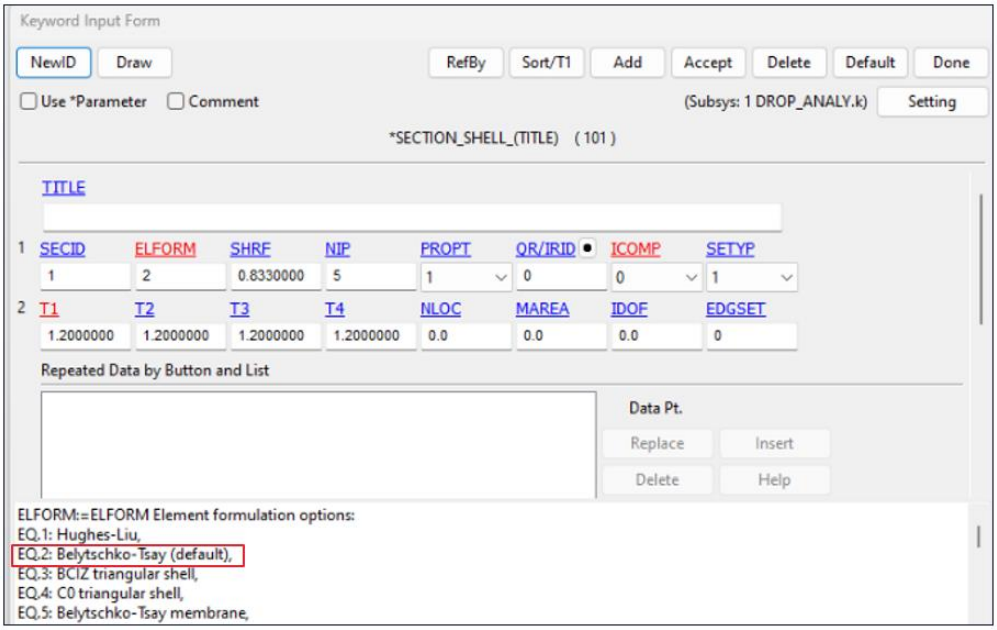


Figure 3.37 FEA model shell elements' formulation setting

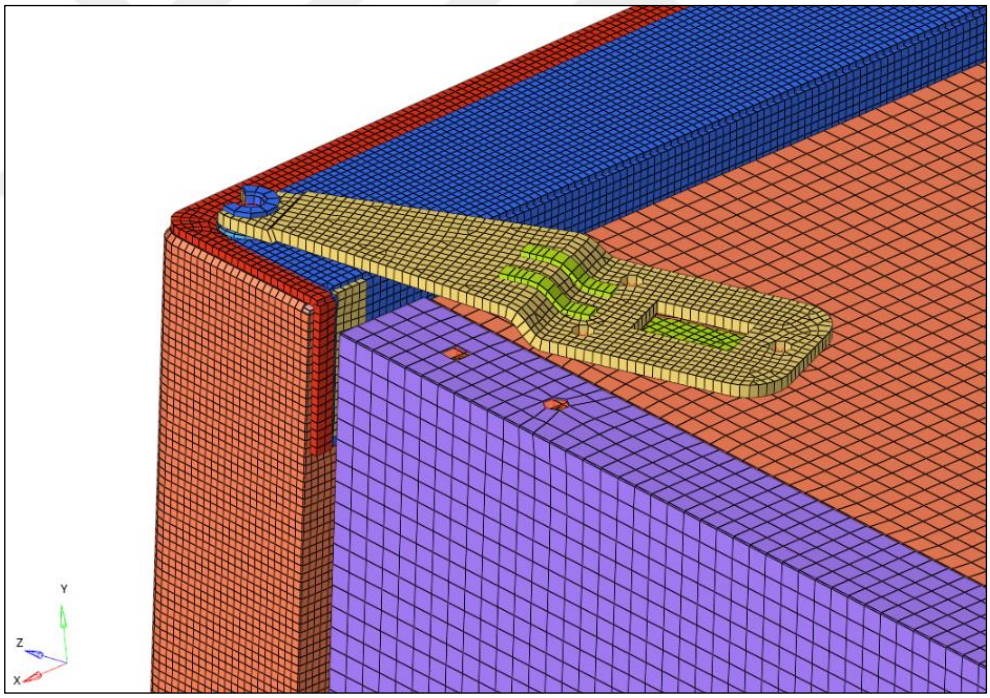


Figure 3.38 Upper hinge meshed model

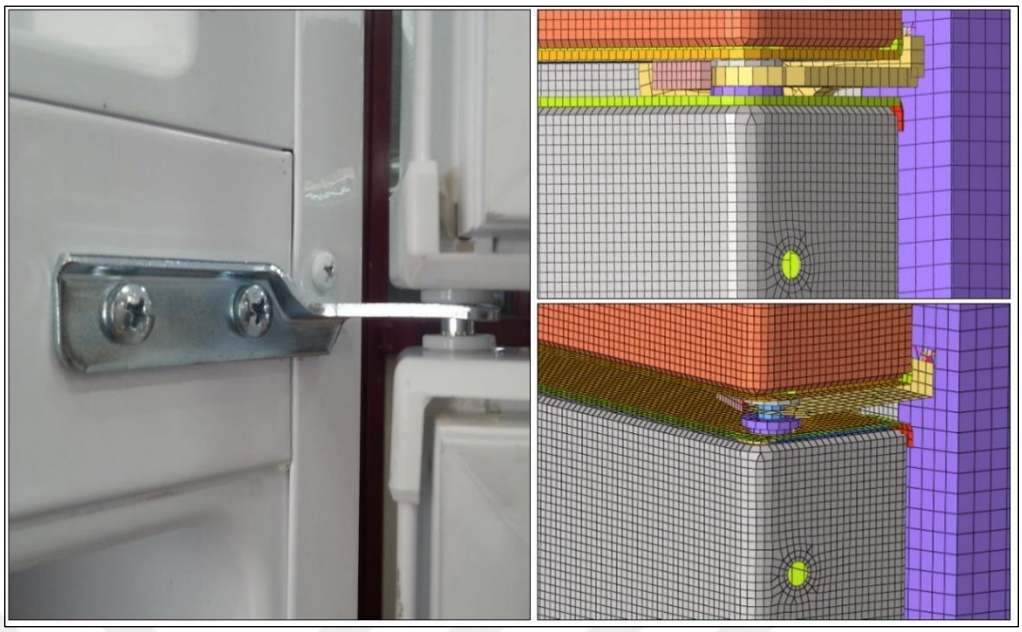


Figure 3.39 Middle hinge meshed model and shell element midplane view

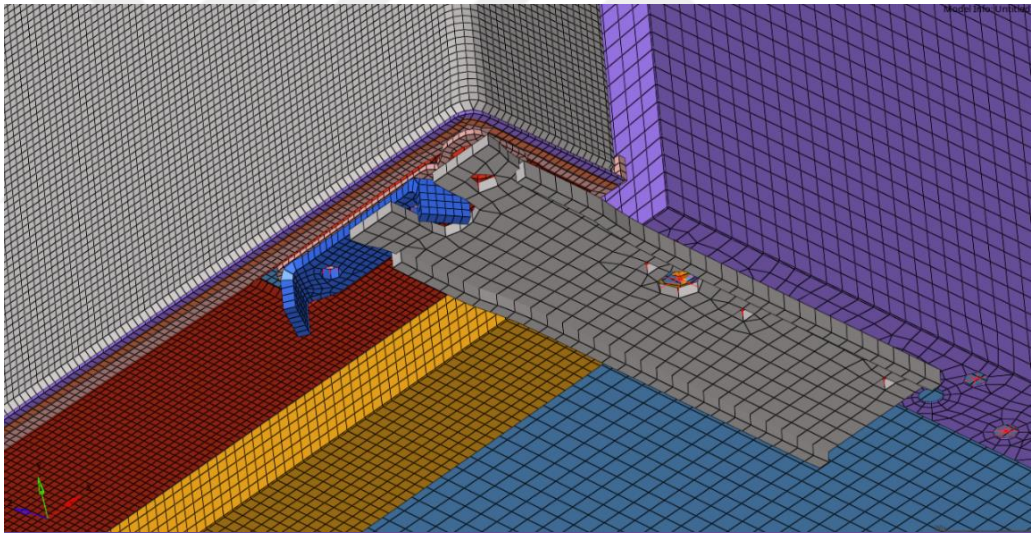


Figure 3.40 Bottom hinge meshed model

This thesis details a step-by-step approach for optimizing a mesh in LS-DYNA to simulate drop impacts on refrigerators. The process starts with crafting an initial mesh based on the refrigerator's geometry and materials, along with its packaging. Through a series of iterations, the mesh is refined, guided by sensitivity analyses and convergence studies, to strike a balance between precision and computational efficiency. The final mesh is then employed in drop impact simulations, with the results compared to experimental data to validate the model's accuracy and reliability.

3.4.5.2 Material Characterization for Drop Impact Analysis

Selecting the materials and sizes is crucial to make sure that the test conditions are realistic and that the samples can endure impact forces without deforming much. The materials chosen to rely on their characteristics, like strength, rigidity and resilience which must align with the products makeup and structure. The size and shape of the samples should mirror those of the product in line with testing guidelines. The thickness is modified according to the stress levels with samples crafted to withstand greater stresses.

Assessing the properties of materials includes evaluating factors, like yield strength, elastic modulus, and density at the stage of model preparation as presented in the Table 3.3. Simulation model tests and real life drop tests are performed under various loading rates to account for how materials respond to different strain rates (Kari, White & Sherwood, 2018).

Furthermore, it is essential to consider factors like the cushioning coefficients of packaging materials to ensure the accuracy of simulations. (Guo, 2012).

Table 3.3 The material properties of the analyzed model

Materials	**Elastic Modulus (MPa)**	**Poisson's Ratio**	**Density (kg/m³)**	**Refrigerator Components**
DC04 EN 10130 (Cold-Rolled Steel)	180000	0.283	7851	Hinge, Reinforcement, Chassis
POM (Polyoxymethylene)	3500	0.499	1410	Hinge connection structures, Panel reinforcement structure
DC01 EN 10130 (Cold-Rolled Steel)	210000	0.300	8000	Sheet metal (0.5mm)
HIPS (High Impact Polystyrene)	1900	0.350	1040	Interior plastic surface structure

ABS (Acrylonitrile Butadiene Styrene)	2890	0.230	12.5	Door caps
PP (Polypropylene)	1400	0.400	1400	Plastic bushing structures
PU (Polyurethane)	2	0.430	27	Insulation walls
EPDM (Ethylene Propylene Diene Monomer)	4826	0.480	860	Door gasket
EPS (Expanded Polystyrene)	22	0.000	20	EPS Absorption foams
PET (Polyethylene Terephthalate)	2.30	0.400	140	Straps
Carton (Corrugated Fiberboard)	2194	0.340	800	Carton box

When conducting the refrigerator drop test simulation, with LS DYNA we utilized material models to depict the behavior of different parts. The finite element model was constructed in HyperMesh 2019 incorporating a combination of mesh elements tailored to each component of the refrigerator. For example, we represented DC04 steel using the MAT_PIECEWISE_LINEAR_PLASTICITY (MAT24) model to showcase its elastic plastic characteristics with properties such as a density of 7.85e 09 kg/mm³ an elastic modulus of 180 GPa a Poisson's ratio of 0.283 a yield stress of 165 MPa and a tangent modulus set at 0.0 for piecewise linear hardening. Additionally other materials like STEEL_MAT1 were modeled using the MAT_ELASTIC approach for behavior while FOAM_MAT63 utilized the MAT_SOIL_AND_FOAM model to replicate foam like material attributes. As for components such as indenters, impactors, projectiles, and fixtures, we employed the MAT_020_RIGID material model (see Figure 3.41).

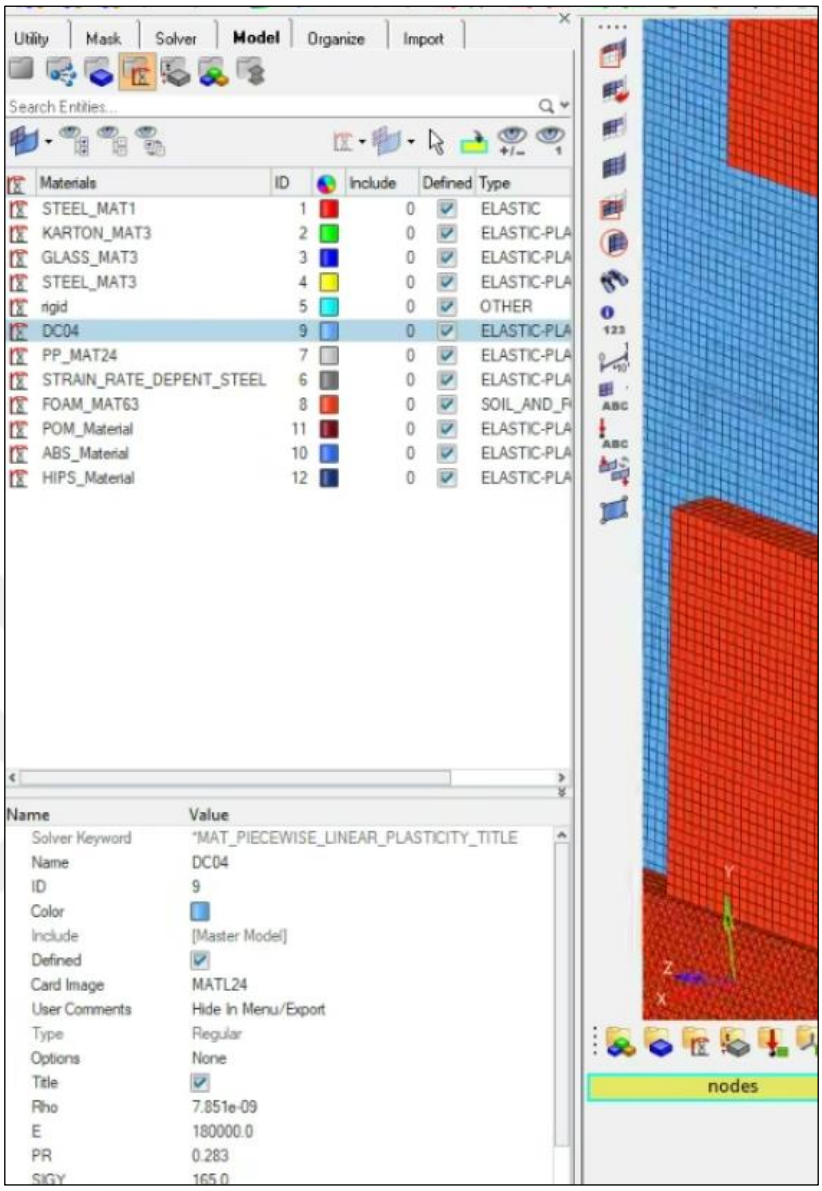


Figure 3.41 Material LS-DYNA keywords

While Johnson and Cook (1983) provide JC material model that approaches considering the impact of strain rate and temperature, we opted for models tailored to simulate the refrigerator drop test in this study. For instance, the MAT_PIECEWISE_LINEAR_PLASTICITY (MAT24) model pretty effective in capturing the elastic plastic behavior of the DC04 steel in the refrigerator without requiring adjustments for strain rate effects. In addition, we utilized the MAT_ELASTIC model for linear elasticity MAT_SOIL_AND_FOAM for foam components and MAT_RIGID for elements such as indenters and fixtures.

To sum up we utilized MAT_PIECEWISE_LINEAR_PLASTICITY, MAT_ELASTIC, MAT_SOIL_AND_FOAM and MAT_RIGID models, within LS DYNA to replicate the refrigerator drop test. However, we did contemplate models such as Cowper Symonds and Johnson Cook due to their ability to handle strain rate and temperature effects the selected models offered a reliable foundation for the study conditions and materials. Subsequent studies could explore incorporating these models to enhance simulation precision further.

3.4.5.3 Connection to Material Models

The choice of material models, like MAT_PIECEWISE_LINEAR_PLASTICITY (MAT24) for DC04 steel and MAT_ELASTIC (MAT01), for steel parts was thoughtfully aligned with the central difference time integration technique applied in the simulation. This pairing guarantees that the simulation faithfully captures the responses of the materials during impact scenarios.

By employing these methods, the simulation was able to offer thorough insights into the behavior of refrigerator components during drop tests. This strategy highlights the significance of combining techniques with precise material models to attain reliable and significant simulation outcomes.

3.4.5.4 Contact and Interaction Definitions

In LS DYNA when defining contact and interactions, it is important to choose contact types that accurately represent how entities interact. For example, components of a refrigerator could exhibit contact behaviors like sliding, sticking, separating, or impacting components or packaging materials. The software offers a range of contact formulations to address interaction scenarios, including surface to surface contact and self-contact, within a deformable body (Hallquist, 2006).

Defining contact and interactions, in drop impact simulations poses a challenge as it involves capturing the response without encountering numerical instabilities. Addressing concerns like interpenetration stress fluctuations and unrealistic force distributions is crucial. The contact algorithm must be both sturdy and effective to guarantee the dependable transfer of momentum and energy, between interacting entities (Wriggers, 2006).

When creating the simulation model, we started by using the AUTOMATIC_SINGLE_SURFACE mode to establish connections within the assembly as shown in the Figure 3.42. Next, we meticulously enhanced the model paying attention to elements like the door linkage system and intricate plastic parts. We also incorporated contact definitions such as TIED_NODES_TO_SURFACE and TIED_SURFACE_TO_SURFACE to guarantee interactions between various components. In order to effectively handle conditions, we implemented 120 constraints across the entire model.

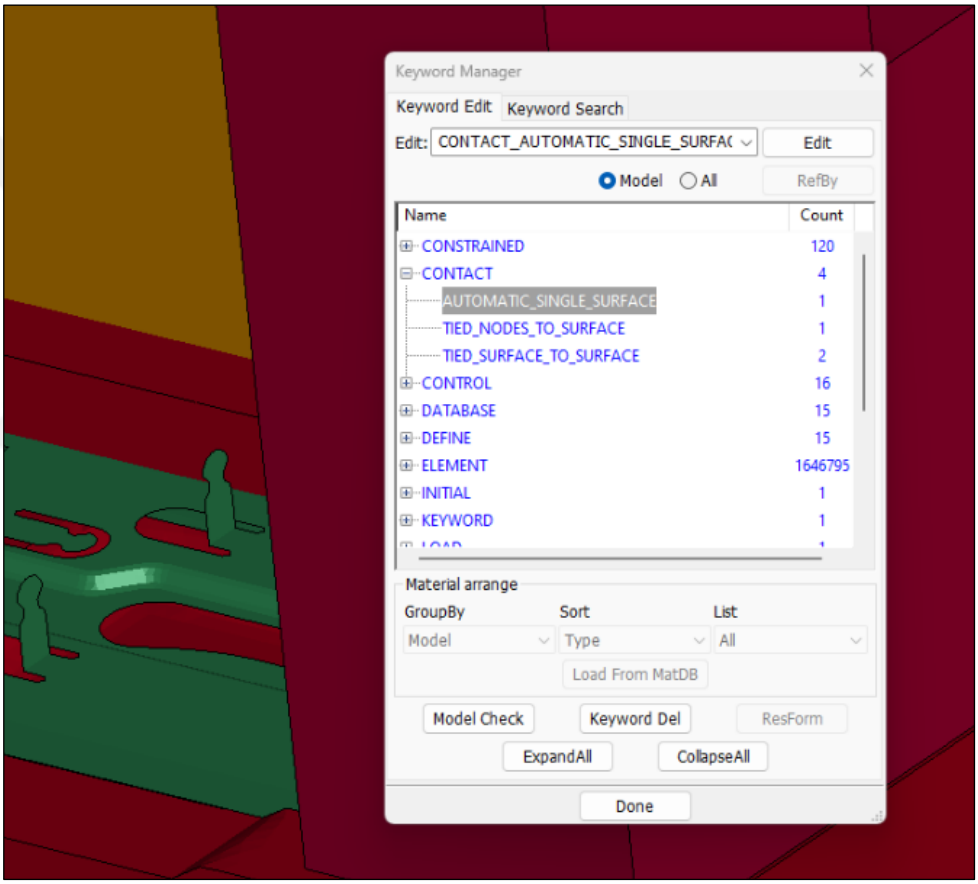


Figure 3.42 Contact and interaction definitions AUTOMATIC_SINGLE_SURFACE selection in simulation

We implemented 120 constraints to handle boundary scenarios. This comprised 119 NODAL_RIGID_BODY limitations, which guaranteed the representation of body actions, at certain points in the simulation. Moreover, we employed one INTERPOLATION term to aid in interpolating nodal movements and forces thereby refining the accuracy of the structural behavior simulation during the drop test. These

restrictions played a role in maintaining the model's precision and dependability in forecasting how the refrigerator would behave under real world impact conditions (see Figure 3.43).

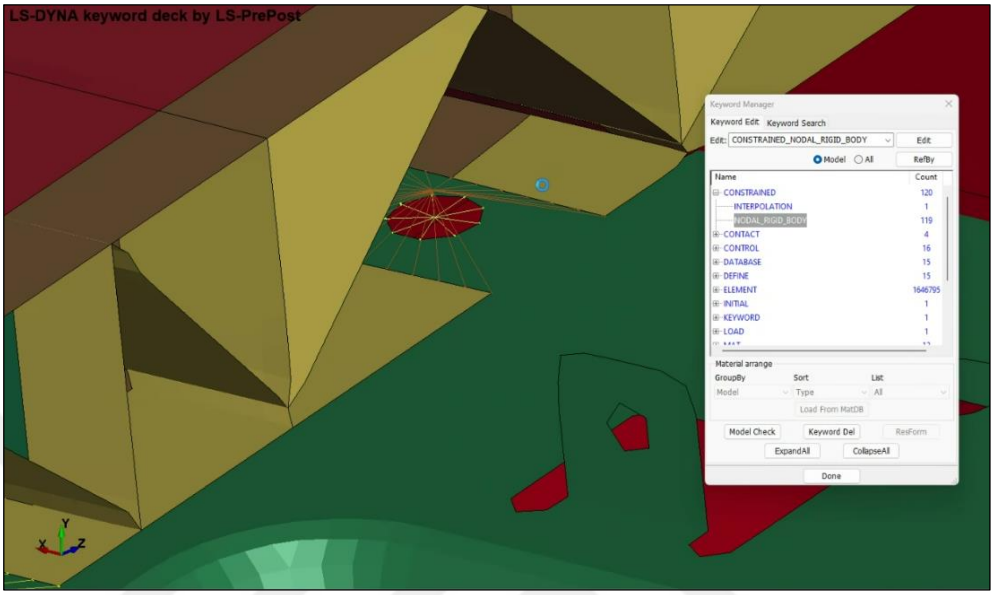


Figure 3.43 Contact and interaction definitions NODAL_RIGID_BODY selection in simulation

3.4.5.5 Simulation Setup and Execution

During the refrigerator drop test the refrigerator is released from a height of 0.25 meters onto the ground. The LS DYNA software automatically computes the impact velocity upon contact with the ground using an equation:

$$Vo = \sqrt{2gh} \tag{3.6}$$

where:

Vo is the impact velocity,

g is the acceleration due to gravity (9.8066 m/s^2)

h is the height from which the refrigerator unit is dropped.

For a drop height of 0.25 meters, the impact velocity is calculated as follows:

$$Vo = \sqrt{2 \times 9.8066\, m/s^2) \times 0.25\, m} \tag{3.7}$$

Substituting the values into the equation:

$$Vo = \sqrt{2 \times 9.8066\, m/s^2) \times 0.25\, m} \tag{3.8}$$

$$Vo = \sqrt{4.9033\, m^2/s^2} \tag{3.9}$$

$$Vo = 2.2147\ m/s \quad (3.10)$$

Therefore, the impact velocity of the refrigerator unit when dropped from a height of 0.25 meters is approximately 2.2147 m/s.

Initial Conditions: The refrigerator unit is positioned at a height of 0.25 meters above a rigid ground surface.

Boundary Conditions: The ground is modeled as a rigid, immovable surface.

Drop Height: 0.25 meters.

Gravity: 9.8066 m/s^2

To simulate gravitational effects accurately in LS-DYNA, the gravitational acceleration must be configured correctly. The standard gravitational acceleration of 9.8066 m/s² is converted to LS-DYNA's units as -9810.000 mm/s² (9.8066 m/s² × 1000 mm/m, rounded for practical use). The setup discrepancies likely due to rounding or unit conversion.

In order to recreate this situation, in the LS DYNA simulation it is important to specify the starting speed and gravitational pull. The below LS DYNA keyword configurations show how this setup is accomplished.

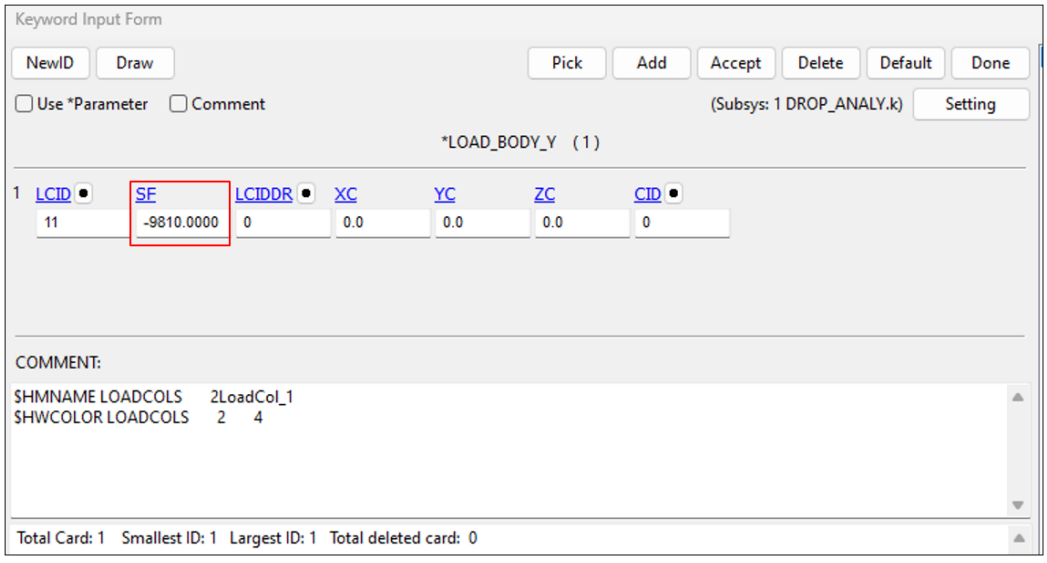


Figure 3.44 Gravity definition shown in the simulation

The gravity that affects the refrigerator unit is determined by using the *LOAD_BODY_Y keyword. Here are the specific parameters that are outlined:

LCID: Load Curve ID for the gravitational force. (11)

SF: Scale Factor for gravitational acceleration.

3.4.5.6 Impact Velocity Calculation

The software calculates the impact velocity based on the free fall from the specified height, resulting in an impact velocity of 2.2150 m/s.

The initial velocity of the refrigerator unit at the moment of impact is set using the *INITIAL_VELOCITY keyword. The relevant parameters are defined as follows:

NSID: Node Set ID for the nodes where the initial velocity is applied. (124)

VY: Initial velocity in the Y-direction (vertical).

Based on the calculated impact velocity, the VY value is set to -2215.000 mm/s as presented in the Figure 3.45 (since LS-DYNA requires the velocity in mm/s)

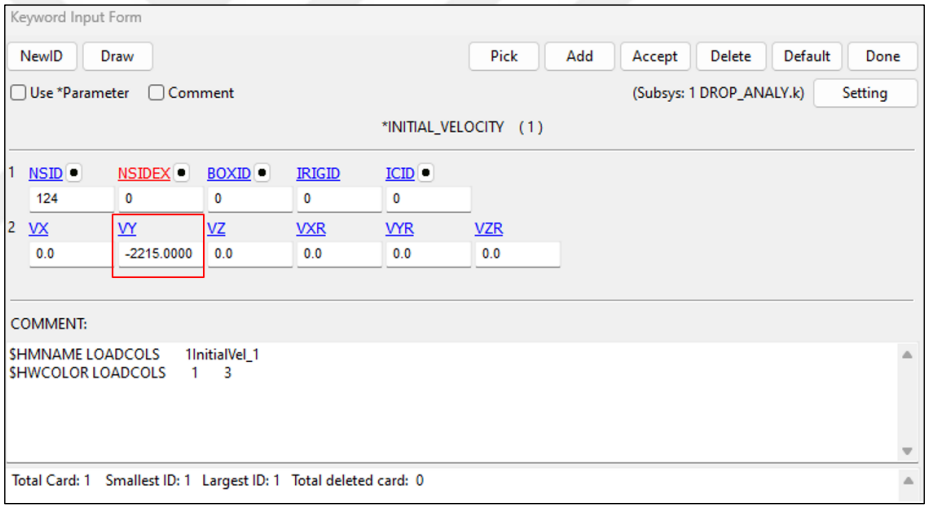


Figure 3.45 FEA simulation drop impact velocity setting

3.4.5.7 Modeling of Compressor Weight

In the LS-DYNA simulation, accurately representing the weight of the compressor is crucial for realistic results. The compressor, being one of the heaviest components in the refrigerator, greatly influences the dynamic behavior during the drop test. To model the compressor weight, we use mass elements. These elements simulate the mass and inertial effects of the compressor without explicitly modeling its geometry.

In the simulation the compressors mass is determined using the *ELEMENT_MASS keyword. This method provides a precise way to depict how

weight is distributed and its influence on the response when it falls for the selected refrigerator’s drop impact condition.

The compressors' mass elements are positioned at points in the element model that align with the compressors' placement at the back side of the refrigerator at the bottom. The overall weight of the compressor, which is 9.2 kg, is spread out among these points to accurately depict the center of mass and inertial characteristics (see Figure 3.46, 3.47). This allocation is vital for capturing the reaction during impact.



Figure 3.46 Compressor position in refrigerator

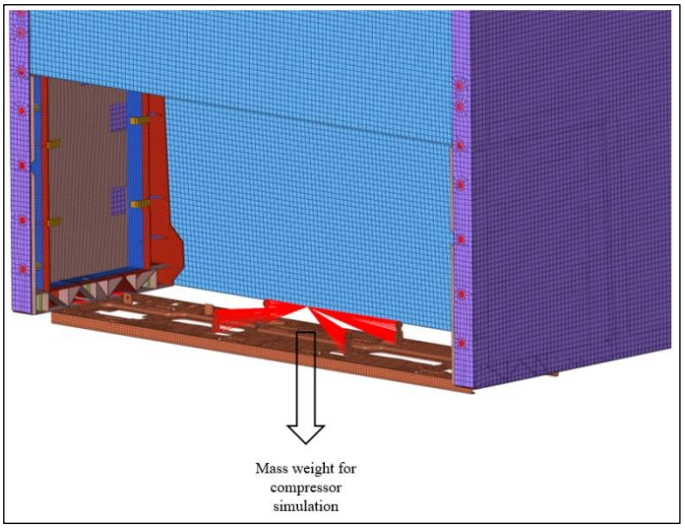


Figure 3.47 Compressor weight in simulation

By describing the mass components, in this manner the simulation can precisely consider the gravitational and inertial forces applied by the compressor. This method is essential to guarantee that the outcomes of the drop test genuinely mirror the actions

of the refrigerator encompassing both impact forces and stress patterns that arise as a result.

3.4.5.8 Modeling of the Packaging Strap

In this study, the simulation models two straps as beam elements, each with a torque value of 2.5 N·m, based on internal experiments for refrigerator packaging (see Figure 3.48). Therefore, PET material properties are not included in the drop test simulation software.

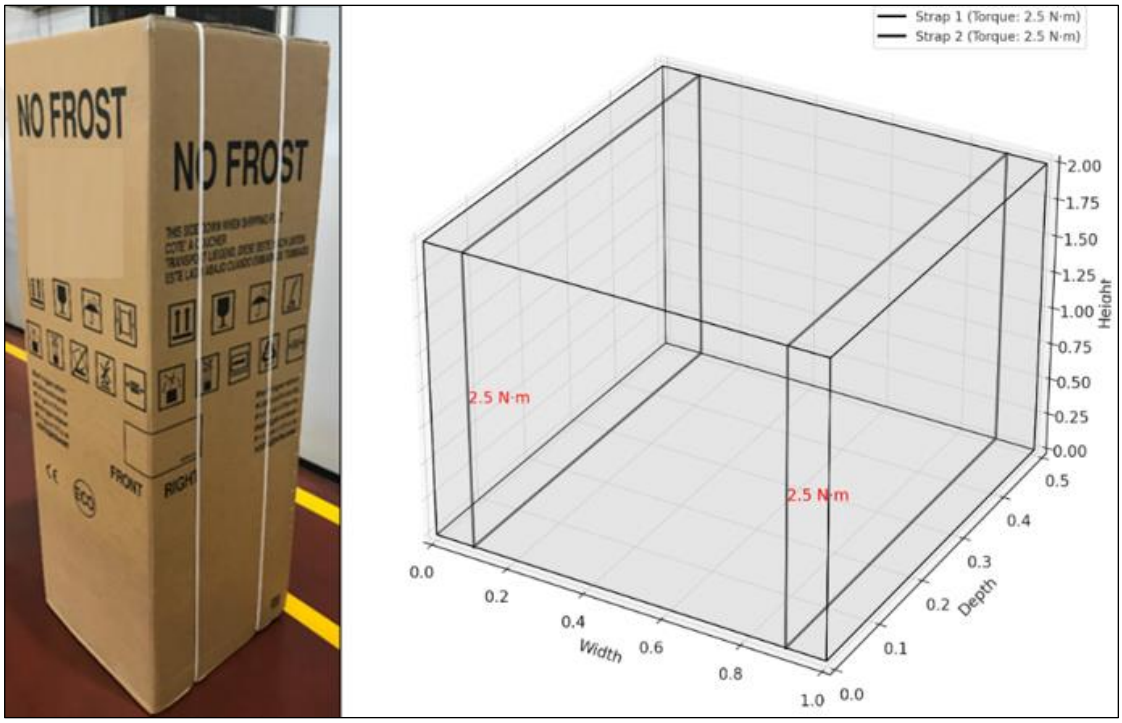


Figure 3.48 FEA strap modeling representation with beam load, 2.5 N·m torque

3.4.5.9 Computational Resources and Output Management

In this research, Massively Parallel Processing (MPP) and the explicit method were employed to enhance the efficiency and capabilities of simulations, for drop impact tests. The explicit method, known for its time stepping approach is well suited for capturing events and high impact scenarios. Nevertheless, conducting these simulations, with models and precise time increments demands computational resources.

MPP addresses these needs by distributing the tasks among processors. By employing Central Processing Unit (CPU) types in an MPP setup tasks can be divided for processing enabling simultaneous handling of different segments of the model and multiple time intervals (see Figure 3.49). This parallel approach greatly accelerates simulations. Enables the handling of extensive models and intricate impact scenarios that would pose difficulties, on a single processor. In this research, a 32-core processor computer was used for FEA analysis, significantly enhancing the efficiency and speed of the simulations.

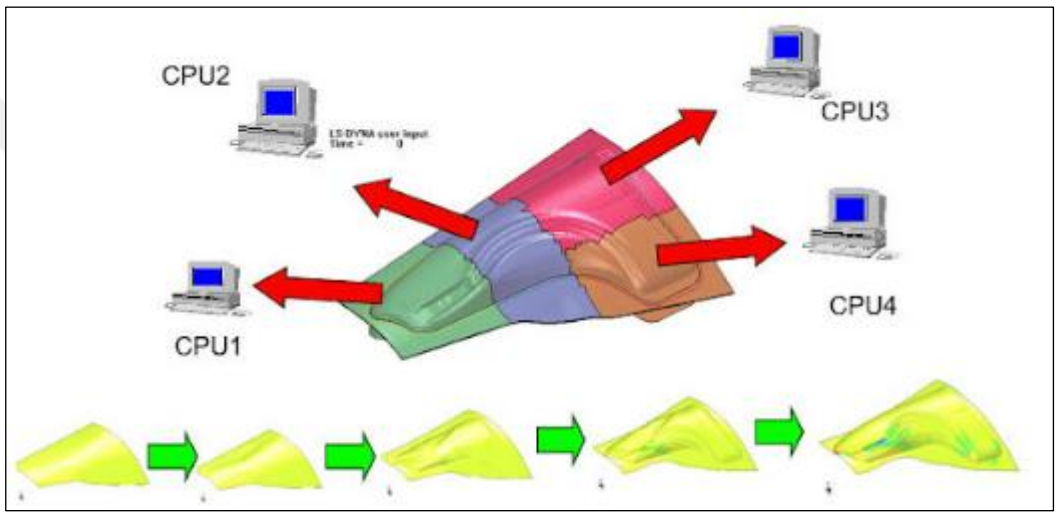


Figure 3.49 MPP working methodology example (Simware, 2017)

To improve performance and effectively handle resources in LS DYNA simulations we utilized the precision edition of LS Prepost R13. This particular version is crafted to leverage LS DYNAs Massively Parallel Processing abilities by spreading out tasks across various processors thereby reducing the time taken for computations.

Additionally, to streamline file handling and reduce overhead, we utilized the "MPP_IO_BINOUTONLY" keyword. This setting limits output to binary format only, which helps minimize the size of the output files and speeds up the writing process. As a result, post-processing and data analysis were much quicker, ensuring that we could handle the large datasets generated during the simulations efficiently.

To make file management more efficient and reduce work we made use of the "MPP_IO_BINOUTONLY" keyword as shown in the Figure 3.50. By using this setting, we restricted the output to format, which reduced the size of output files and

accelerated the writing process. This led to processing and data analysis allowing us to effectively manage the large datasets produced during the simulations.

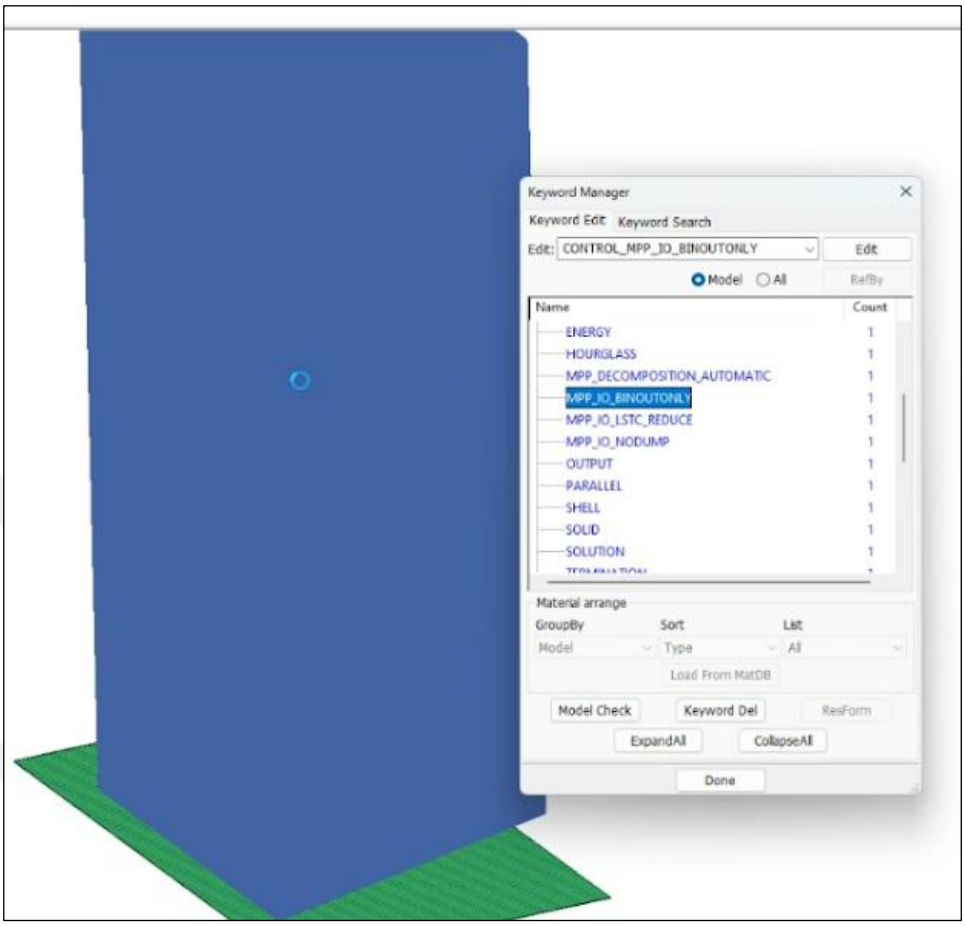


Figure 3.50 FEA Drop simulation computational setting “MPP_IO_BINOUTONLY’’ keyword

To sum up, integrating MPP with the approach and adjusting parameters such as formatting can greatly enhance the effectiveness and usability of dynamic simulations in engineering. This does not only boost the efficiency of simulations. Also facilitates in-depth analysis and precise adjustment of outcomes. Once these settings are implemented a new simulation will be conducted to validate the revised model and enhance the results further. The upcoming section will elaborate on this simulation procedure examining the specifics and outcomes of these enhancements (see Figure 3.51, 3.52).

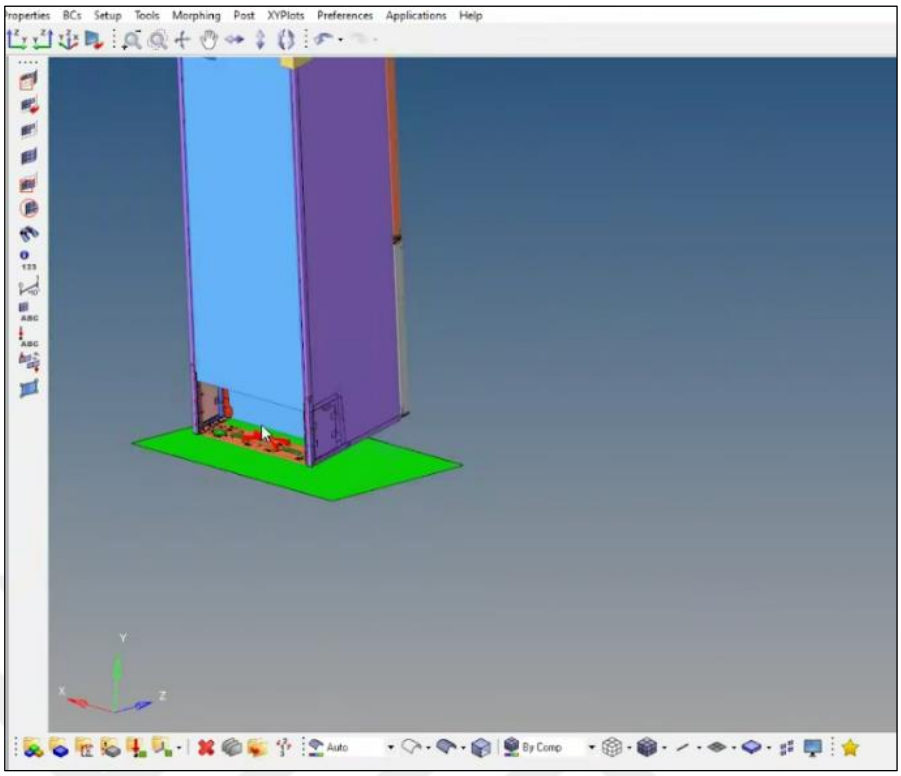


Figure 3.51 Improved design final FEA model and drop condition

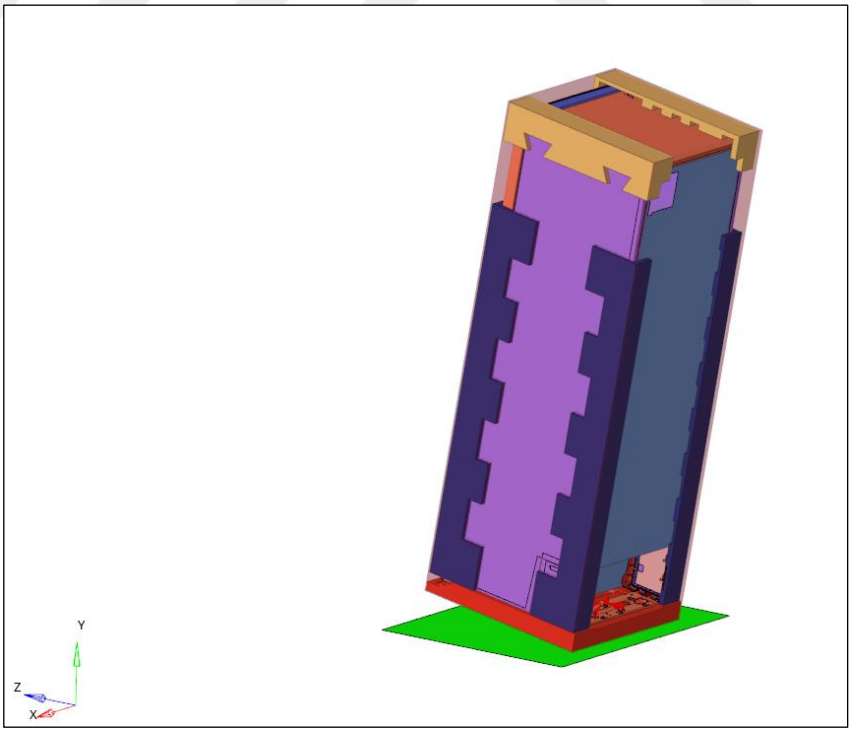


Figure 3.52 Improved design final FEA model and drop condition with EPS components

CHAPTER FOUR
RESULTS

4.1 Baseline Design FEA Results

The von Mises stress analysis of the refrigerator assembly highlights several areas of concern. The highest stress $\Sigma_v{}^{max}$, reaching 354.74 MPa is located at the back of the compressor suggesting it may be susceptible to impact forces. The chassis area shows stress levels between 283.80 and 319.27 MPa indicating it experiences loads during impacts. Moreover, σ_v stress values ranging from 248.32 to 283.80 MPa are detected at the hinge locations prompting concerns about the door's strength and operational effectiveness (see Figure 4.1).

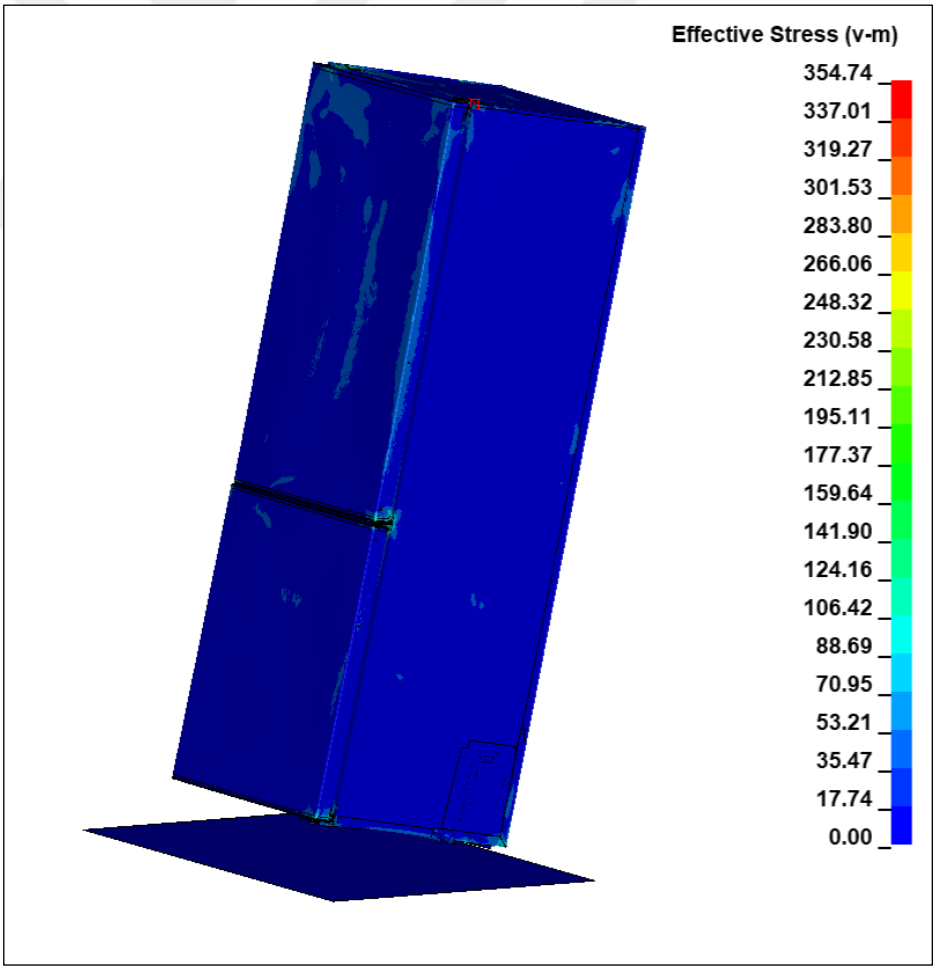


Figure 4.1 Baseline design assembly model Von Mises stress results

While the stress levels in the zones stay within ranges (17.74 to 88.69 MPa) these σ_v have an impact on the door functions. The simulated drop test, created to mimic real life scenarios shows stresses at the hinges, which are crucial for the door functionality. This connection between the simulation outcomes and real-world performance highlights the need to address these stress points to guarantee that the refrigerator unit remains reliable during impact situations.

The plastic deformation findings provide insight into regions where the material has undergone lasting changes, from impact pressures. The significant plastic strains occur mainly in the compressor section and surrounding the pivot points which are key areas of intense stress.

In the compressor section, the plastic strain ϵ_p findings show deformation with strains, in the zones ranging from 0.12 to 0.21 with ϵ_p^{max} values reaching up to 0. 27 (see Figure 4.2). This suggests a requirement for design enhancements to enhance durability such levels of deformation could affect the functionality and performance of the refrigerator door emphasizing the necessity for design upgrades in these areas.

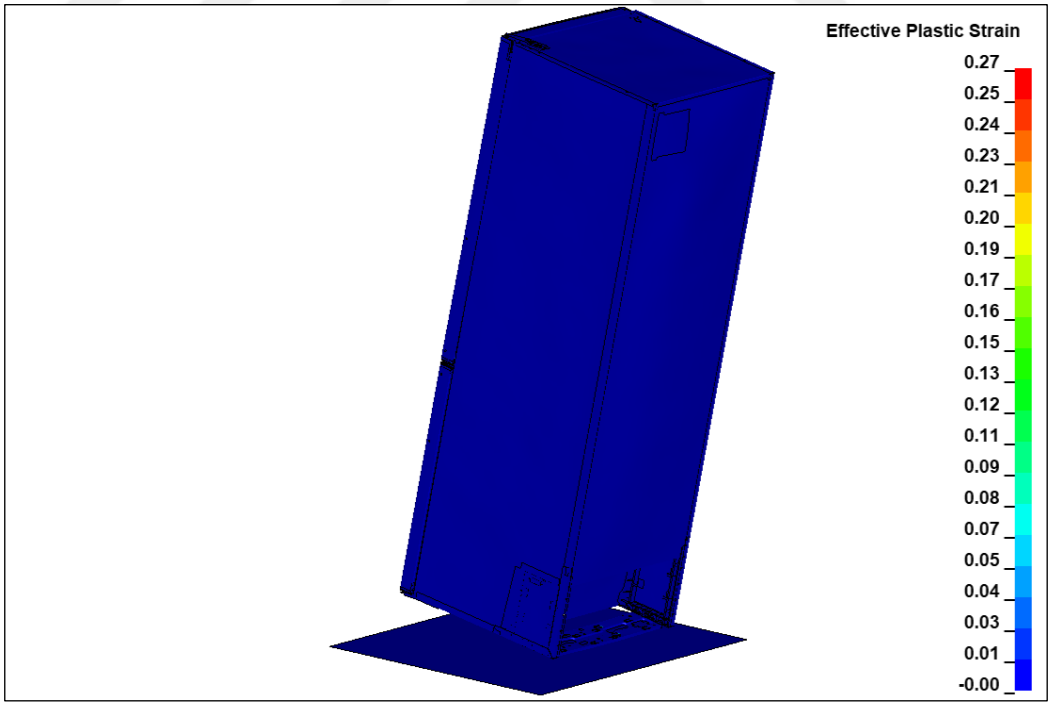


Figure 4.2 Baseline design assembly model plastic strain results

During the stress analysis of the refrigerator assembly, it was found that there are stress concentrations, near the hinges at the fastening parts and junctions as shown in

the Figure 4.3. The von Mises stress (effective stress) and maximum principal stress assessments show that these specific areas experience the most impact forces.

For the top hinge, σ_v^{top} values peak at 303.71 MPa, with maximum principal stress σ_{max}^{top} reaching around 207.71 MPa. The middle hinge shows σ_v^{middle} up to 267.35 MPa and σ_{max}^{middle} of approximately 192.67 MPa. The bottom hinge, however, experiences the highest stress concentrations, with σ_v^{bottom} values reaching 343.19 MPa and σ_{max}^{bottom} of 222.18 MPa (see Figure 4.3).

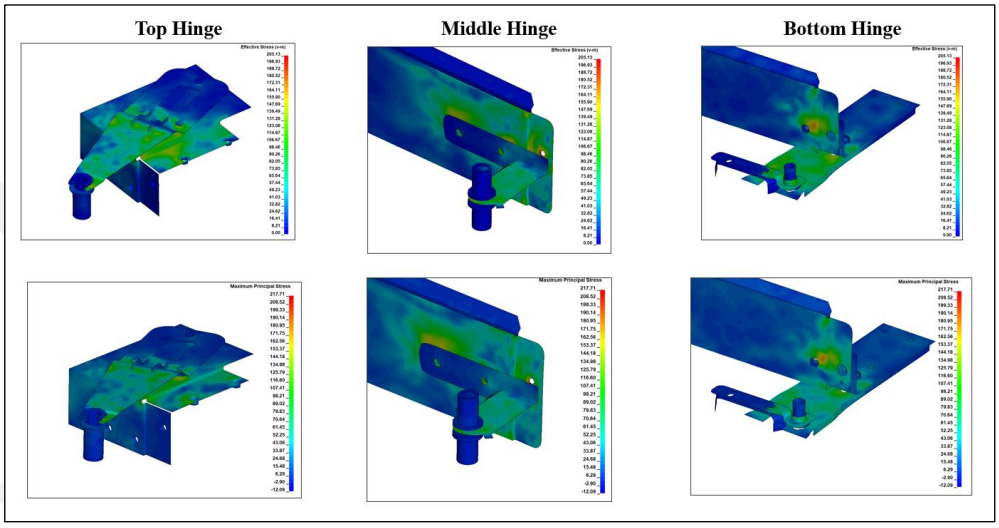


Figure 4.3 Baseline design door hinges Von Mises stress results

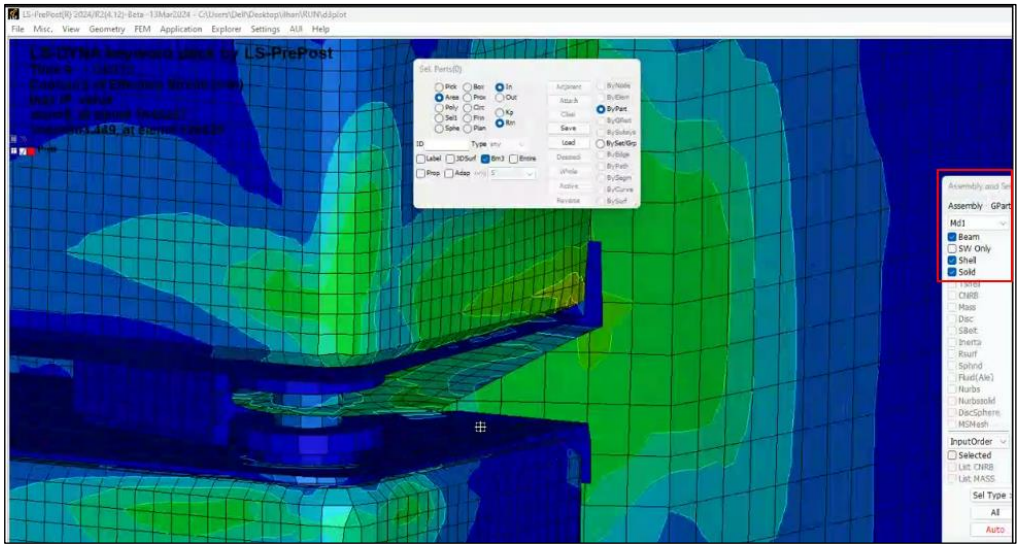


Figure 4.4 Middle hinge shell model stress dissipation

The different levels of stress shown emphasize how various forces are distributed during impacts. Even though the stress levels are high they are not intense, to the point of causing movement or harm to the hinge system that could impact the doors' placement or how well it works. Despite facing stress, the hinges stay strong structurally and continue to work properly.

The examination of stress in the expanded polystyrene (EPS) component indicates that significant stress points are found at the edges aligning with the conditions simulated during drop testing. This stress distribution is largely attributed to the structure of the refrigerator and how the compressors' weight and proximity to the EPS region impact it. The corners bear the brunt of impact forces intensified by both the weight and positioning of the compressor (see Figure 4.5).

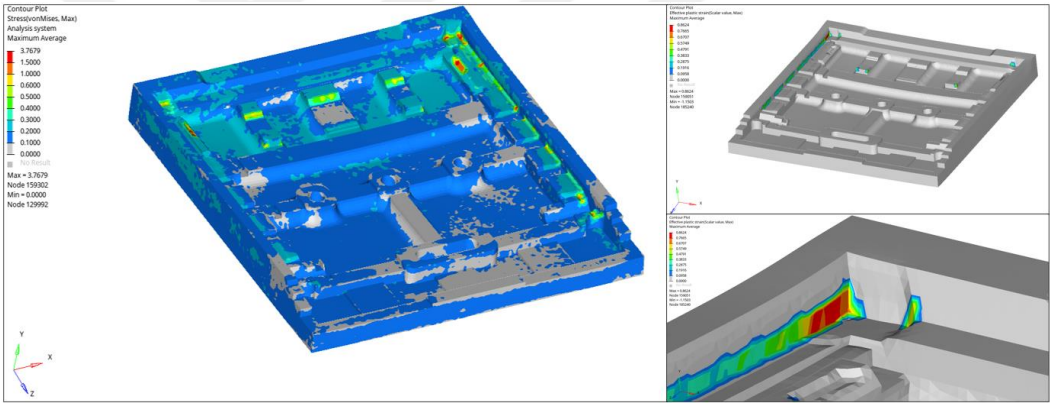


Figure 4.5 Bottom Styrofoam von mises stress and strain examination results

Based on these discoveries the plan is to enhance the areas that are most impacted. Specifically, we will work on improving the corners of the product and the lower EPS component. These changes aim to tackle the stress points identified, ultimately boosting the hinge assembly's ability to withstand impacts and its overall longevity.

4.1.1 Baseline Design FEA Simulation Door Distance Measurements

The door distance data was gathered from ten points as mentioned before. This group consists of eight measurements, for distances between the door and the body and two for distances, between doors as specified in the Figure 4.6. Every

measurement was thoroughly examined to pinpoint the maximum distance values at these spots.

The theoretical default distance for all points is set at 12 mm. Graphical representations of these measurements highlight deviations from this default value. Negative values indicate that the components are positioned closer together, while positive values show that they are positioned further apart (see Figure 4.7, 4.8, 4.9, 4.10, 4.11, 4.12, 4.13, 4.14, 4.15, 4.16).

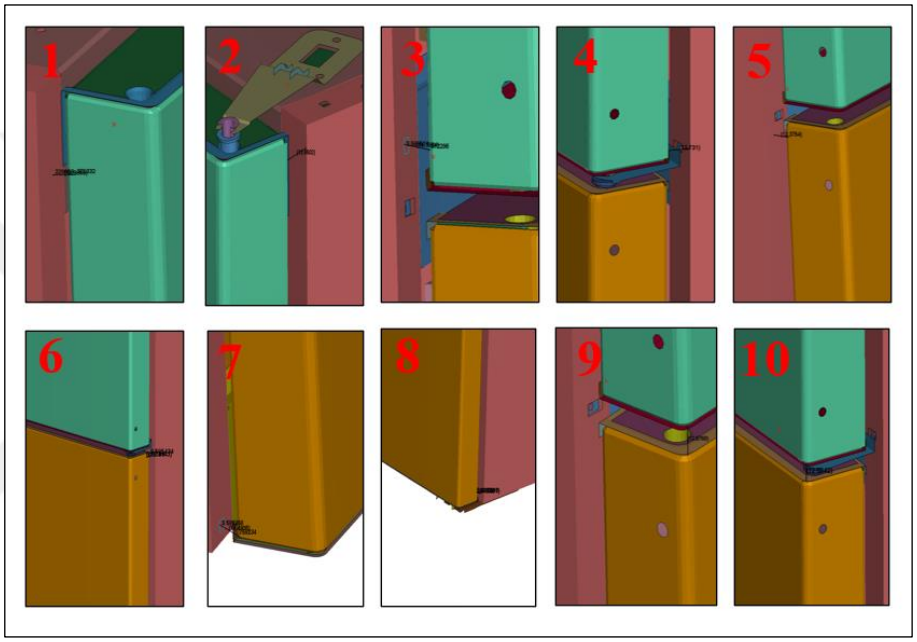


Figure 4.6 FEA model door distance measurement points

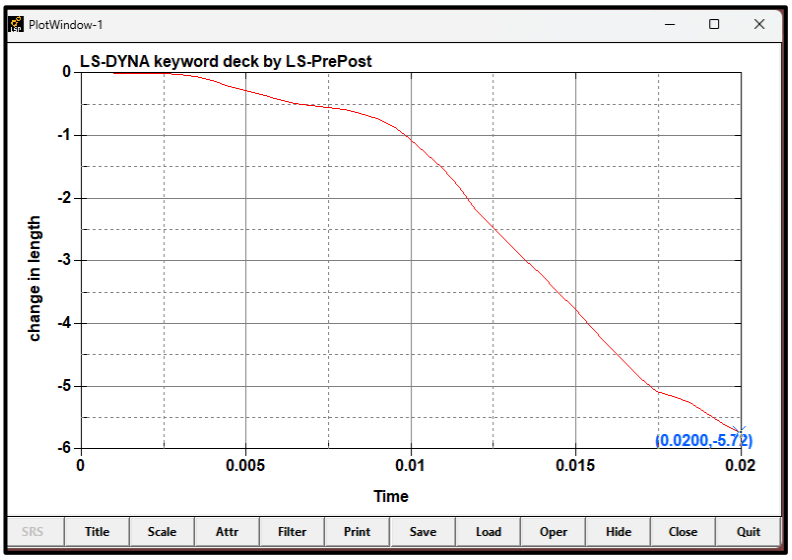


Figure 4.7 Baseline design FEA simulation point 1 change in length at contact duration

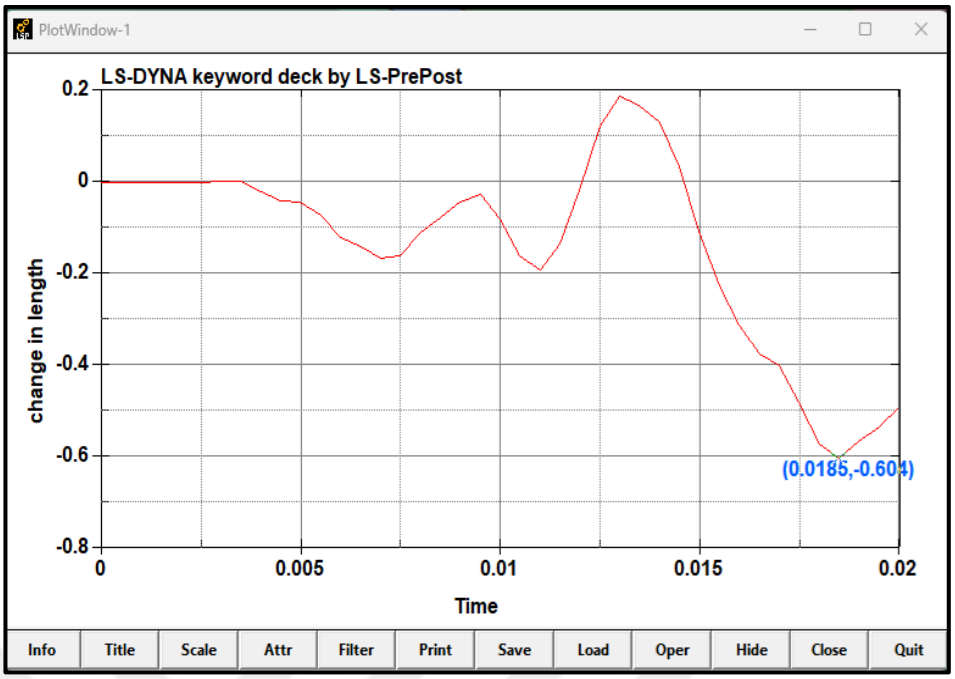


Figure 4.8 Baseline design FEA simulation point 2 change in length at contact duration

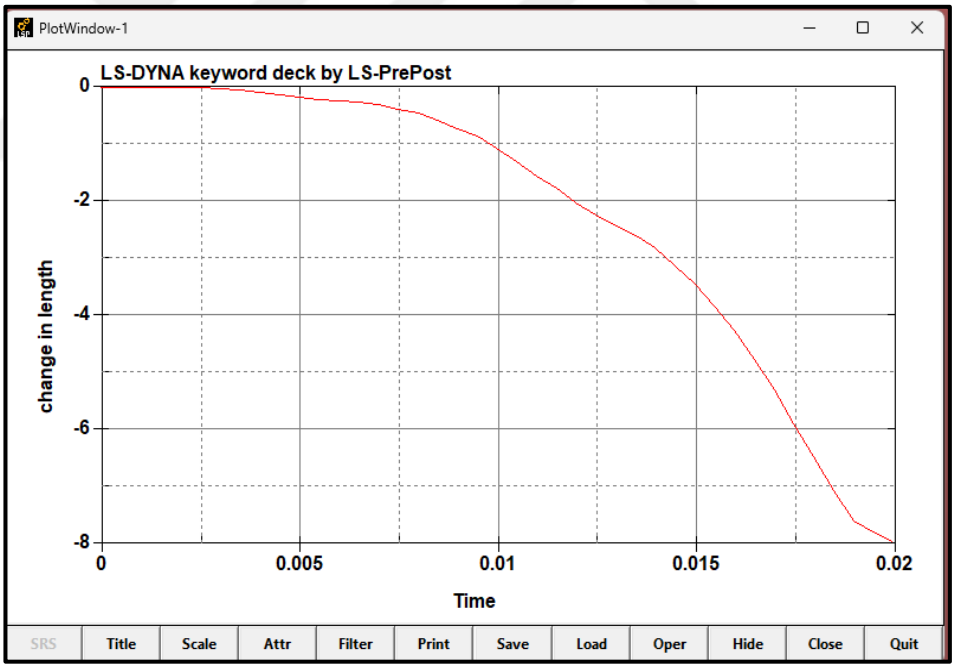


Figure 4.9 Baseline design FEA simulation point 3 change in length at contact duration

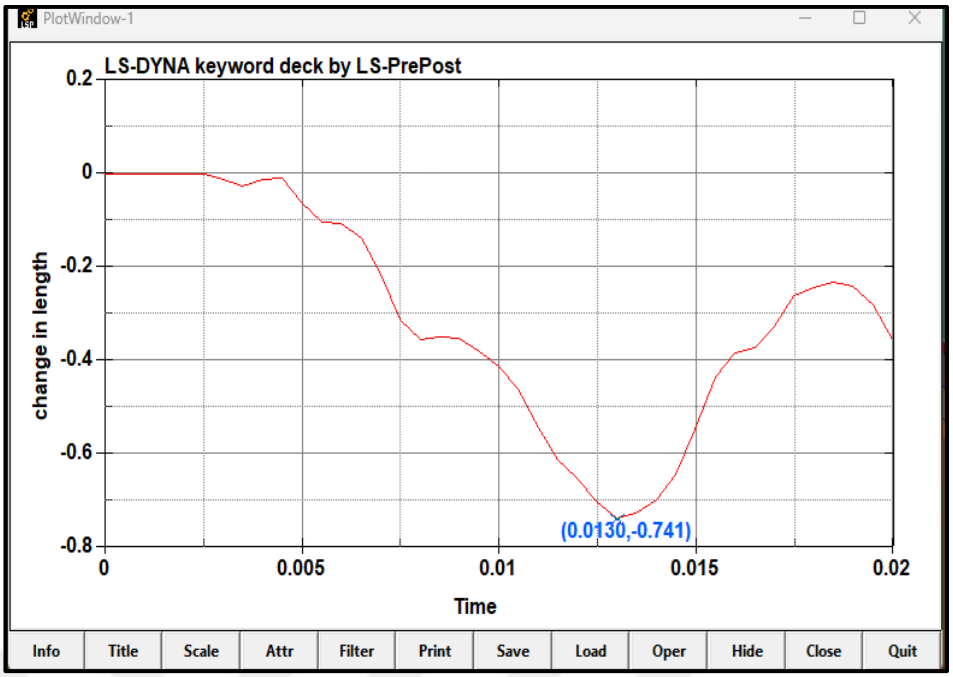


Figure 4.10 Baseline design FEA simulation point 4 change in length at contact duration

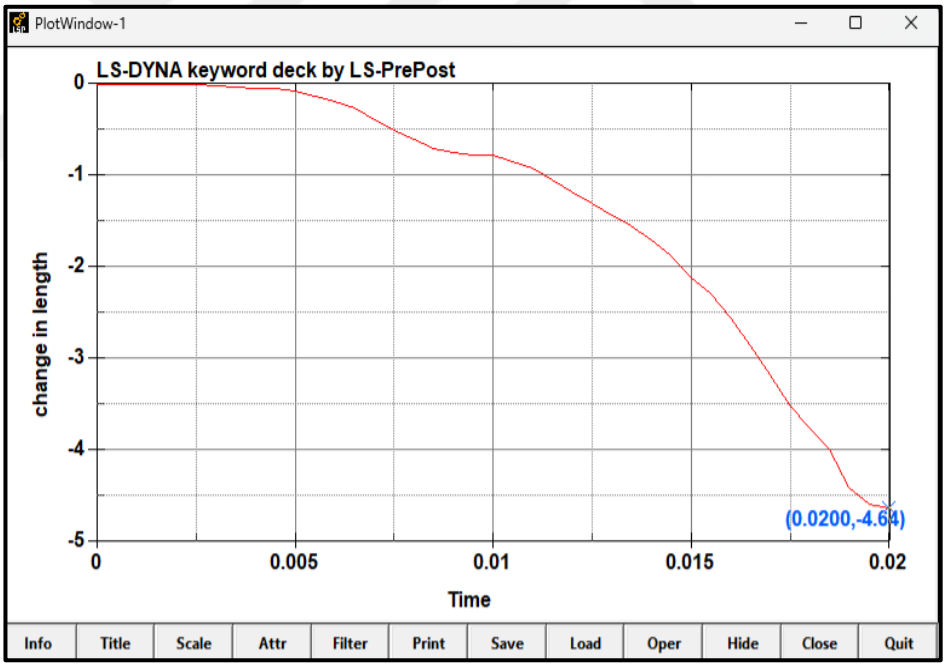


Figure 4.11 Baseline design FEA simulation point 5 change in length at contact duration

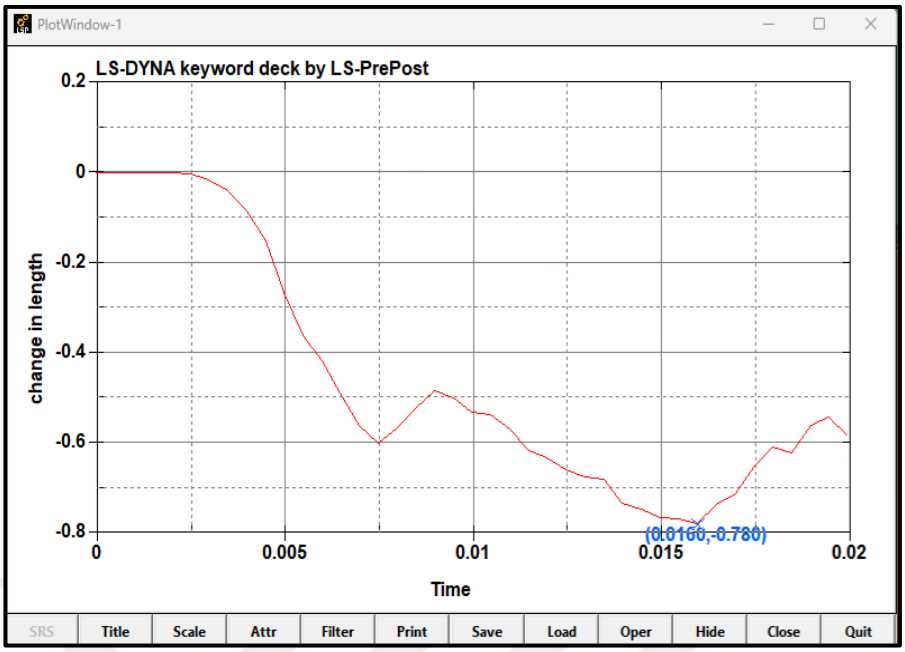


Figure 4.12 Baseline design FEA simulation point 6 change in length at contact duration

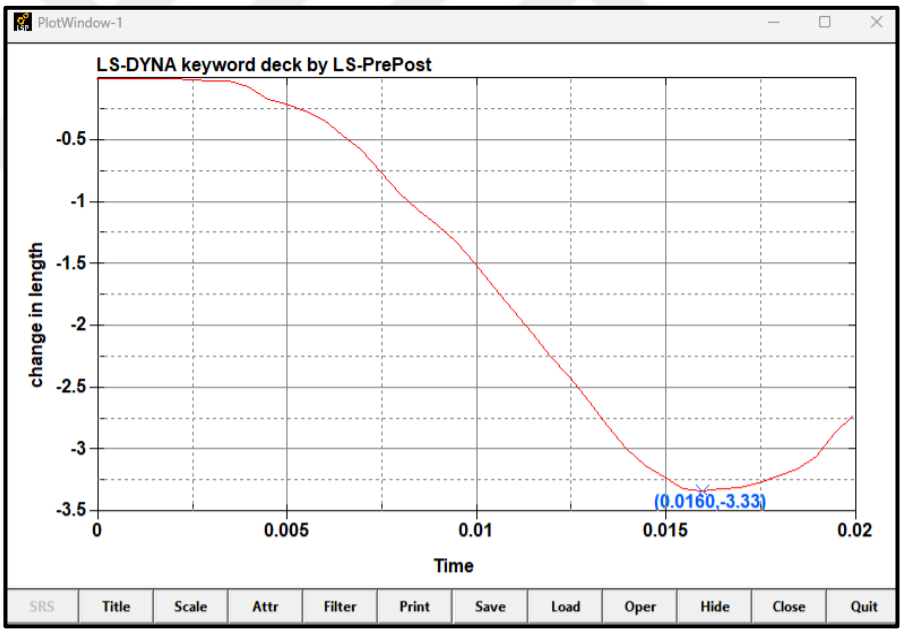


Figure 4.13 Baseline design FEA simulation point 7 change in length at contact duration

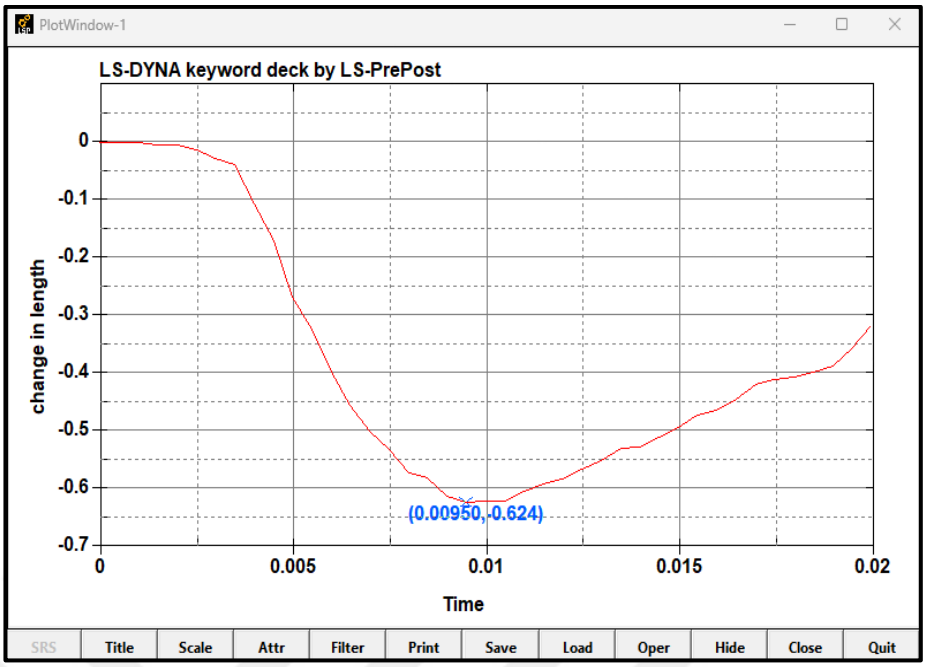


Figure 4.14 Baseline design FEA simulation point 8 change in length at contact duration

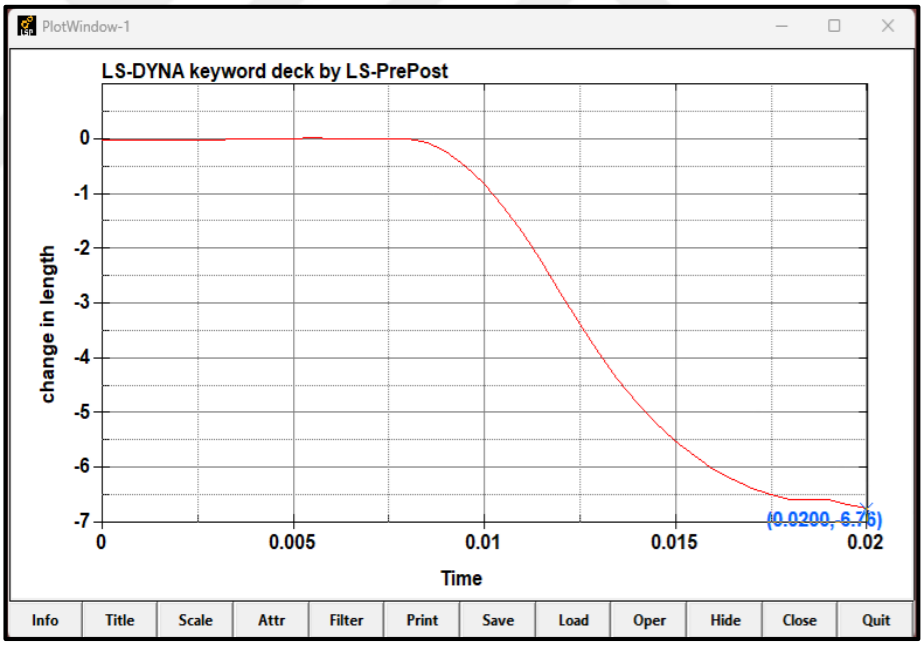


Figure 4.15 Baseline design FEA simulation point 9 change in length at contact duration

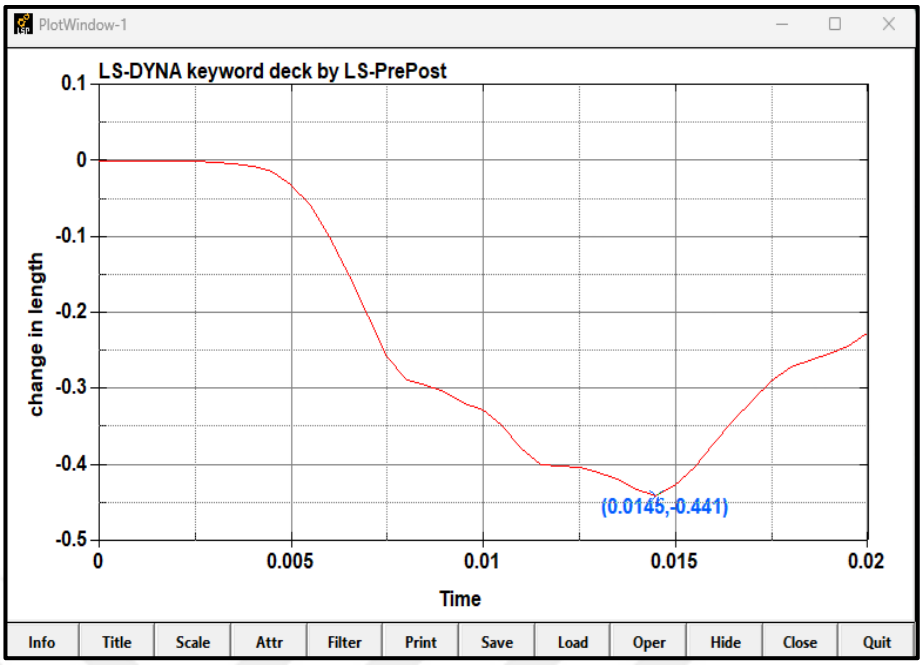


Figure 4.16 Baseline design FEA simulation point 10 change in length at contact duration

The graphics also depict the motion and variations in door distances throughout the drop impact simulation of the product. These visualizations reveal how the distances between the door and body, as well as between the doors, change during the impact event. This detailed representation offers valuable insights into the dynamic behavior of the components under the simulated drop conditions.

The visual representations of the FEA findings also depict the shifting and adjustments, indoor distances during the impact simulation of product drops. The visual data demonstrates the evolution of gaps between doors and between doors and the body as the impact scenario unfolds in drop tests. This intricate portrayal provides conclusions about how components react under simulated drop conditions.

4.2 Implementation and Validation of Design Improvements

At the stage of this research, we worked on creating and running a finite element analysis (FEA) model of the product. These FEA simulations played a role in evaluating how the product performs when subjected to drop impacts pinpointing areas that required enhancements. Using these insights, we implemented design improvements as needed.

The design changes mainly targeted two aspects. Initially enhancements were implemented in the compressor section to strengthen its structure. This modification was intended to increase the compressors' ability to withstand impact forces by improving its rigidity and durability ultimately reducing the likelihood of failure in case of impacts. Subsequently, adjustments were carried out on the expanded polystyrene (EPS) component. These changes aimed to enhance the EPSs capacity to absorb and distribute impact energy thereby enhancing the products resistance to impacts (see Figures 4.17 and 4.18).

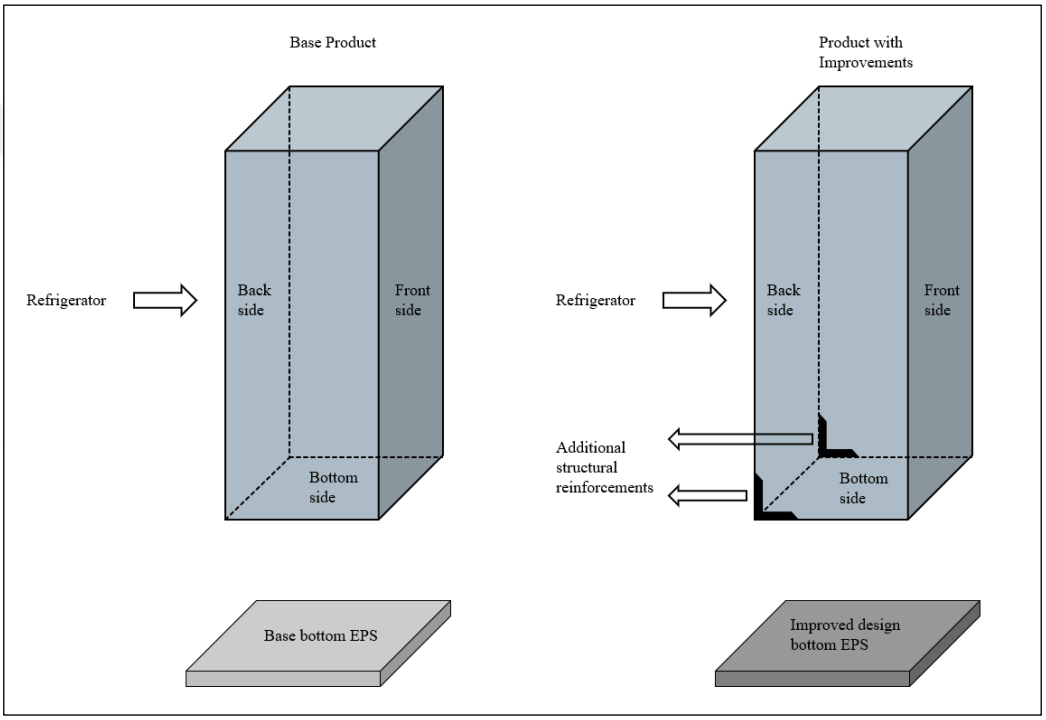


Figure 4.17 Design improvements

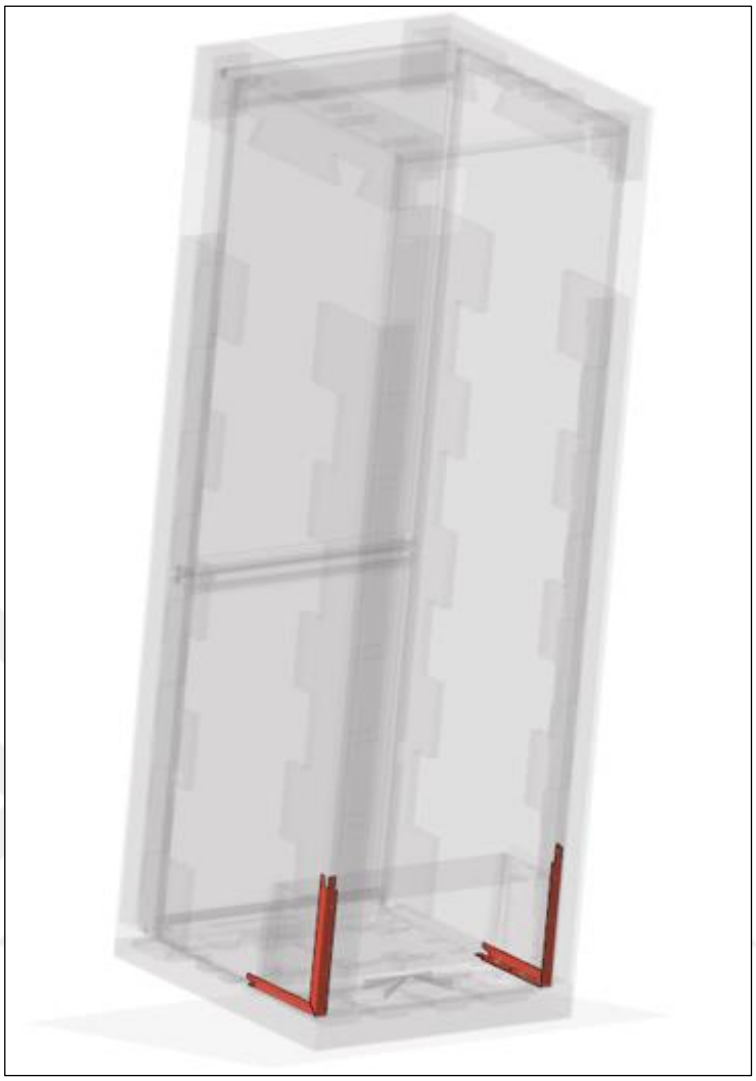


Figure 4.18 Design improved model: reinforcement added view

After making the design enhancements, the new design was incorporated into an element analysis (FEA) model as shown in Figure 4.19. This updated model, which included the reinforcements in the compressor section and changes to the expanded polystyrene (EPS) component underwent a series of new FEA simulations. These simulations were conducted to assess how the design performed under drop impact conditions. The objective was to ascertain if the design alterations effectively increased impact resistance and to gauge the effectiveness of these improvements.

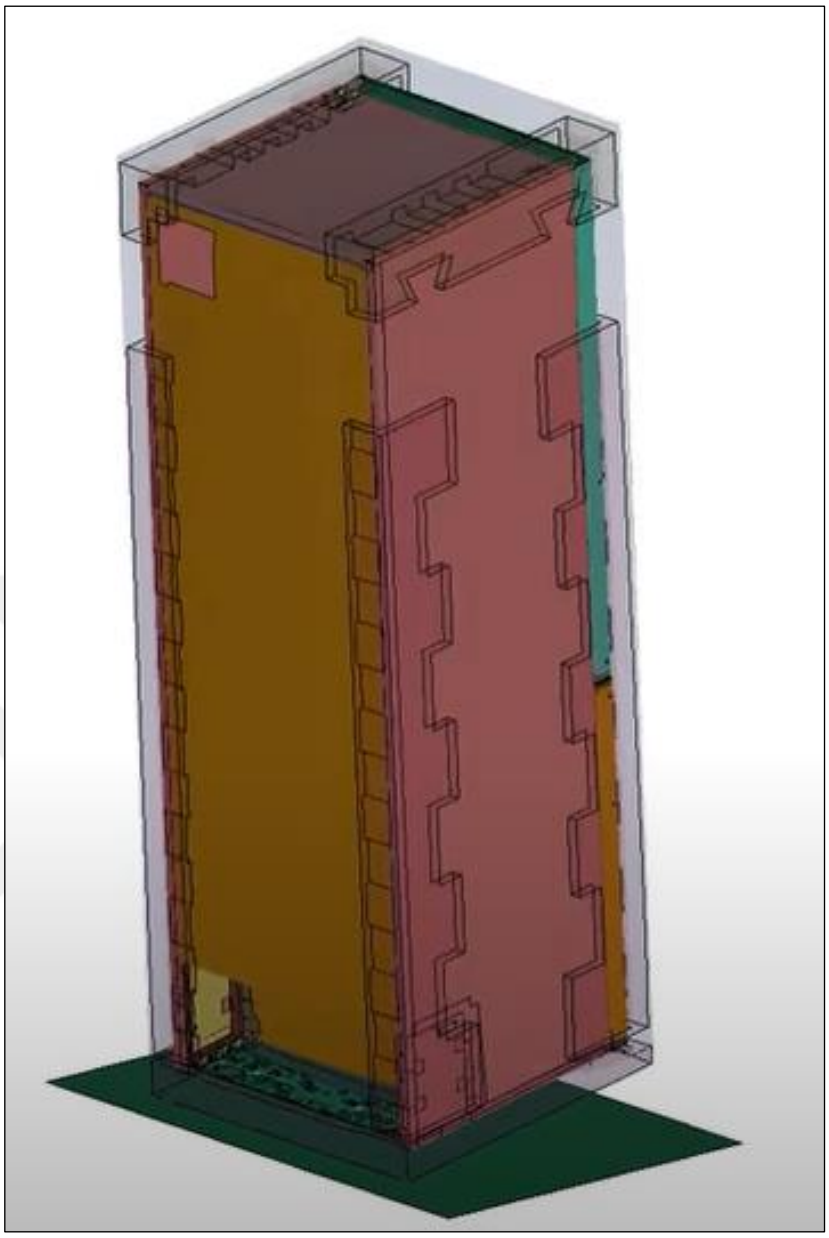


Figure 4.19 Final FEA model and simulation

4.3 Post-Improved Design FEA Results

The post-improvement finite element analysis (FEA) of the refrigerator model indicates a significant reduction in effective stress levels. The highest von Mises stress recorded is 349.53 MPa, primarily concentrated in the lower regions near the compressor. This stress concentration suggests that the compressor area remains a critical point susceptible to impact forces.

The σv values in the upper areas of the refrigerator are notably lower, varying between 0 to 265.64 MPa. This suggests that the design changes have successfully

shifted the stress away from zones. Particularly the green regions indicate stress levels ranging from 0 to 83.89 MPa showcasing areas, within thresholds and underscoring the effectiveness of the design enhancements that were put in place (see Figure 4.20).

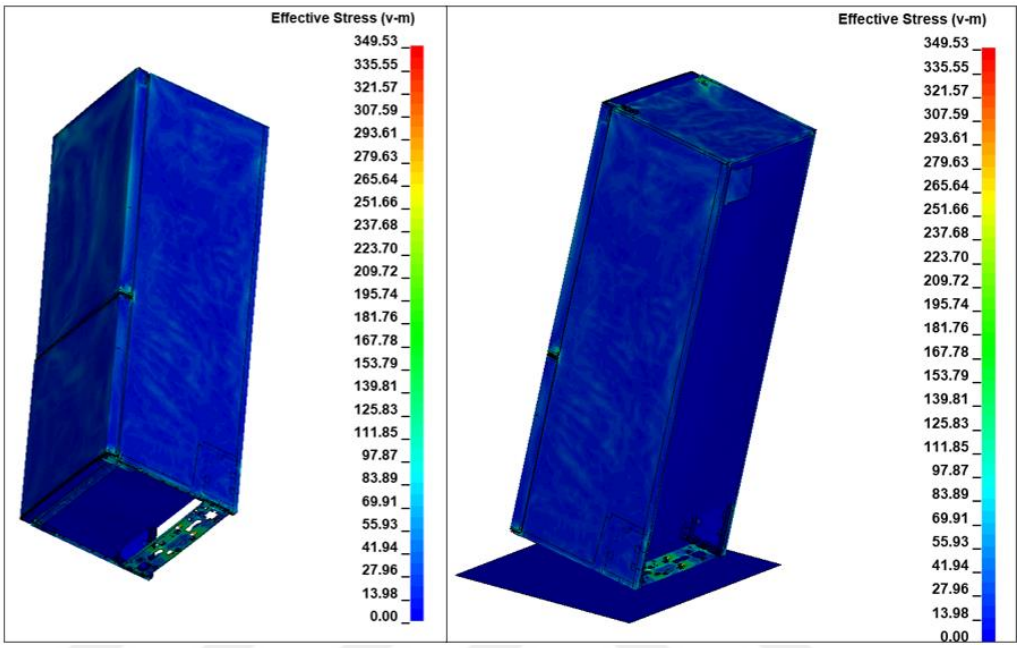


Figure 4.20 Post-improvement Von Mises stress results

The reduced stress concentrations in previously identified critical areas imply that the design enhancements have mitigated high-stress regions, thereby improving the structural performance of the refrigerator under impact conditions. This overall reduction in effective stress signifies an increase in the robustness and impact resistance of the product.

The FEA results for effective plastic strain reveal regions where the refrigerator has undergone permanent deformation due to impact forces. The highest plastic strain values ϵ_p^{max}, peaking at 0.26, are located near the compressor area. These areas are critical points of stress concentration and require targeted design improvements.

In the compressor section, there are plastic deformations with areas showing strains ranging from 0.12, to 0.20. This indicates that the material in these zones has undergone shaping requiring strengthening for improved longevity (see Figure 4.21).

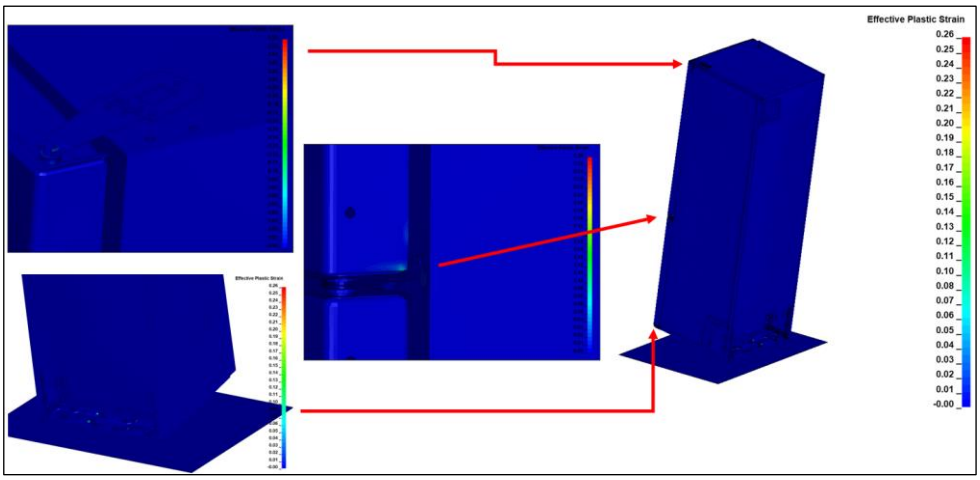


Figure 4.21 Post-improvement plastic strain results

The door distance measurements were taken at the same ten points as before, including eight for door-to-body distances and two for door-to-door distances. (see Figure 4.22, 4.23, 4.24, 4.25, 4.26, 4.27, 4.28, 4.29, 4.30, 4.31).

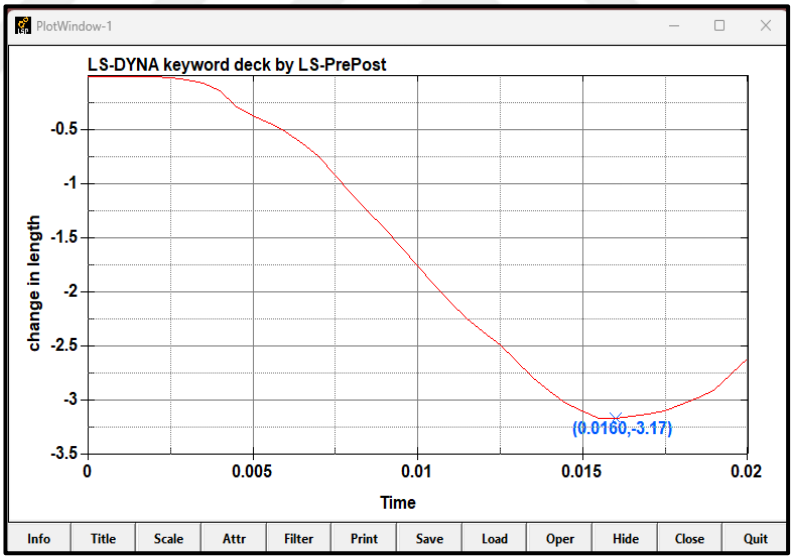


Figure 4.22 Post-improvement design FEA simulation point 1 change in length at contact duration

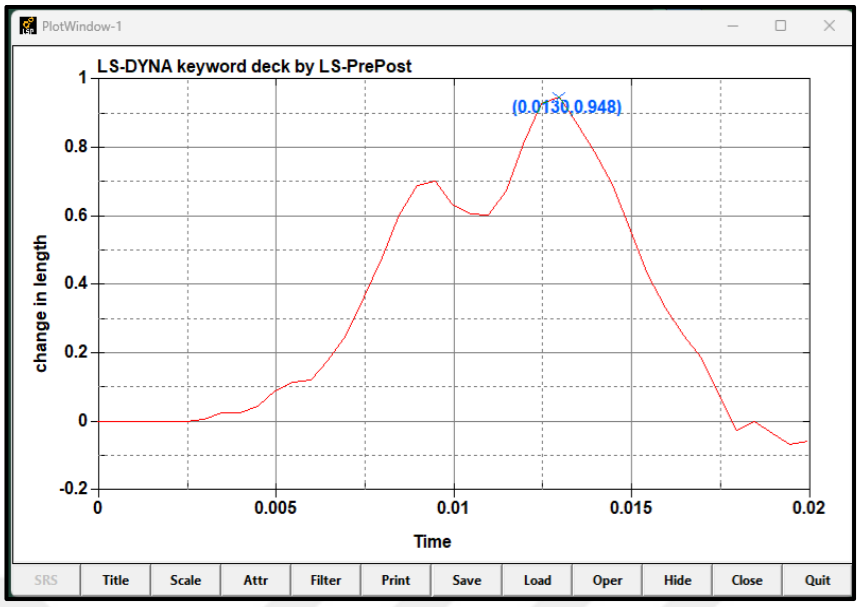


Figure 4.23 Post-improvement design FEA simulation point 2 change in length at contact duration

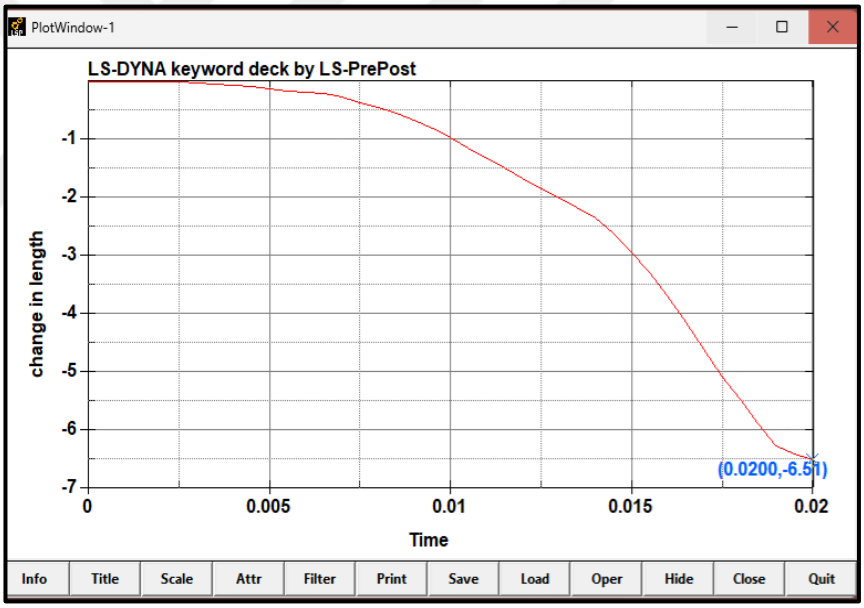


Figure 4.24 Post-improvement design FEA simulation point 3 change in length at contact duration

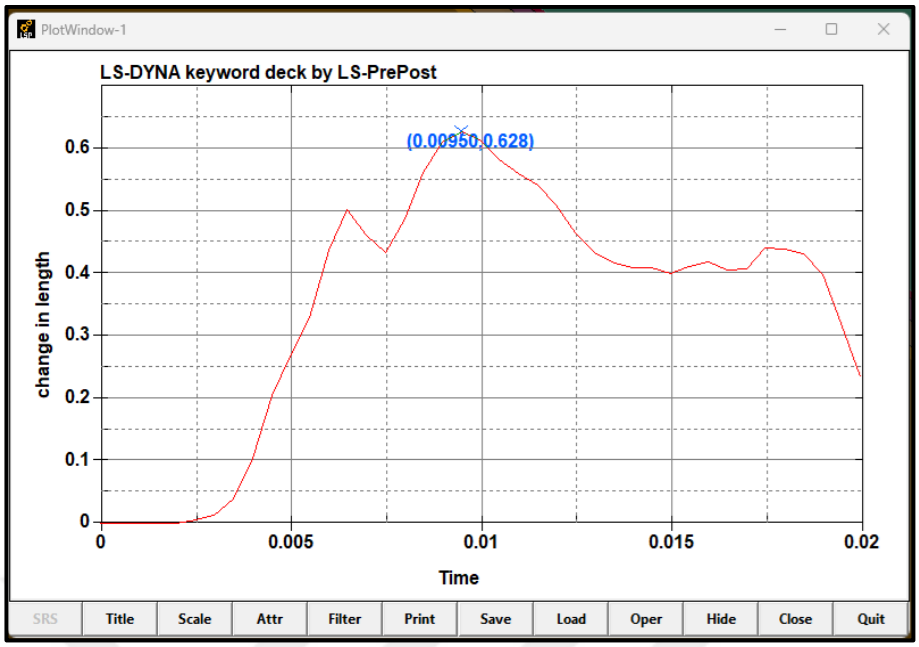


Figure 4.25 Post-improvement design FEA simulation point 4 change in length at contact duration

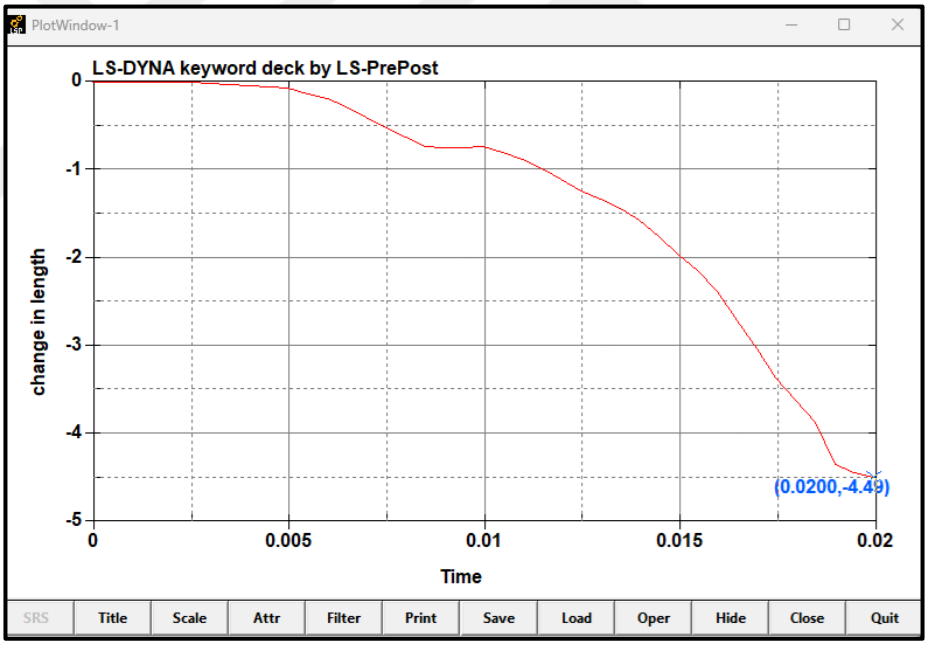


Figure 4.26 Post-improvement design FEA simulation point 5 change in length at contact duration

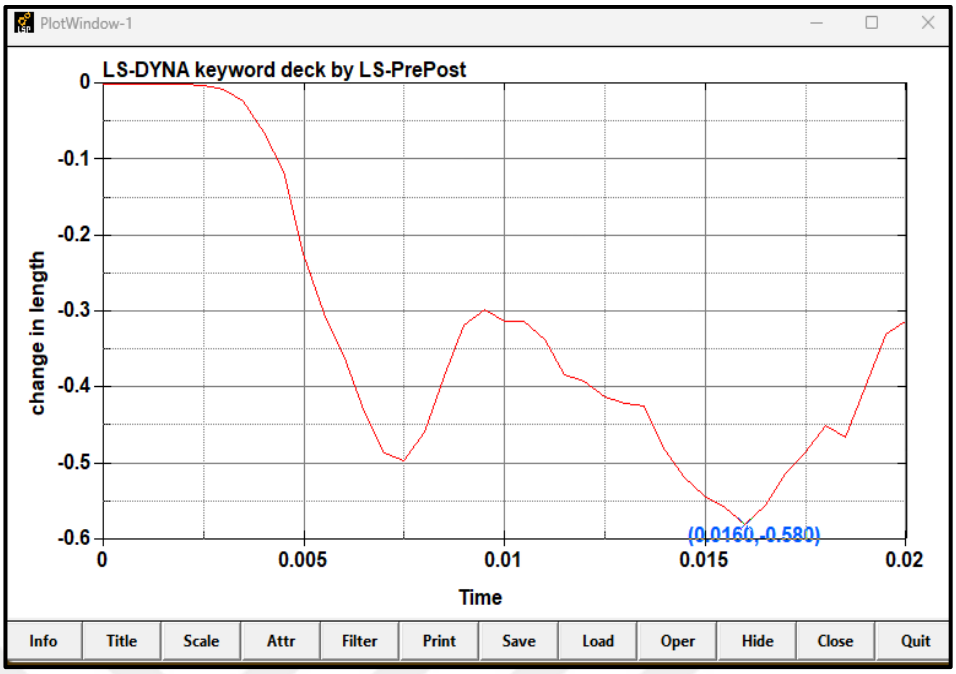


Figure 4.27 Post-improvement design FEA simulation point 6 change in length at contact duration

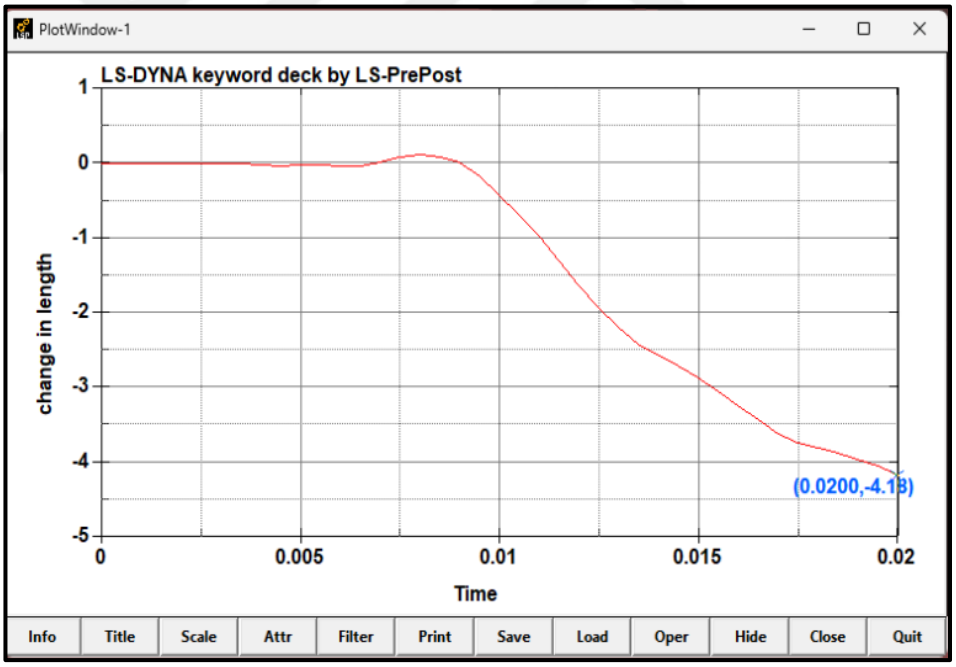


Figure 4.28 Post-improvement design FEA simulation point 7 change in length at contact duration

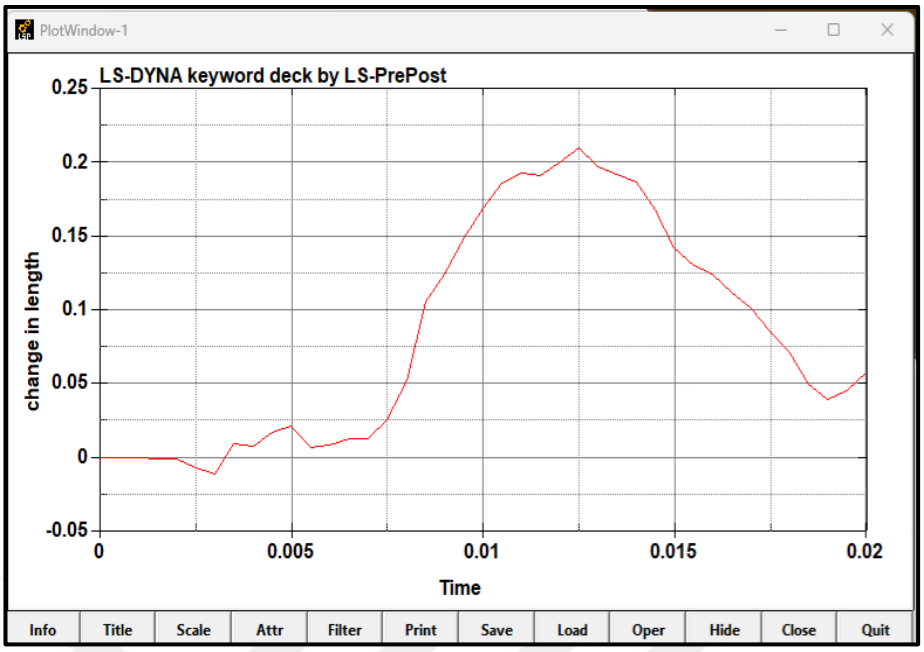


Figure 4.29 Post-improvement design FEA simulation point 8 change in length at contact duration

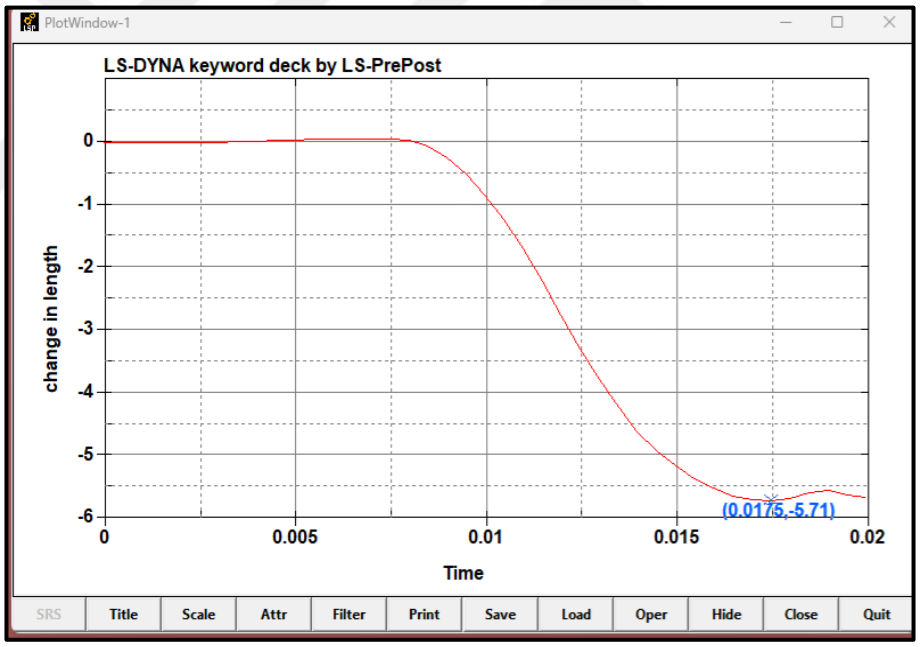


Figure 4.30 Post-improvement design FEA simulation point 9 change in length at contact duration

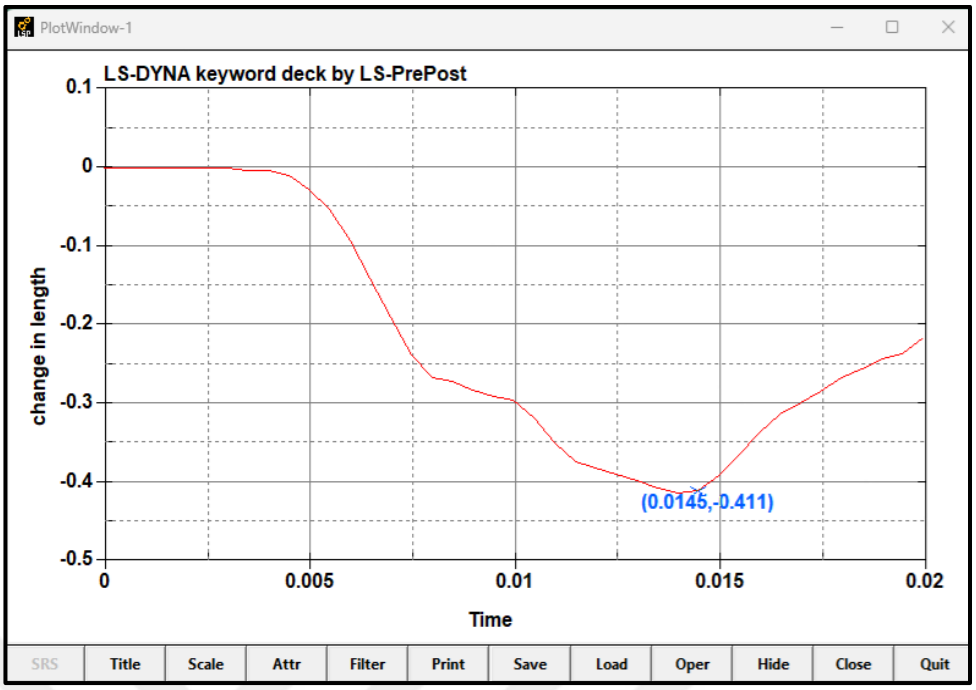


Figure 4.31 Post-improvement design FEA simulation point 10 change in length at contact duration

4.4 Comparison between Baseline FEA Results and Improved FEA Results

In table 4.1, we compare the peak deformation values and length changes seen in our element analysis (FEA) simulations, for both the original and updated designs of the refrigerator assembly. This table illustrates how the assembly reacted to simulated drop impacts before and after the design adjustments showing performance at measurement points. It gives us a view of how the updates have addressed weaknesses. By reviewing these findings, we can see improvements in impact resistance. Evaluate how well the design changes have enhanced the product's durability, in practical scenarios.

Table 4.1 FEA analysis door distance peak value and change in length measurements

	Baseline Design FEA Measurements (mm)		**Post-Improvements Design FEA Measurements (mm)**	
	Peak Value	**Change in length**	**Peak Value**	**Change in length**
1	-5.72	-5.72	-4.18	-4.18

2	-0.601	-0.5	0.98	-0.06
3	-8	-8	-6.51	-6.51
4	-0.741	-0.35	0.628	0.24
5	-4.64	-4.64	-4.49	-4.49
6	-0.78	-0.59	-0.58	-0.32
7	-3.33	-2.75	-3.17	-2.65
8	-0.624	-0.32	0.21	0.01
9	-6.76	-6.76	-5.71	-5.71
10	-0.411	-0.23	-0.411	-0.21

The first findings indicated distortions at measuring points with Measurement Points $d_{point\text{-}3}$, $d_{point\text{-}5}$ and $d_{point\text{-}9}$ displaying maximum measurements of 8 mm, 4.64 mm, and 6.76 mm correspondingly. These outcomes emphasized the regions that are most prone to damage from impacts.

After implementing the design enhancements, the updated results indicated reductions in deformation values at various critical locations. The peak deformation at Measurement $d_{point\text{-}3}$ improved from 8 mm to 6.51 mm while Measurement $d_{point\text{-}5}$ saw an enhancement from 4.64 mm to 4.49 mm and Measurement $d_{point\text{-}9}$ showed a decrease from 6.76 mm to 5.71 mm. Additionally there was an improvement in the length change at Measurement $d_{point\text{-}2}$, which went from 0.5 mm to 0.06 mm indicating a more stable structure.

4.4.1 Peak Values Comparison

The chart shows the peak values for each point in both the baseline and post-improvement designs (see Figure 4.32).

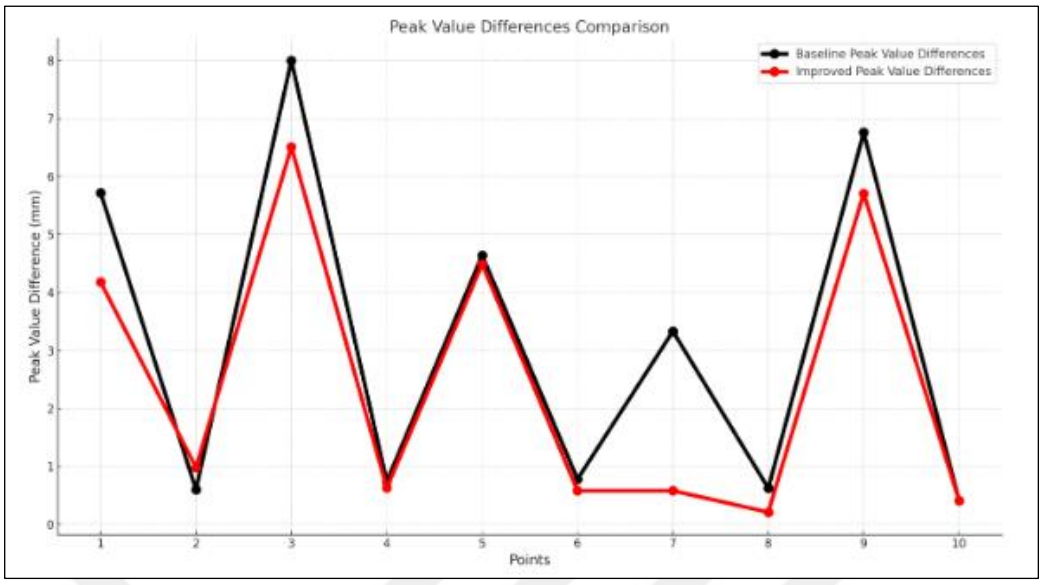


Figure 4.32 Peak value comparison between baseline FEA results and improved FEA results

The graph indicates that the highest points in the updated design are consistently nearer to zero than those in the design. This suggests a decrease in the severity of impact forces felt by the material.

Specifically points 3, 7 and 9 which displayed high points in the original design exhibit noticeable enhancement with less severe values in the updated design.

The uniform enhancement at all points implies that the alterations made to the design were successful, in reducing impact forces.

4.4.2 Change in Length Values Comparison

The chart illustrates the change in length for each point in the baseline and post-improvement designs (see Figure 4.33).

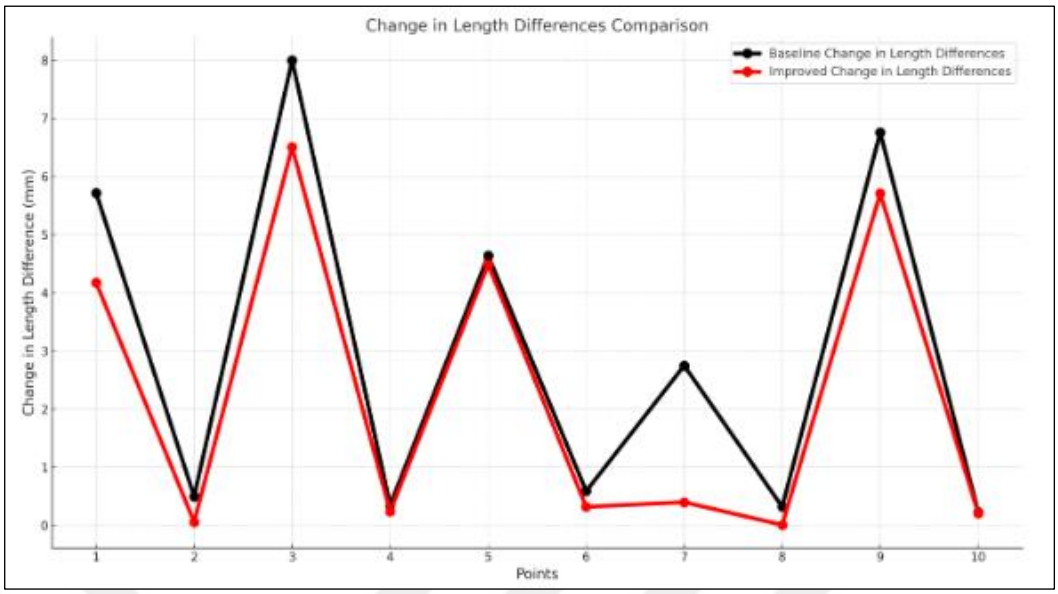


Figure 4.33 Change in length comparison between baseline FEA results and improved FEA results

The differences in length values in the improvement design are usually minimal or near zero when compared to the initial design showing improved stability and less distortion upon impact.

Notably sections $d_{point\text{-}3,}$ $d_{point\text{-}7}$ and $d_{point\text{-}9}$ exhibit enhancements indicating the effectiveness of the design modifications in reducing deformation caused by impact.

The general pattern reveals a spread of length changes, in the post improvement design implying that these enhancements have resulted in a more balanced reaction to impact forces.

4.5 Drop Test Results

4.5.1 Base Design Drop Test Analysis

The base design shows significant deviations from the 12 mm baseline distance after each drop test as specified in Table 4.2. Specifically:

Table 4.2 Baseline design drop test door distance measurement results

Measu-rement Points	**Baseline Design Theorical/ 3D Door Distances** $d_{theoretical}$	**Baseline Door Distances** $d_{baseline}$	**Post Drop Test Distances** d_{post} **(mm)**					
		Before Drop Test	**After Drop Tests**					
			1	**2**	**3**	**4**	**5**	**6**
1	12mm	12.22	8.87	9.65	9.14	8.95	9.71	9.75
2	12mm	11.95	11.56	11.64	11.47	11.55	11.57	11.62
3	12mm	12.15	5.56	6.24	6.45	5.97	7.12	5.63
4	12mm	11.98	11.55	11.43	11.66	11.62	11.57	11.45
5	12mm	12.17	7.56	8.05	7.91	7.45	8.34	7.97
6	12mm	11.92	11.23	11.35	11.36	11.39	11.45	11.39
7	12mm	12.06	9.34	8.94	9.23	8.85	8.77	9.14
8	12mm	11.96	11.31	11.46	11.58	11.42	11.33	11.35
9	12mm	11.9	5.76	5.85	6.12	6.05	5.99	6.08
10	12mm	11.87	11.64	11.56	11.51	11.48	11.65	11.57

After conducting tests post drop it was found that the actual measurements of the baseline design differed significantly from the 12 mm distance revealing weaknesses in the structure caused by the impact. The initial measurements, at point 1 and point 3 showed values of 12.22 mm and 12.15 mm respectively indicating alignment initially. However subsequent tests revealed deviations. For example, point 3 saw a decrease to 5.56 mm after the drop test followed by measurements fluctuating between 5.56 mm and 7.12 mm. Similarly, point 9 showed a reduction with readings ranging from 5.76

mm to 6.08 mm. These findings suggest that the baseline design faces challenges in maintaining stability at point 3 and point 9 emphasizing the importance of reinforcing these areas structurally as shown in the Figure 4.34.

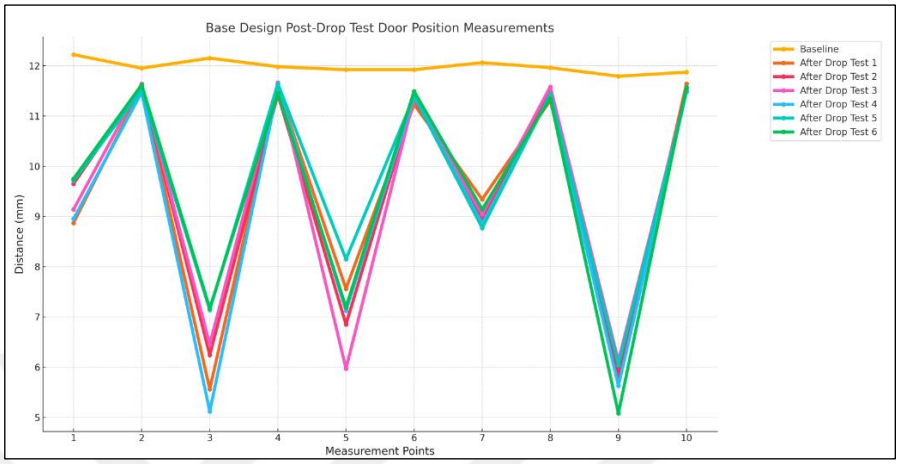


Figure 4.34 Baseline design drop test door distance measurement results in chart

4.5.2 Post-Improved Design Drop Test Results

In order to verify the accuracy of the FEA simulation outcomes, for the upgraded design, a set of conclusive drop trials were carried out. These assessments were conducted to validate the efficacy of the design alterations, in improving the products' ability to withstand impacts.

Six drop tests were conducted on the enhanced design to mimic impact situations and assess how the product performs in real world scenarios. Measurements of door distances were recorded at ten points, for each test following the approach as before. These points cover eight distances from door to body and two distances between doors.

The results of the drop tests were recorded and are presented in the accompanying table (see Table 4.3).

Table 4.3 Post-improved design drop test door distance measurement results

Measurement Points	**Baseline Design Theorical /3D Door Distances** $d_{theoretical}$	**Baseline Door Distances** $d_{baseline}$	**Post Drop Test Distances** $\Delta d_{post-improvement}$ **(mm)**							
		Before Drop Test	**After Drop Tests (Improved design)**						**After FEA**	**After FEA**
			1	**2**	**3**	**4**	**5**	**6**	**Baseline design**	**Improved design**
1	12mm	12.17	9.15	9.66	9.51	9.86	9.78	9.8	6.28	7.82
2	12mm	11.96	11.91	11.93	11.92	11.92	11.94	11.92	11.50	11.94
3	12mm	12.08	6.54	6.61	7.13	7.45	7.86	6.23	4.00	5.49
4	12mm	11.96	11.7	11.63	11.72	11.69	11.75	11.53	11.65	12.24
5	12mm	12.11	8.87	8.13	8.27	7.96	8.12	7.81	7.36	7.51
6	12mm	11.94	11.35	11.46	11.21	11.53	11.42	11.79	11.41	11.68
7	12mm	12.04	9.9	10.23	9.56	9.67	9.45	9.21	9.25	9.35
8	12mm	11.94	11.86	11.9	11.83	11.92	11.89	11.87	11.68	12.01
9	12mm	11.86	7.61	8.86	7.71	7.12	6.24	6.73	5.24	6.29
10	12mm	11.79	11.78	11.95	11.84	11.82	11.79	11.85	11.77	11.79

The improved design shows significant enhancement in maintaining door position stability after drop tests. Baseline measurements remain close to 12 mm, with initial values such as 8.87 mm at point 1 and 5.56 mm at point 3. Post-drop test measurements indicate reduced deviations compared to the base design. $d_{improvement\text{-}3}$ shows distances ranging from 6.12 mm to 6.73 mm, while $d_{improvement\text{-}9}$ ranges from 6.47 mm to 8.86 mm. These values demonstrate that the improved design mitigates the structural weaknesses identified in the base design, leading to greater consistency and adherence to the 12 mm baseline as presented in the Figure 4.35.

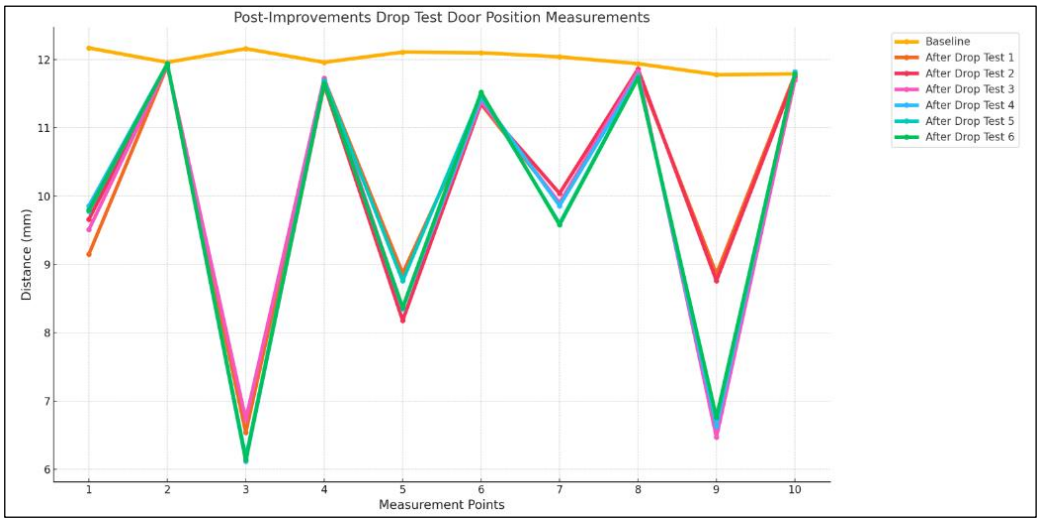


Figure 4.35 Post-improved design drop test door distance measurement results in chart

4.5.3 Drop Test Comparative Analysis

When we compare the design to the updated design it's clear how much the design improvements have positively affected the stability of the door position. In the design, there were deviations at measurement point 3 with post drop test distances varying from 5.56 mm to 7.12 mm. On the hand in the design, these distances range from 6.23 mm to 7.86 mm at that same point showing a noticeable decrease in deviation. Likewise, at measurement point 9 in the base design distances ranged from 5.76 mm to 6.08 mm while in the improved design ($d_{improvement\text{-}9}$) they varied from 6.24 mm to 8.86 mm. These comparisons clearly demonstrate that the improved design has greatly reduced deviations compared to the one ultimately enhancing overall structural stability (see Figure 4.36).

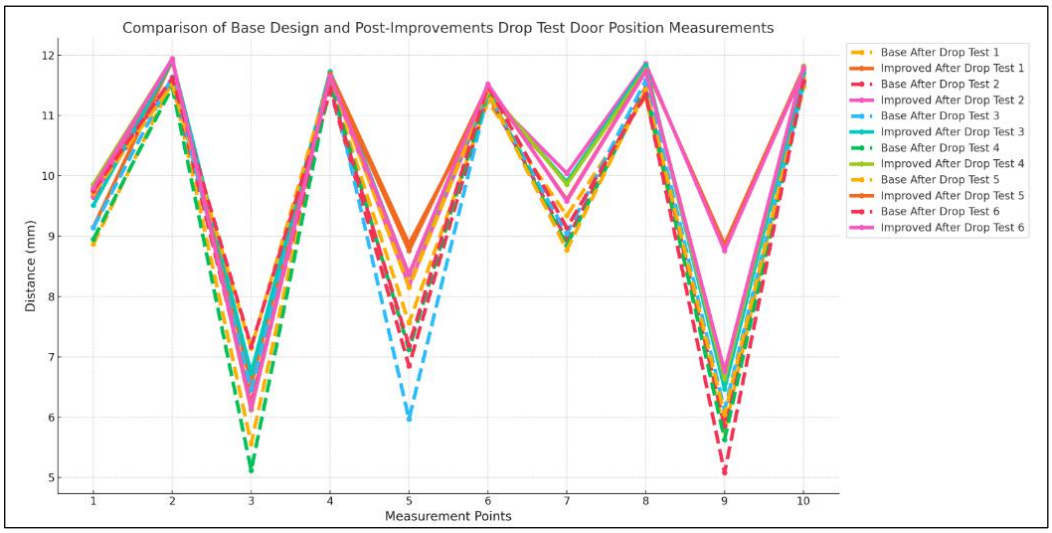


Figure 4.36 Baseline design and post-improved design drop test door distance measurement result comparison in chart

The results, from the drop test distances, highlight how effective the design improvements are. The initial design showed fluctuations in distances at different measurement points indicating inconsistent performance during repeated impacts. For instance, at $d_{point\text{-}3}$ the average distance ranged from 5.56 mm to 7.17 mm. In contrast, the upgraded design demonstrated average distances at $d_{improvement\text{-}3}$ ranging from 6.12 mm to 6.73 mm. After FEA measured drop test distance averages for baseline design 9.014 mm and for the improved design is 9.612 mm. Physical drop test distance measurement results average for the baseline design is 9.58 mm and for the post-improved design is 10.18 mm. Due to reference distance is 12 mm and improved design average values are closer to the reference value, we can say that the improvements resulted better performance. This consistency was also observed at measurement points suggesting that the enhanced design maintains an alignment, with the original distances leading to improved stability and performance overall (see Figure 4.37).

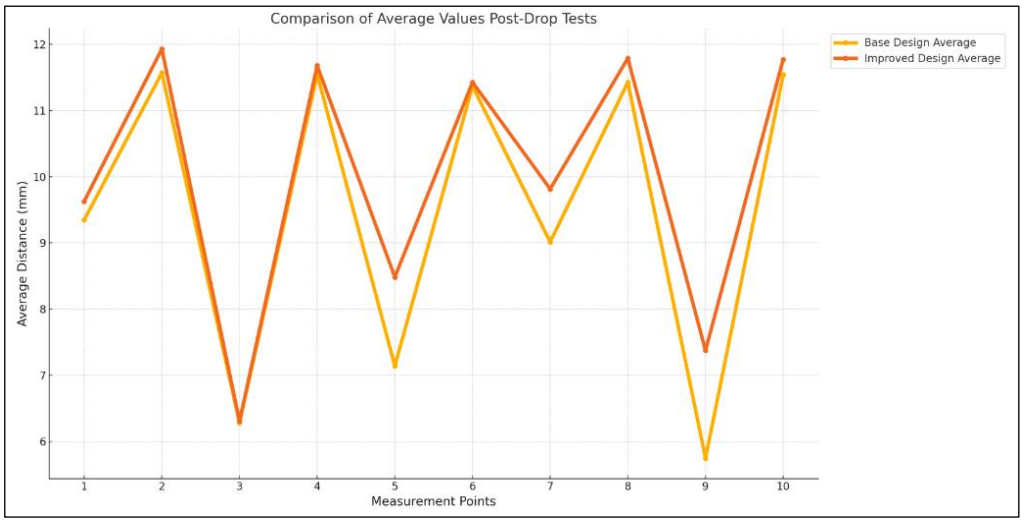


Figure 4.37 Baseline design and post-improved design drop test door distance measurement average results comparison in chart

CHAPTER FIVE
CONCLUSION

The comparison study emphasizes how design enhancements greatly influence the stability and resistance to impacts. The changes made have resulted in variations, improved performance consistency and better stability when facing situations. Through a combination of FEA analysis and real world testing the success of these design alterations is proven, affirming that the revised design provides better impact resistance and increased structural strength.

5.1 Discussion and Summary

The results from both finite element analysis (FEA) simulations and physical drop tests underscore the effectiveness of the design improvements made to the refrigerator assembly, particularly in maintaining door position stability under impact conditions. The drop test experiments reveal a marked contrast between the base design and the post-improvements design. Initially, the base design showed significant deviations from the baseline distance of 12 mm, with $d_{point\text{-}3}$ and $d_{point\text{-}9}$ experiencing reductions to as low as 5.56 mm and 5.76 mm, respectively, after the first drop test. These points consistently recorded lower distances in subsequent tests, highlighting inherent weaknesses in the original design.

In contrast, the improved design demonstrated notable enhancements. Measurement points, point 3 and point 9 exhibited improved distances respectively, following the first drop test. Although these values are still below the baseline, they reflect a significant reduction in deviation compared to the base design. The overall performance of the improved design was more stable, with all measurement points showing better adherence to the 12 mm baseline. FEA simulations support these findings, revealing reduced peak stress values and smaller changes in length across all measured points. This suggests that the improved design is more resilient and better equipped to handle impact forces. Although stress concentrations at the hinges persist, they do not significantly affect the distance measurements, indicating that the hinge design remains robust despite stress variations.

In general, the research shows that the enhancements in design have significantly improved the strength and ability to withstand impact of the refrigerator door setup. These upgrades result in a performance when subjected to impacts reducing any positional variations and aligning closely with the intended design standards. It might be beneficial to concentrate on tuning the design to rectify any remaining discrepancies and boost overall longevity.

5.2 Future Studies and Recommendations

After analyzing the study, results there are possibilities for expanding research and development to improve the design and functionality of refrigerator assembly. The knowledge obtained from element analysis (FEA) and real world drop tests lays the groundwork for pinpointing further enhancements and confirming the success of design changes. Below are some suggestions highlighting directions for efforts focusing on enhancing the products durability, structural strength, and overall dependability.

- Future studies could delve into enhancing the characteristics of expanded polystyrene (EPS) foam, with the goal of decreasing its size while maintaining its ability to safeguard components from damage.
- In the future it is important to keep refining designs to reduce errors and enhance product performance.
- By placing strain gauges at every spot of damage, in orientations (x, y and z) we can improve the precision of stress readings and gather a wider range of information.
- Expanding the elements in the mesh, for finite element studies could enhance result accuracy ultimately refining our understanding of performance.
- Trying out types of plastic for the door and hinges could lead to enhancements in how well they withstand impacts and last, over time ultimately making the design stronger.
- The techniques established in this research could potentially be applied to refrigerator models, including those with diverse designs or features to investigate their wider usefulness.

- Although this study used von Mises stress values, exploring other failure criteria better suited for plastics might offer deeper insights into potential failure modes and improve the understanding of material behavior.
- Placing cameras within the fridge to capture the drop test procedure could yield information for comparing it with the outcomes of finite element analysis giving a more comprehensive perspective on the dynamics of impact.

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