Fatigue failure analysis of washing machine top frame under cyclic loading – an investigative study in mitigating market complaint

Análisis de fallas de fatiga del marco superior de la lavadora bajo la carga cíclica: un estudio de investigación mitigando la queja del mercado

Análise de falha de fadiga do quadro superior da máquina de lavar sob carga cíclica - um estudo de investigação na mitigação de queixa do mercado

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Recibido: 20/05/2024 Aceptado: 12/10/2024

Summary. - This study paper looks into the structural integrity and failure mechanisms of washing machine top frames, with the goal of improving household appliance durability and reliability. Critical regions prone to fatigue failure were identified using SolidWorks software. Stress analysis and deformation analysis revealed the failure prone areas but upon assessing the costs associated with designing new molds for modified design and performing the breakeven calculation, we decided to go with an approach of using an alternate material which will not cause any change in existing mold. Polycarbonate (PC) with 50% long glass fiber reinforcement, were investigated to improve fatigue resistance. A new top frame of this material was made along with existing material ABS. Testing on a door simulator machine demonstrated a considerable improvement in durability, with the PC-based top frame demonstrating a 1128% increase in cycle endurance over the ABS counterpart. Top frame made up of ABS broke after 297 cycles and PC with 50% long glass fiber top frame broke after 3697 cycles. These findings highlight the significance of systematic design optimization and material selection for assuring long-term performance and safety in washing machine top frames.

Keywords: Finite element analysis, Fracture mechanics, Fracture behavior, Fatigue, Modelling, Simulations, Stress-Strain measurements.

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Memoria Investigaciones en Ingeniería, núm. 27 (2024). pp. 145-160
https://doi.org/10.36561/ING.27.10
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

Resumen. - *Este documento de estudio analiza los mecanismos de integridad y falla estructural de los mejores marcos de la lavadora, con el objetivo de mejorar la durabilidad y la confiabilidad del aparato doméstico. Las regiones críticas propensas a la falla de fatiga se identificaron utilizando el software SolidWorks. El análisis del estrés y el análisis de deformación revelaron las áreas propensas a la falla, pero al evaluar los costos asociados con el diseño de nuevos moldes para el diseño modificado y realizar el cálculo de equilibrio, decidimos ir con un enfoque de usar un material alternativo que no causará ningún cambio en el molde existente. Se investigaron policarbonato (PC) con un refuerzo de fibra de vidrio 50% largo para mejorar la resistencia a la fatiga. Se realizó un nuevo marco superior de este material junto con el material de material existente. Las pruebas en una máquina del simulador de puerta demostraron una mejora considerable en la durabilidad, con el marco superior basado en PC demostrando un aumento del 1128% en la resistencia del ciclo sobre la contraparte de ABS. El marco superior compuesto por ABS se rompió después de 297 ciclos y PC con un marco superior de fibra de vidrio de vidrio al 50% que se rompió después de 3697 ciclos. Estos hallazgos resaltan la importancia de la optimización de diseño sistemático y la selección de materiales para asegurar el rendimiento y la seguridad a largo plazo en los marcos superiores de las lavadoras.*

Palabras clave: *Análisis de elementos finitos, mecánica de fractura, comportamiento de fractura, fatiga, modelado, simulaciones, mediciones de tensión-deformación.*

***Resumo*. -** *Este documento de estudo analisa os mecanismos de integridade estrutural e falhas dos quadros superiores da máquina de lavar, com o objetivo de melhorar a durabilidade e a confiabilidade dos aparelhos domésticos. Regiões críticas propensas a falhas de fadiga foram identificadas usando o software SolidWorks. A análise de estresse e a análise de deformação revelaram as áreas propensas a falhas, mas, ao avaliar os custos associados ao projeto de novos moldes para o design modificado e executar o cálculo do ponto de equilíbrio, decidimos seguir uma abordagem de usar um material alternativo que não causará nenhuma mudança no molde existente. O policarbonato (PC) com reforço de fibra de vidro de 50% de comprimento foi investigado para melhorar a resistência à fadiga. Um novo quadro superior desse material foi fabricado junto com o material de material existente. Os testes em uma máquina de simulador de porta demonstraram uma melhoria considerável na durabilidade, com a estrutura superior baseada em PC demonstrando um aumento de 1128% na resistência ao ciclo sobre a contraparte do ABS. A estrutura superior composta de ABS quebrou após 297 ciclos e PC com quadro superior de fibra de vidro de 50% de comprimento quebrou após 3697 ciclos. Esses achados destacam o significado da otimização sistemática do projeto e da seleção de materiais para garantir o desempenho e a segurança a longo prazo nos quadros superiores da máquina de lavar.*

Palavras-chave: *Análise de elementos finitos, mecânica de fratura, comportamento de fratura, fadiga, modelagem, simulações, medições de tensão-deformação.*

List of abbreviation and symbols
PC – Polycarbonate
ABS – Acrylonitrile Butadiene Styrene
ANN – Artificial neural network
CNN – Convolutional neural network
LSM – Large scale manufacturing
WM – Washing machine
FEA – Finite element analysis

1. Introduction. - The need for durable and effective home appliances products is growing, thus it is critical to comprehend the mechanics behind fatigue failure and crack propagation in washing machine top frames. These frames' structural integrity reduces potential risks to user and environmental safety in addition to ensuring optimal operation [1]. Washing machines are essential tools for contemporary homes since they make doing laundry easier and more efficient. Although it's frequently disregarded, a washing machine's top frame, especially on top-loaded models, is essential for housing internal components and granting access to the washing drum. In order to improve user accessibility and operational functionality, the top frame piece that connects with the hinge mechanism makes it easier to open and close the lid [2].

A washing machine's top frame is essential to its general stability and performance. It acts as a cover, protecting internal parts from the elements and offering a practical surface for loading and unloading laundry. The hinge mechanism in top-loaded washing machines must be accommodated in the top frame design to ensure smooth and dependable lid operation without sacrificing structural integrity. Throughout its operating lifecycle, the top frame of washing machines experiences cyclic loading and polymers behavior under cyclic loading has been extensively studied because of its significant impact on economy and environment [3].

The top frame of washing machines is often made using the injection molding process, which allows for the precise and fast construction of complex geometries. In this context, ABS (Acrylonitrile Butadiene Styrene) is the material of choice due to its good mechanical qualities and ease of processing. Acrylonitrile butadiene styrene (ABS) is widely used in various essential components in the consumer electronics sector since it is lighter than metal. ABS offers excellent impact, heat and tensile strength characteristics. ABS plastic works well for creating consumer goods that are meant to be used frequently [4].

The upper frame's material grade is Starex QU-0191s, which is known for its exceptional performance in structural applications. Starex QU-0191s provides a compelling set of characteristics that make it excellent for washing machine components. Its strong impact resistance ensures longevity against mechanical stresses and vibrations encountered during use, protecting the top frame's integrity over time. Furthermore, ABS' intrinsic stiffness contributes to the top frame's total structural rigidity, increasing its capacity to sustain cyclic loading conditions without deformation or failure.

The injection molding process highlights the benefits of ABS by allowing to produce complicated designs with constant quality and dimensional accuracy. ABS's adaptability enables the top frame's geometry to be customized and optimized to fulfill specific functional and aesthetic needs, enabling perfect integration with the overall design of the washing machine.

In recent observations, incidences of breakdown in washing machine top frames, particularly in areas which interfaces with hinges, have been reported within Company A's product range. Due to marketing considerations, the company's identity is kept hidden. These issues have been reported in the market from consumers and was observed during rigorous testing in Company A's lab. Complaints about top frame breakdowns in washing machines highlight a critical issue that requires thorough research and resolution. The observed failures, particularly in parts where top frame interfaces with hinge, pose substantial difficulties to the structural integrity and reliability of Company A's washing machines. Such failures have a negative influence on consumer confidence while also incurring significant expenses connected with warranty claims, repairs and potential brand reputation damage. Understanding the underlying causes of these failures and executing effective mitigation methods is critical for Company A's commitment to product quality, customer satisfaction and market competitiveness. By resolving these problems, the company may improve the longevity and functionality of its washing machine top frames, resulting in a better user experience while lowering the chance of future failures.

The purpose of this study is to undertake a detailed stress analysis of the top frame of a top-loaded washing machine, with an emphasis on the component that interfaces with the hinge mechanism. Objectives include:

1. Evaluating the structural performance of ABS top frames under different loading circumstances, with a special focus on stress concentrations around hinge interfaces and to identify critical stress areas and failure modes in top frame’s hinge area.
2. Usage of alternate materials to improve the longevity of washing machine top frame.

The results of this study have important impact on improving the durability and structural integrity of top load washing machines, especially those in Company A's product range and for all the home appliances manufacturers in general. Manufacturers, especially in home appliances industry, can improve design processes and investigate alternate materials to effectively prevent failures by evaluating stress distribution patterns and failure mechanisms inside top frames of washing machines made up of ABS material. Adopting creative strategies demonstrates a dedication to raising customer confidence, cutting maintenance costs and increasing product reliability. The results of the study add to the larger conversations surrounding material selection and design optimization in the appliance manufacturing sector, which in turn promotes continual development and raises the value offer for stakeholders and customers alike.

2. Literature review. - The material properties of different polymers are widely studied by number of researchers [5-7]. A material will experience fatigue failure if it is repeatedly subjected to cyclic loads below its ultimate tensile strength. This condition is characterized by progressive and localized structural damage. The accumulation of microstructural damage in a material, which is triggered by cyclic loading conditions, is the cause of fatigue failure [8]. Cycle loading causes fatigue failure, which leads to crack initiation and propagation over an extended period of time. This is in contrast to static loading, which causes failure abruptly when the material achieves its maximal strength. Comprehending the underlying principles of fatigue failure necessitates acknowledging the correlation among stress levels, cycle count and fatigue life of the material [9].

Determining the fatigue life of structural elements is essential to evaluating their robustness and dependability. Numerous techniques are used to predict fatigue life based on S-N curve data, stress analysis and material parameters, including empirical, semi-empirical and analytical approaches [10]. Predictive models that help with fatigue life prediction include Miner's rule, Goodman diagram and Palmgren-Miner rule. These models provide insights into the process of cumulative damage accumulation [11]. Along with these models now there are several machine learning techniques that can serve the same purpose of predictive failure analysis by using machine learning algorithms especially designed for the purpose of remaining useful life (RUL) estimation [12]. Those machine learning algorithms include linear regression [13], decision trees [14], support vector machines (SVM) [15] and different neural network techniques like ANN or CNN [16] that can extract complex nonlinear relationship between input features like operating conditions, torque application, material properties, load distribution and different type of stresses like shear stress, torsional stress etc. and fatigue failure.

Fatigue life of a component depends on several factors. Material properties and loading conditions are the factors that are most relevant to our study. Washing machine top frame is usually made up of different grades of Acrylonitrile Butadiene Styrene (ABS) as it is a cost-effective material while exhibiting extremely good mechanical and thermal properties [17]. The impact resistance, durability, chemical resistance and ease of processing of ABS make it a preferred material among manufacturers. ABS is a popular material to use in the production of many parts for household appliances like microwaves, refrigerators, washing machines and dishwashers because of these qualities [18]. In industry, different components of home appliances products are manufactured from ABS pallets by the processes of injection molding and extrusion. Along with ease of manufacturing ABS is very durable and reliable material thus making it most popular material amongst home appliances manufacturers.

Secondly loading conditions also have a significant impact on how structural components behave when fatigued. Crack propagation rates and fatigue life are strongly influenced by variables such as stress ratio, load amplitude, mean stress and loading frequency. Premature failure is caused by high stress concentrations, sudden changes in loading direction and changing loads that intensify fatigue damage [19].

In this investigative study, we will delve into the details of how the crack in the washing machine's top frame in the hinge interface area came to be. Every time you open and close the washing machine door, this area endures torsional stresses. Top frame area which interfaces with the hinge undergoes torsional stress whenever door is open or closed and this leads to crack formation and propagation as this formation and progression of pre-existing cracks is due to fatigue damage when cyclic loads surpass the fatigue threshold of the material [20]. Determining the structural integrity and estimating the fatigue life of components that remain is dependent on an understanding of the factors that drive crack development [21].

Torsional stress results from applying torque to a structural member, causing it to twist and deform. The material experiences torsional strains when a torque is applied to one end of a shaft or beam while the other end stays fixed [22]. The element's cross-section twists in relation to its longitudinal axis as a result of angular deformation brought on by these stresses. The polar moment of inertia of the cross-section and the applied torque are inversely related to the torsional stress magnitude. During opening and closing of washing machine's top frame in the hinge interface area undergoes torsional stress because of its design and in this investigative study we will find its root cause and potential countermeasures for issue resolution.

Usually, fatigue cracks start at locations where there is a concentration of stress, including material inclusions, surface imperfections or geometric discontinuities. Crack initiation under cyclic loading is initiated at the nucleation sites of microscopic defects present in the material. The susceptibility of materials to crack initiation is influenced by various factors, including stress conditions, environmental factors and material qualities [23].

This experimental study of finding root cause and development of improved design of top frame of washing machine is unique as no other study specifically related to crack formation in washing machine top frame near area which interfaces with hinges has ever been done.

3. Methodology. - A door simulator (open/close) testing machine will used in this study's research methodology to replicate home environments similar to those encountered while a washing machine is operating. With the help of this machine, it is possible to replicate the cyclic loading and strains that are frequently experienced by washing machine top frame area that interface with the hinge by accurately simulating the conditions of household use.
After that, SolidWorks software will be used to design the washing machine top frame. For precise analysis, a detailed model of the top frame will be created using the original dimensions and accurate geometry of top frame of WM. ABS material will be defined before the commencement of analysis in order to get the accurate data. After that Finite Element Analysis (FEA) in the SolidWorks will be used to do thorough stress analysis, deformation analysis and factor of safety (FOS) study after the design phase. These evaluations will provide valuable insight about the top frame design's safety margins, performance under load and structural integrity.
After that a sample of top frame will be made with alternate material through injection molding and it will be tested on open/close machine in order to improve the life cycle of top frame without changing the current design.

3.1. Experimental planning. -

3.1.1. Machine. - A custom-built door simulator machine was used in order to simulate the market condition in which washing machine was open/closed and is shown in figure 1.

Figure I. Door Simulator (open/close) machine

3.1.2. Material. - Washing machine top frame is made up of ABS (Acrylonitrile butadiene styrene) and an improved design will be made up of PC (Polycarbonate).

3.1.3. ABS (Acrylonitrile Butadiene Styrene). - The thermoplastic polymer Acrylonitrile Butadiene Styrene (ABS) is a common material that is valued for its strength, resilience and adaptability. Because of its advantageous qualities, ABS material is widely used in the production of home appliances. When it was first introduced to the market, production procedures saw a dramatic change because manufacturers could now use this sturdy yet lightweight material for a wide range of components. Appliances for the home, including kitchenware, vacuum cleaners, refrigerators and washing machines are frequently made up of ABS. Because of its heat resistance, impact resistance and ease of molding, it is perfect for crafting complex shapes and designs without sacrificing structural integrity. Furthermore, because ABS is so easily colored and treated to provide desired textures and appearances, it is well renowned for its aesthetic appeal.

3.1.4. SolidWorks. - SolidWorks was used for designing the top frame of washing machine as well as the analysis

4. Design & Analysis of top frame. - Existing CAD model design of washing machine top frame was made in SolidWorks. Isometric views are available in Fig 2 & Fig 3

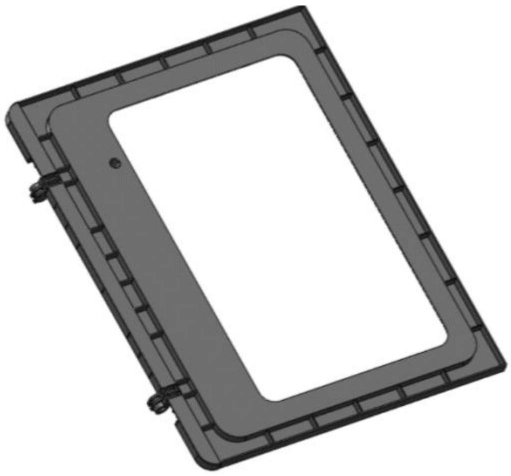


Figure II. Isometric view of top frame.

Figure III. Back view of Top frame.

Simplified design of the hinge is shown in Figure IV.

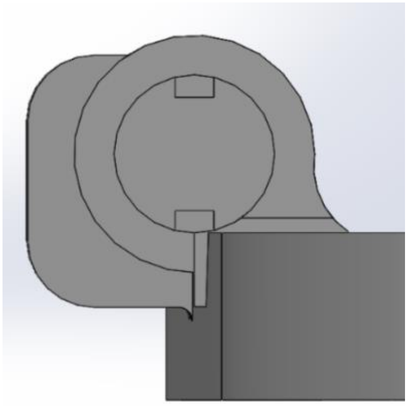


Figure IV. Side view of the hinge.

Motion study was done to calculate loads and dynamics of frame. For this counter torques were provided to both hinges and applied torque was onto the edge to open or close the frame.

Average torque values provided are **3000 N/mm** for counter torques and **9000 N/mm** for applied torque. Moreover, a Handle was attached to make applied torque uniformly distributed.

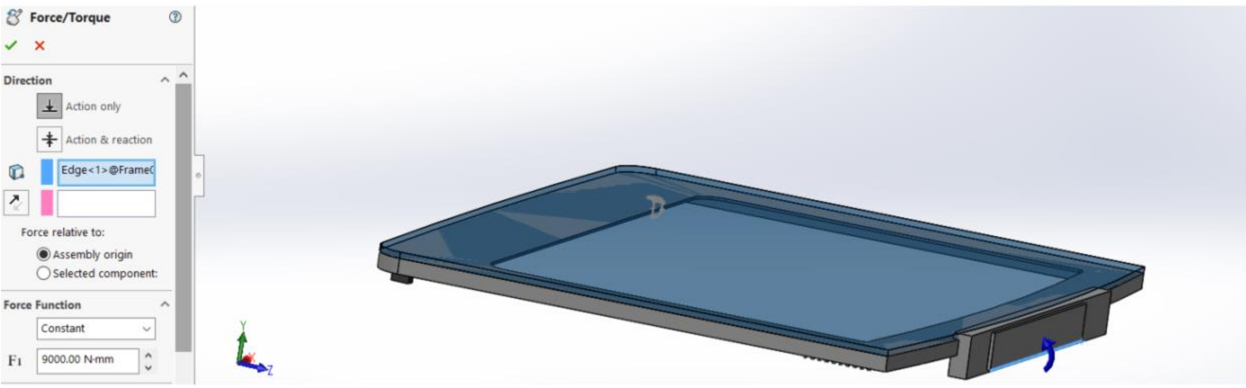


Figure V. Applied torque on the handle of the door.

Memoria Investigaciones en Ingeniería, núm. 27 (2024). pp. 145-160
https://doi.org/10.36561/ING.27.10
ISSN 2301-1092 • ISSN (en línea) 2301-1106 – Universidad de Montevideo, Uruguay

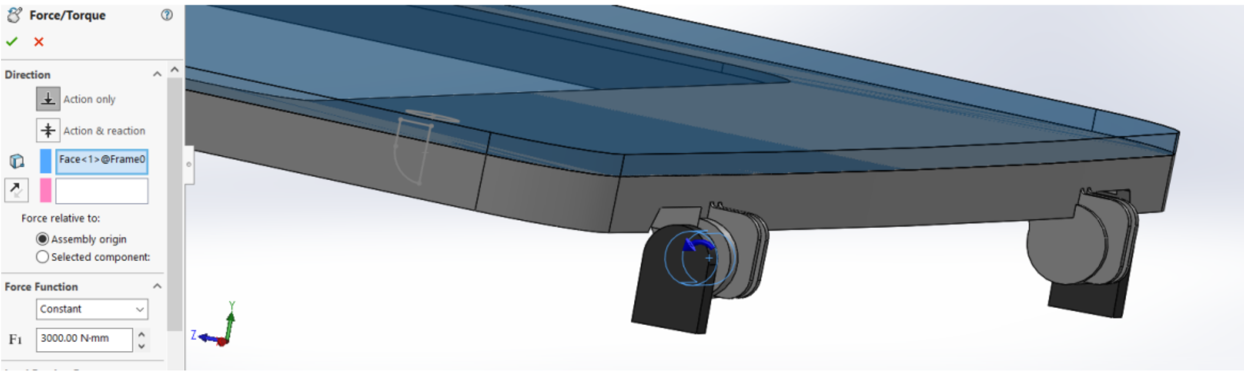


Figure VI. Counter torque on door hinges (same on both hinges).

Load bearing faces were given for applied torque as well. All three torques are applied and motion analysis was done.

Figure VII. Current design of top frame.

Considerable changes were made to the design in the modified design in order to improve the top frame durability and structural integrity. The area between both hinges, which had been flagged as a possible weak point in the preliminary research, was the main target for reinforcement. Its detailed analysis was done in SolidWorks but minimal improvements were observed in FEA analysis of stress plots, deformation plots and FOS plots.

In order to better disperse stress throughout the frame, more ribs had to added to the design and placed in key locations between the hinges. These ribs could reduce the chance of failure under cyclic loading circumstances and strengthened the structure's overall stiffness.

When the costs associated with creating a new mold for the design modification were evaluated, they were found to be significant. As a result, calculations were made to determine the threshold at which the investment in the new mold development breaks even. But after careful consideration, a different strategy was found to be a more viable option. Instead of changing the mold's design, the decision was made to switch the material in order to prolong the top frame's lifespan. This tactical change promises to increase the product's overall longevity and efficiency while also reducing the high expenses related to mold development.

Modified design of top frame is shown in Figure VIII:

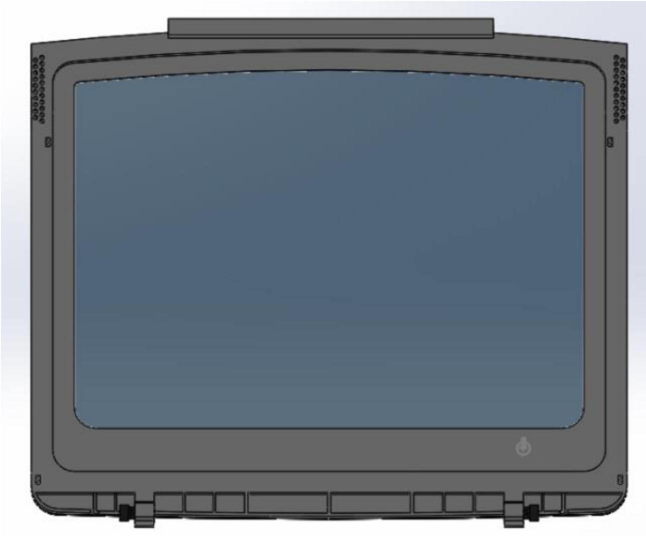


Figure VIII. Improved design of top frame.

A stringent strategy is necessary in order to systematically pick a suitable material to replace ABS in the construction of washing machine top frames. First, CES EduPack 2020 software is used to create a graph that shows fatigue strength versus pricing. With the help of this graph, the list of materials suitable for large-scale production operations can be narrowed without incurring undue material processing expenses. A selection process was carried out among the easily accessible materials in home appliance manufacturing companies, which included HDPE, PP, PC, PC (50% glass fiber reinforced) and ABS. Because ABS has a higher fatigue strength than HDPE or PP, these materials were eliminated. Even though PC's fatigue strength was somewhat higher than ABS's, its higher material cost and not significantly higher fatigue strength made it undesirable. Instead, a PC variation with 50% longer glass fiber was selected. This material is the best option for the application because it has the highest fatigue strength amongst all the available materials. Fatigue strength vs Price graph was prepared in CES EduPack 2020 and is shown in Figure IX.

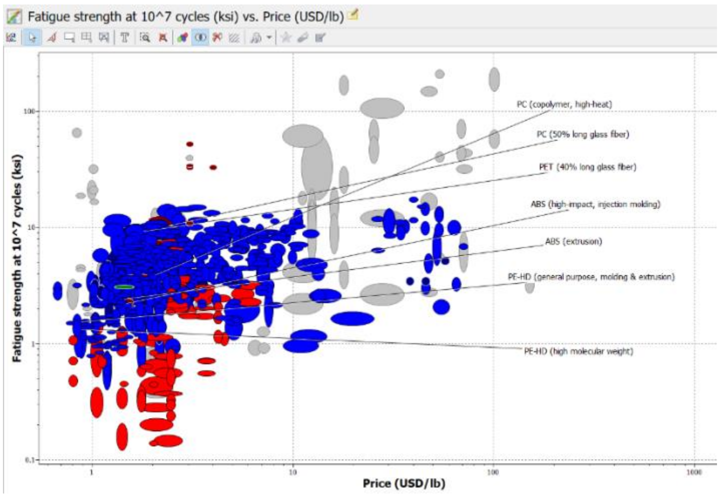
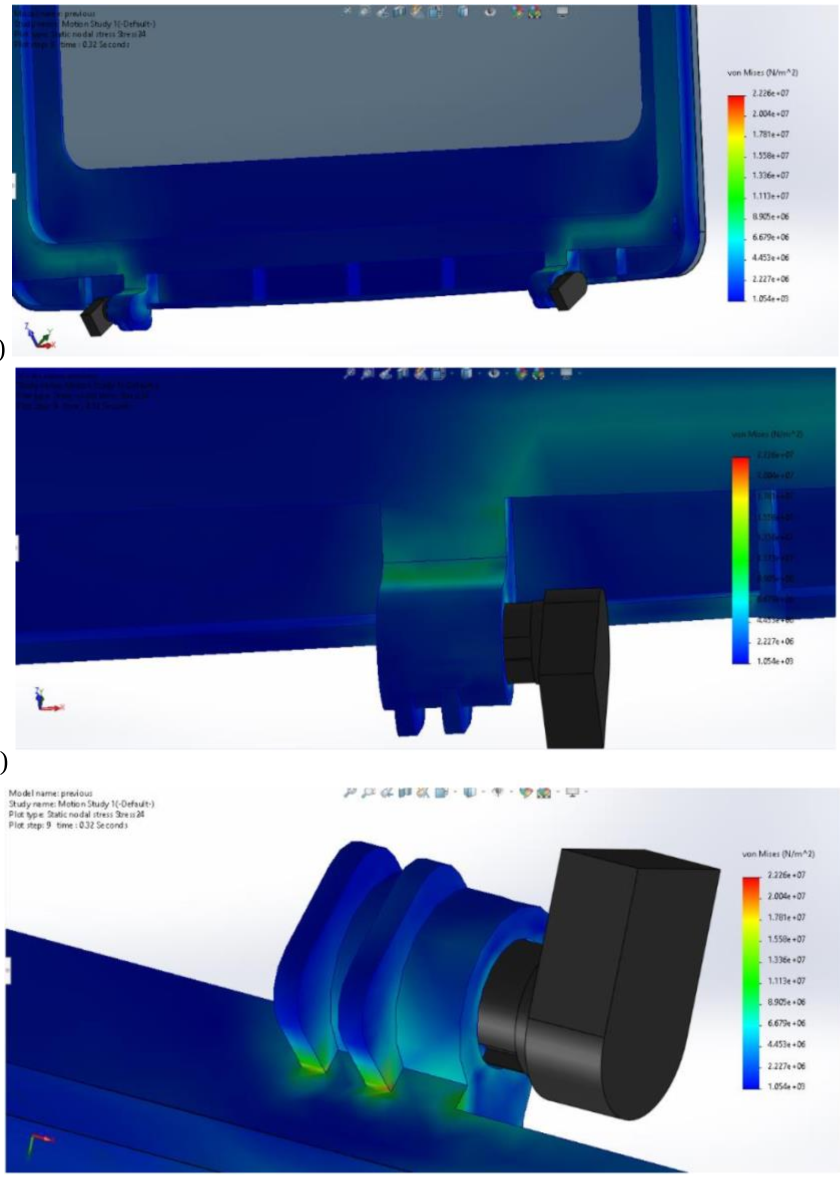


Figure IX. Fatigue strength vs Price graph.

Extensive analyses were carried out on maximum service temperatures as well as processing temperatures after the material was finalized. To make sure that the application complied with the standards, these reviews were essential. The chosen material was found to closely correspond with ABS's processing temperatures and greatly surpass ABS in maximum service temperatures. This alignment upholds operational integrity and process efficiency similar to ABS, giving confidence in the material's suitability for the intended usage in the fabrication of washing machine top frames.

5. Results and Discussion. - In order to identify weak places for future redesign and modification, the first and maybe most important step in the process entails a thorough examination of the stresses and deformations applied to the frame. A number of precise procedures were carefully followed in order to complete this crack initiation and propagation investigation. In order to analyze, visualize and quantify the stress distribution, deformation patterns and factor of safety throughout the frame structure, stress Plot, deformation Plot and factor of safety (FOS) Plot were made. We were able to identify possible weak points or failure sites by using these charts, which gave us crucial insights into how different forces and loads interacted with the frame so that we can have an understanding of the reason and points of failure in washing machine top frame.
Now through the utilization of stress, deformation and factor of safety plots we formulated tailored approaches to strengthen weak areas, maximize material efficiency and improved the frame's overall structural integrity and performance. Therefore, using SolidWorks tools was essential to the iterative design process and made sure that the final frame design satisfied strict reliability and performance requirements.
The original design of the top frame in which crack was getting developed during opening and closing was mentioned in Figure VI. In the original top frame design, von mises stress levels, particularly where the hinge area and the top frame crossed, were really high.

Stress analysis of top frame is show in Figure IX:



(a) (b) (c)

Figure IX – Stress analysis of top frame while opening.

It can be clearly seen in figure IXc that top frame hinge area shows higher von misses stresses i.e., $2.2*10^7$. This excessive stress was compromising the structural integrity of washing machine top frame, and this condition exacerbates when that part is under constant cyclic loading thus causing the hinge to break because of fatigue during operation of washing machine.

Whenever washing machine is operation, hinge region undergoes cyclic loading and deformation will be high in this region.

(a)

(b)

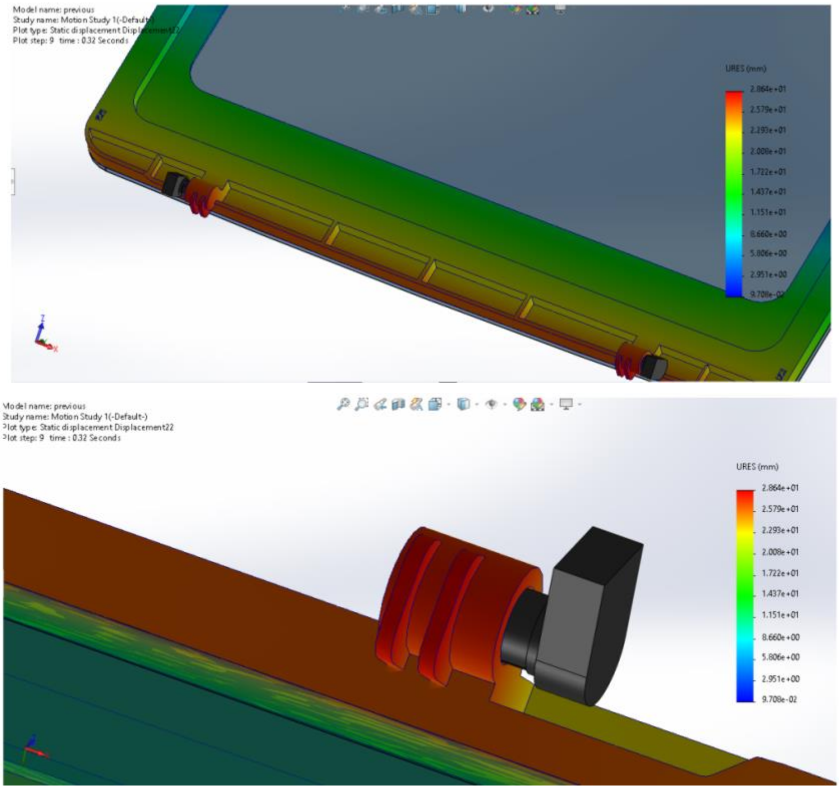


Figure X. Deformation analysis while opening.

During analysis in SolidWorks, 28mm of deformation was observed. 9000 Nm-2 was applied on top frame in order to open and close it. Counter torque of 3000 Nm-2 was applied on hinges

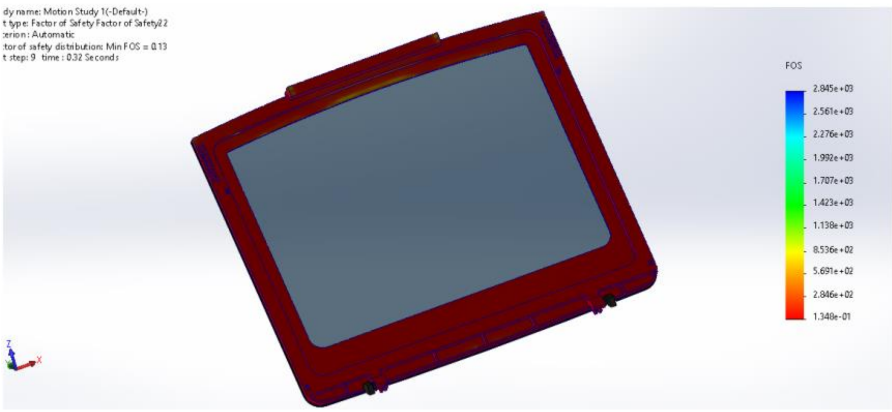


Figure XI. FOS analysis while opening.

Factor of safety of top frame was calculated using SolidWorks software under same boundary conditions and it came out to be $2.845x10^3$.

(a) (b) (c)

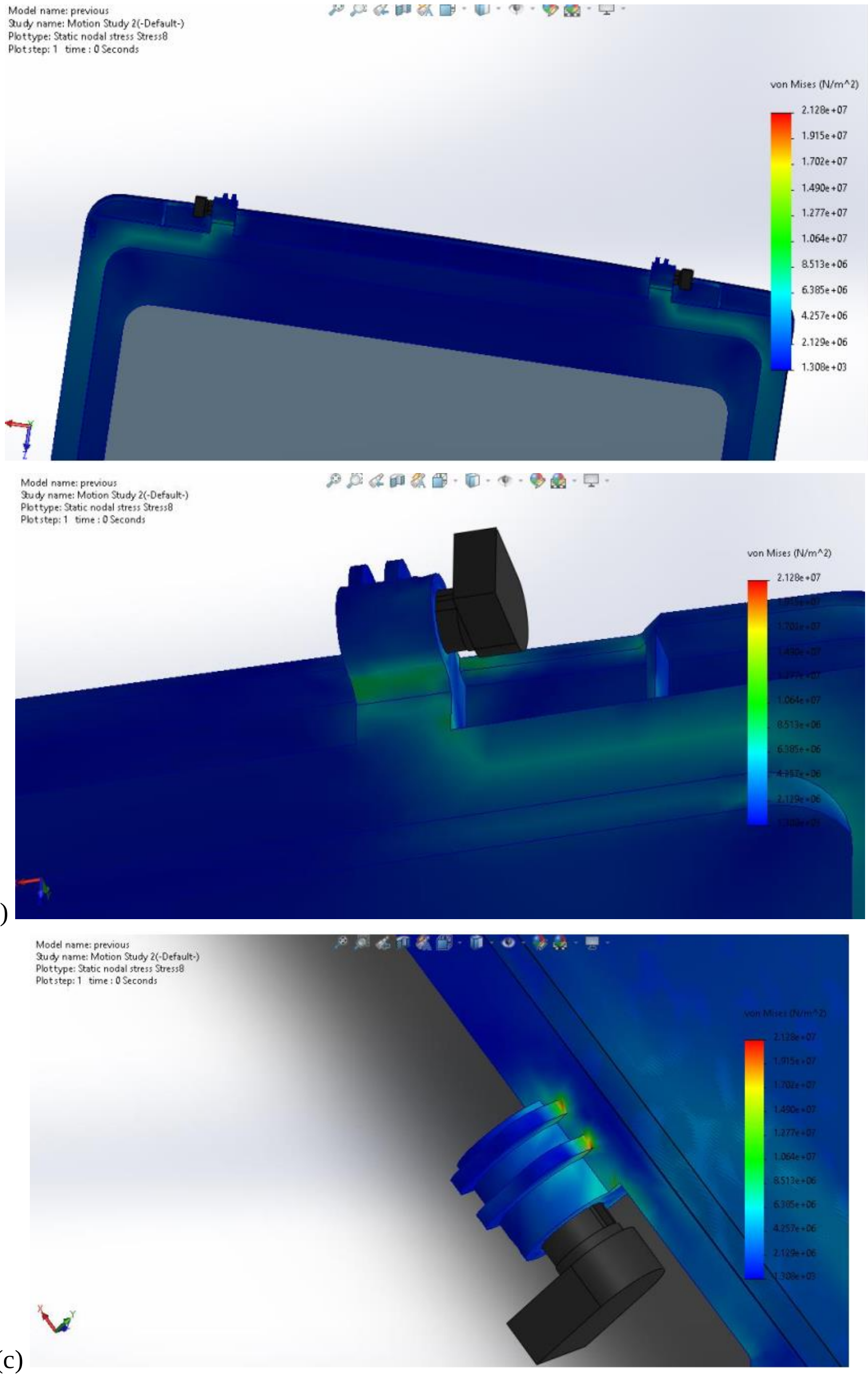


Figure XII. Stress analysis of top frame for closing.

The Von Mises stresses on the washing machine's top frame in closed position were also calculated using SolidWorks software. A careful inspection of Figures 12a, 12b and 12c shows that the overall frame and hinge assembly keep stress levels within a generally safe range. However, closer analysis reveals that the exact place where the top frame integrates with the hinge, which is characterized by acute angles, exhibits increased stress concentrations, even when the washing machine is firmly closed. This discovery implies that, while the frame and hinge assembly can sustain the expected loads, the presence of sharp angles at this key junction remains a source of concern due to the high stress levels it experiences.

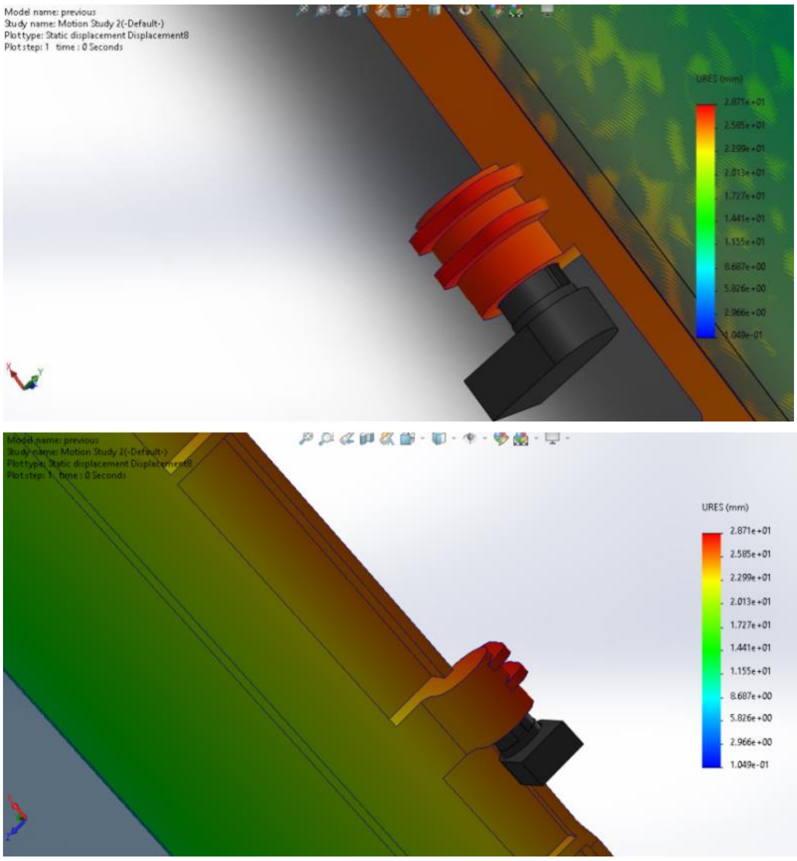
(a)
(b)


Figure XIII. Deformation analysis of top frame for closing.

During analysis of deformation in top frame in close position using SolidWorks software, 28 mm deformation is observed similar to open position. This indicates that the whole top frame structure is prone to failure under cyclic loading.

Factor of safety analysis was also done using SolidWorks software.

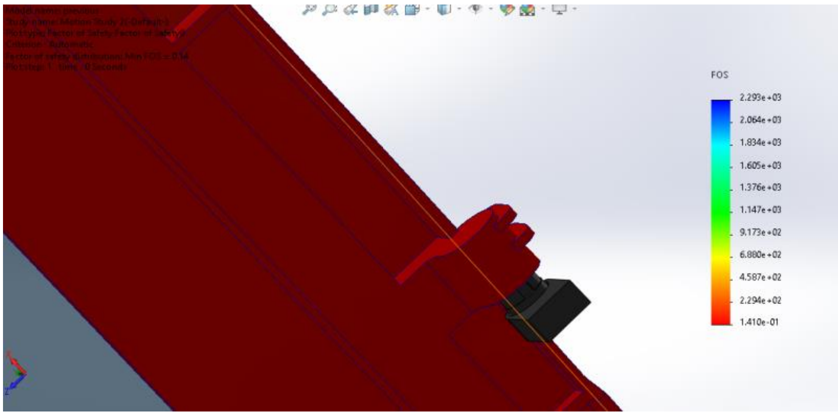


Figure XIV. FOS analysis of top frame for closing

Factor of safety in close position near to hinge interfacing with top frame is extremely low i.e., 0.14 which is extremely less.

Owing to the expenses linked with redesigning, two top frames were produced and put through testing on a door simulator machine, as figure 1 shows. The first top frame was made of ABS (Injection molding grade), which was used for production, and it was first installed on a washing machine. Next, the door simulator machine's open/close test was started. After 297 cycles, the top frame failed at the hinge interface area. The same testing process was then used to a second top frame made of PC with 50% long glass fiber. A crack developed at the hinge interface location of this top frame just after 3647 cycles.

Improvement of 3350 cycles was observed which ultimately resolves the market defect rate problem and improves the cycle %age by 1128%.

6. Conclusion. - Investigations into the failure processes and structural integrity of washing machine top frames have yielded important insights into the material and design choices that are essential to improving durability and dependability. Thorough stress analysis and deformation analysis have allowed for the identification and treatment of important fatigue failure points, especially at the hinge interface.

Given the financial implications associated with modifying the top frame, a different strategy was considered. An alternative material, PC, was carefully chosen in this experimental method. Testing was then done utilizing a door simulation machine to compare how well the top frame constructed of the current material, ABS, performed. There was significant improvement in result as open/close cycle of washing machine top frame improved from 297 to 3697 cycles which is a 1128% improvement. This resolved the performance issue of washing machine and reduced the market defect rate drastically. A lot of work can be done in improving the design of washing machine top frame as well as development of advanced material like composites with enhanced fatigue resistance and lower processing cost. Machine learning programs can be developed in order to calculate remaining useful life (RUL) for different high stress parts of top frame and hinge. By addressing these prospective areas of work will allow researchers and industry practitioners to continue to develop the state-of-the-art in washing machine top frame design, hence boosting product reliability, sustainability, and customer pleasure in the dynamic home appliances market.

Acknowledgement

We are grateful to Pakistan Elektron Limited (PEL) for providing access to resources and facilities essential for conducting experiments and analysis. We also acknowledge the Madiha Salam for her constructive feedback and guidance, which greatly improved the quality of this manuscript. Without the collective efforts of everyone involved, this research would not have been possible.

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Nota contribución de los autores:

1. Concepción y diseño del estudio
2. Adquisición de datos
3. Análisis de datos
4. Discusión de los resultados
5. Redacción del manuscrito
6. Aprobación de la versión final del manuscrito

MPRV ha contribuido en: 1, 2, 3, 4, 5 y 6.
RRPL ha contribuido en: 1, 2, 3, 4, 5 y 6.
JSLY ha contribuido en: 1, 2, 3, 4, 5 y 6.

Nota de aceptación: Este artículo fue aprobado por los editores de la revista Dr. Rafael Sotelo y Mag. Ing. Fernando A. Hernández Gobertti.