

Original Article

Comparative Finite Element Analysis of Hinges: Butt Hinge and Concealed Hinge for Residential Opening Systems

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Abstract - Hinge elements are critical structural elements used in opening systems for homes. Most of the time, the selection of one hinge over another is done empirically, without performing numerical comparisons between the various hinge configurations. The current study investigates the structural behavior of butt and concealed hinges by Finite Element Analysis (FEA) under the same loading conditions. Real hinge geometries were modeled in ANSYS, applying static load with a safety factor of 2.0, in accordance with ANSI/BHMA A156.1, for a 35 kg door. Two positions were modeled: closed (180°), which includes both vertical and horizontal loads, and open (90°), with pure vertical load. The outcomes obtained show that both types of hinges exhibit critical behavior in opposite positions: butt hinges are more vulnerable when opening (236.35 MPa, SF 1.06) and optimal when closing (87.54 MPa, F 2.86), while concealed hinges show the opposite behavior (199.57 MPa in closing, F 1.25; 82.04 MPa in opening, SF 3.05). Based on the safety criteria presented in the ANSI/BHMA A156.1 standard, it can be concluded that none of the proposed configurations meet the minimum safety criteria ($SF \geq 1.5$) in both positions. These results show that the choice of hinges must take into account the specific mode of operation, while providing quantifiable technical criteria for a specification based on actual structural performance.

Keywords - Butt hinge, Concealed hinge, Finite Element Analysis, Residential door systems, Safety Factor.

1. Introduction

Hinges are one of the structural elements that receive all the loads associated with opening systems in residential structures, such as gravitational loads, operating moments, and repetitive use cycles, which can reach hundreds of thousands of operations during the hinge's life cycle [1]. Therefore, the type of hinge will directly influence the safety of the enclosure [2]. However, the specification criteria used at present are based on manufacturer specifications, empirical experience, and minimum compliance levels with the specification set by standards, leaving the lack of rigorous analysis that quantifies the comparative structural behaviour between different configurations in the market, evident [3, 4].

Two types of hinges are mainly employed by the industry: the butt hinge, which has a visible mechanism consisting of a cylindrical pin between two metal plates; and the concealed hinge, which has an integrated joint to the thickness of the door or frame. The first ones are cheap and simple to install; however, they cause localised stresses, whereas the second

ones have better load distribution and aesthetic, but are more expensive and complex to install [5]. Although they are used in every building, the decision between these two configurations is more often than not based on aesthetic and economic factors rather than a detailed technical examination of the differences in structural performance [6].

There is a lack of articles that make a systematic comparison of the structural behavior of butt hinges with concealed hinges, when they are subjected to the same loading conditions in a residential setting, and using Finite Element Analysis. The empirical acceptance tests found in international standards ANSI/BHMA A156.1 [7] and EN 1935 [8] provide only tests of acceptance, but do not provide insight into stress distributions or criteria for comparing the different configurations quantitatively [9]. This weak analysis is not suitable for design professionals to optimize their specifications according to the actual structural performance, and is not suitable for design decisions to be taken based on quantitative analysis and empirical practice [10].



Although both butt and concealed hinges are commonly used, no systematic and quantitative structural comparison has been made between these two types of hinges under standard residential conditions, and this is an important research need that has not been reported in the literature. These are chosen because of their opposing market presence, but hinges that are hidden have a more complex, multi-jointed design and are a better alternative to the traditional and cheaper to install visible hinges.

This work is novel in that it moves beyond empirical or aesthetic preferences to strict structural performance metrics in choosing the material. Using a comparative Finite Element Analysis (FEA) using the ANSI/BHMA A156.1 standard loads, this study shows stress distribution patterns and the reversal of critical positions for these two systems that have not been reported previously, and advances over the traditional way of assessing hardware in isolation.

2. Literature Review

FEA is now a vital tool used to study the performance of mechanical parts in articulated components in door and window systems. With regard to the comparison of hinges, Abdul Razak et al. [11] showed the effectiveness of Finite Element Analysis (FEA) software with the program ANSYS as a tool to analyze the automotive hinge where they carried out linear static analysis to simulate the overload test and compared the results achieved with the test carried out physically which is the basis of the analysis of the automotive hinge by the Finite Element Analysis (FEA) software.

In a similar way, Zhou et al. [12] investigated the behaviour of deformation and stress distributions in furniture doors by using ANSYS and found FEA to be a proper technique for the prediction of the mechanical behaviour of an opening system under static loading conditions. The fundamental research thus confirmed the feasibility of using numerical simulation to correctly predict the stress distributions and failure mechanisms of hinged parts.

The behavior of conventional hinges in various mounting configurations has been the subject of analysis in different studies. Zhou et al. [12], who worked with the choice of mounting two hinges, indicated that the distance to the end (Tp) should not exceed 1/8 of the length and, when using four hinges, the middle hinge (Sp) should be mounted at 1/3. The simulations revealed an even Mises stress distribution with stress concentrations at the hinges, and the maximum deformation possible with the best set-up was 0.0093 mm. In the studies of wooden doors, Görgülü et al. [13] have also found that the middle installation provides better load distribution with up to 75.614 MPa for the upper installation and 78.809 MPa for the middle installation.

Topological optimization has been a valid tool for increasing the structural performance of hinge elements

without increasing mass. On interior door hinges, Wu et al. [14] proposed an effective BESO method with great structural integrity of hinges and low usage of materials. Optimal design of refrigerator hinges was obtained by Gao et al. [15] using an optimization strategy, resulting in a weight savings of 13.1% and of 37.2% in maximum stress under load conditions. These methods illustrate the possibilities of using computational methods to reach structurally efficient and sustainable solutions.

Consistent patterns of critical stress localization in hinge systems have also been found in previous studies. Razak et al. [11] examined maximum concentrations, obtained within the plug region, with stresses of up to more than 770 MPa, higher than the official value of SAPH 440 steel (302 MPa), and found that increasing the pin thickness to 2.5 mm reduced the stress by 300.5 MPa. Based on this, Zhou et al. [12] calculated that the stress is diffused almost uniformly across the entire globe, but the localized stress values are found around the fixing points. This justifies the need to implement more complex numerical analysis in order to detect areas that are susceptible to damage for specific configurations.

As far as specifications are concerned, there are no technical indications on how to design the hinges best, and no guidelines on the best placement of the hinge based on the geometry of the door, other than the minimum load and cycle requirements set by ANSI/BHMA A156.1 and EN 1935. However, as highlighted by Razak et al. [11], the guidelines are empirical preferences that do not reflect the internal distribution of forces, nor offer aspects that could be used to enhance the design beyond what is prescriptive. The other drawback noted by Zhou et al. [12] is that the guidelines lack sufficient detail regarding the proper installation of hinges, depending on the shape of the door, for which this remains a matter of personal experience. This emphasises the normative method; technical analyses are needed to justify the choice and specification of hardware.

In recent years, the study of hinges has shifted to topology optimization, novel material interactions, and system-level performance. In the field of topology optimization, for example, Wu et al. (2024) successfully implemented a Bi-Directional Evolutionary Structural Optimization (BESO) algorithm to optimize the interior door flat hinges with 60% saving of material volume; at the same time, they maintained the maximum stress constraint [14].

From the aspect of advanced materials and system-level analysis, Seker et al. (2024) performed detailed experimental and FEM fatigue testing on door systems, revealing that the base materials (MDF vs. Particle Board) and torque of the screws have a significant influence on the structural integrity and deformation of the door hinges [16]. Moreover, Dziwis et al. (2023) numerically studied brass movable joints and proved that the distribution of the mounting holes directly

influences the propagation of stresses and failure to yield when subjected to different structural loading conditions [17]. The recent studies published are very important in terms of structural optimization, materials optimization, or behavior studies of furniture systems at a macro level, but they only study particular hinge types, specific materials, or macro furniture systems.

The novelty of the present research is to directly compare the two structurally antagonistic hinges under identical standardized residential loading conditions in terms of a quantitative FEA [11].

It differs from recent optimisation studies that aim to minimise the mass of a single, defined shape by providing a clear baseline understanding of the intrinsic geometry of these two common domestic systems and how this influences a 'reversal of critical positions' in their working conditions, thereby filling a gap in the literature that evaluates hardware individually.

This work fills this gap by comparing two different structures using finite elements and taking into consideration load conditions typical of residential use and technical criteria that can be reproduced. The results achieved give the opportunity to make selection decisions based on quantified structural performance, which are better than the traditional empirical approach.

3. Methodology

3.1. Description of Geometries

Two types of hinges, commonly used in residential construction, were chosen as the basis. The butt hinge consists of two rectangular metal plates joined together by a cylindrical pin that acts as a pivot: its dimensions are 100 mm high, 33 mm wide, and 3 mm thick, in line with market standards [18]. The concealed hinge, on the other hand, has a somewhat more complicated design, as its articulated mechanism is integrated into the thickness of its mounting. It is 128 mm high, 21 mm deep, and 22 mm wide [19] and has several contact surfaces and load-bearing elements, which are partially housed in the support structure.

Both geometries were modeled three-dimensionally using SolidWorks software, where modeling simplifications were applied by eliminating secondary geometric features such as screws, minor chamfers, and small radii that do not significantly affect stress distribution but would substantially increase the computational cost of the analysis.

The geometries of both hinges are shown in Figure 1, which shows isometric views of each in their operational configurations. Additionally, Figures 2 and 3 show exploded views of the components that make up each hinge. Tables 1 and 2, which accompany each exploded figure, identify each component, material, and quantity.

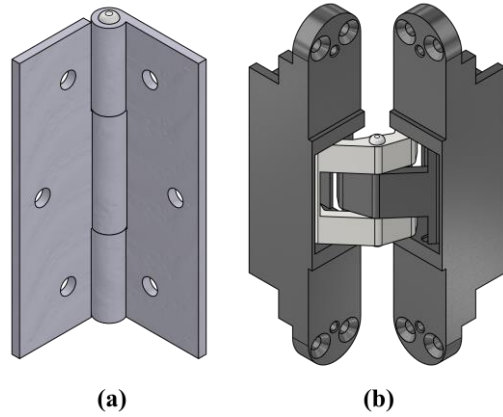


Fig. 1 Isometric view, (a) Butt hinge, (b) Concealed hinge.

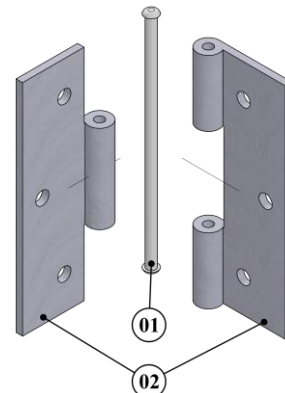


Fig. 2 Exploded view of butt hinge

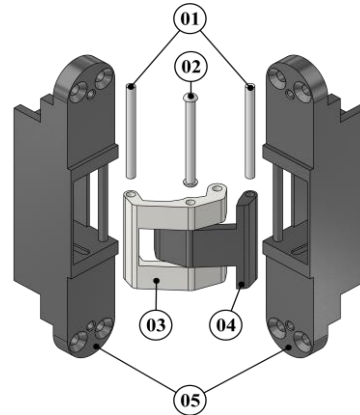


Fig. 3 Exploded view of concealed hinge

Table 1. Butt hinge components

N°	Component	Material	Amount
01	Pin	AISI 1020	1
02	Plate	Structural steel	2

Table 2. Concealed hinge components

N°	Component	Material	Amount
01	Pivot shafts	AISI 1020	2
02	Pin	AISI 1020	1
03	Outer arm	Structural steel	1
04	Inner arm	Structural steel	1
05	Housing	Structural steel	2

3.2. Material Properties

Two main materials were defined for computational analysis, reflecting the actual configuration of each component that makes up residential hinges. The plates, shells, and arms of the hinges were assigned the structural steel material available in the ANSYS library, and only the pins and shafts of the hinges were modeled with AISI 1020 steel [20], which is widely used in mechanical components. The material properties are summarized in Table 3.

Table 3. Properties of assigned materials

Material	E (GPa)	ν	σ_y (MPa)	ρ (kg/m ³)
Structural Steel	200	0.30	250	7850
AISI 1020	186	0.29	350	7870

3.3. Computational Model and Software

ANSYS Workbench 2024 R2 was used to conduct the Finite Element Analysis (FEA). Static Structural analysis was used for this type of analysis, which was suitable since the loads were quasi-static (not dynamic or inertial). To achieve accuracy and reliability of the FEA, a mesh sensitivity and convergence study was conducted. Stresses in the hinge mechanisms were concentrated, and the meshed structural domain was modeled with 10-node tetrahedral solid elements (SOLID186), which are appropriate for highly complicated geometries and highly concentrated stresses. The element size was reduced progressively from 11 mm to 0.3 mm until the difference in the maximum von Mises stress of the two meshes is less than 5%, and a converged mesh with an element size of approximately 0.3 mm having approximately 16026 elements and 31255 nodes. Local meshing refinement was performed in the critical contact areas, e.g., the pivot shafts and pins. As far as material modelling, the model currently employed is linear isotropic elasticity, which sets up a conservative base to assess for stress concentrations before yield. In the coming versions, the non-linear elasto-plastic models will be included to consider permanent deformations.

3.4. Applied Loads

Representative loads for the typical residential door system were used. The nominal loads on the two identical hinges in a symmetrical distribution configuration for a standard 35 kg residential door are:

- Vertical gravitational load of 172 N (door's own weight of 35 kg distributed between 2).
- A horizontal opening force of 25 N is applied to the free edge of the door, which represents the typical manual force exerted by a person opening the door when it is closed.

The Safety Factor (SF) chosen for the analysis was 2.0, which was taken according to ANSI/BHMA A156.1 [7] residential hinge standards and International Building Code (IBC) [21] recommendations. An SF of 2.0 is appropriate for

non-critical structural components. This value is consistent with comparative analyses reported in technical literature similar to Zhou et al. [12]; Razak et al. [11], 2018; Wu et al. [14]. Therefore, by applying the SF of 2.0 to the nominal loads, the design loads used in the analysis were obtained. Table 4 presents the detailed derivation of loads.

Table 4. Derivation of applied design loads

Parameter	Nominal Load	SF	Design Load
Vertical Load	172 N	2	344 N
Horizontal Force	25 N	2	50 N

3.5. Operational Positions Analyzed

The two different modes of operation of the door were studied to determine the structural behavior in different stress situations, as indicated in Table 5.

3.5.1. Closed Door Position

In this setup, the door is closed at 180°. The loading applied was a combination of loads being applied, the maximum load being 344 N vertically (gravity) and 50 N horizontally (operating force). This setting is the maximum setting when opening by hand. Figure 4 illustrates the geometric configuration of both hinges in this position.

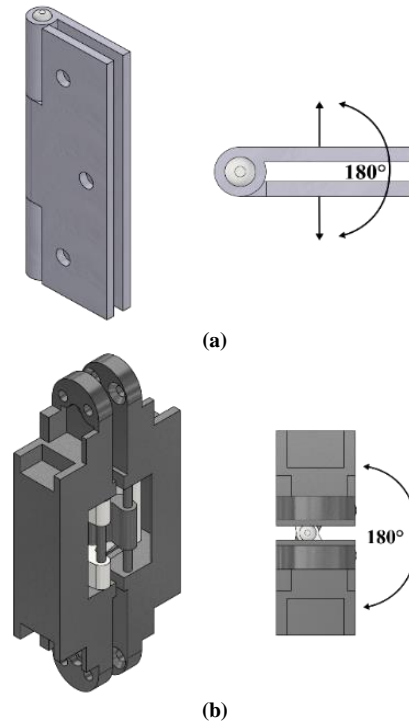


Fig. 4 Hinge view with 180° position, (a) Butt hinge, (b) Concealed hinge.

3.5.2. Open Door Position

With this setup, the door will be fully open at 90°. A lateral force was not applied, and only a vertical gravitational load of 344N was applied. This is the static equilibrium position; the door is open. Figure 5 shows the corresponding geometric configurations for each of the two hinges.

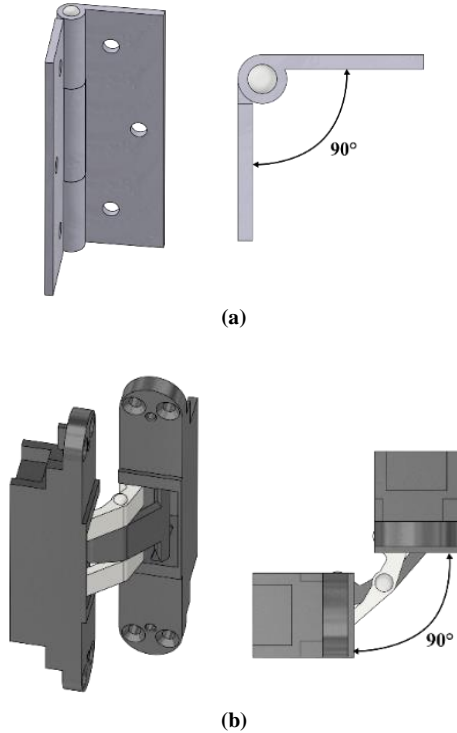


Fig. 5 View of hinges at 90° position, (a) Butt hinge, (b) Concealed hinge.

Table 5. Operational positions analyzed and loads applied in each case

Position	Angle	Vertical Load	Horizontal Load
Closed	180°	344 N	50 N
Open	90°	344 N	0 N

3.6. Border Conditions and Restrictions

The boundary conditions were carefully specified to reflect the physical assembly and operating conditions. Each hinge's fixing plate was put under 'Fixed Support' constraints in all six degrees of freedom (X, Y, Z translations and rotations) with respect to the fixed surface of the frame, to simulate a rigid connection using fixing screws. For accurate modeling of the physical contact under load, the frictional contact elements were set between the moving parts (pins, bushes, plates), and the friction coefficient was assumed to be 0.2. The contact formulation used the 'No Separation' condition for non-rotating structural joints, and standard frictional contacts for the pivot zones to permit the relative sliding without structural penetration. This formulation is representative of the internal load transfer mechanism.

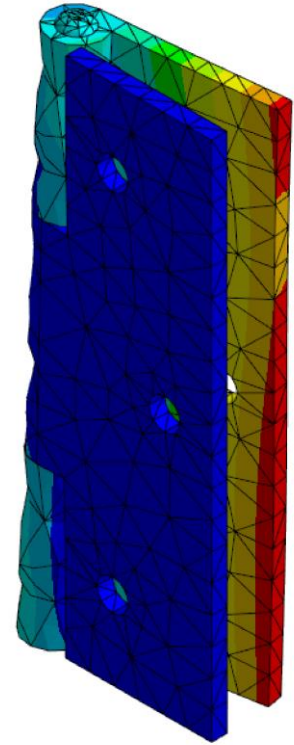
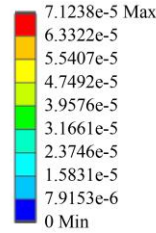
4. Results

The finite element analysis was performed under conservative design load conditions, applying an SF of 2.0 to the nominal operational loads, for two different operational positions: door closed at an angle of 180° and door open at 90°. The results are displayed in a comparative format so that comparisons can be made between the different types of hinges in real operational situations.

4.1. Total Displacements

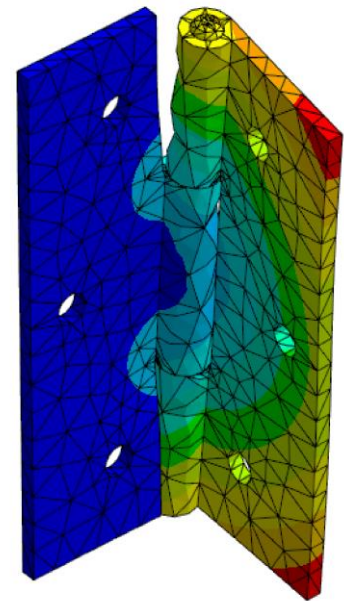
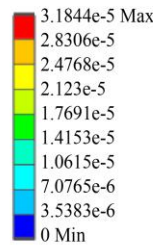
The structural deformations under design loads showed large differences between the two configurations and between the operating positions. Both total displacement contours for both hinges in both 180° and 90° orientations are shown in Figures 6 and 7. Table 6 summarizes these results.

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
25/10/2025 16:31



(a)

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1 s
26/10/2025 11:49



(b)

Fig. 6 Total displacement of butt hinge, (a) 180° position, (b) 90° position.

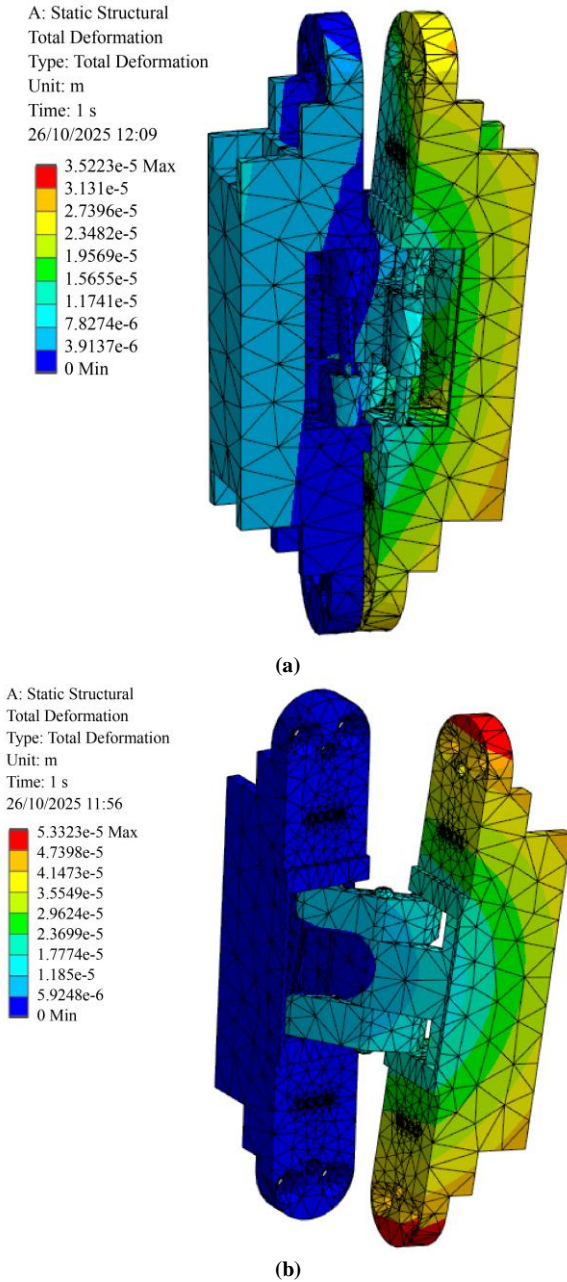


Fig. 7 Total concealed hinge displacement, (a) 180° position, (b) 90° position.

Table 6. Total displacements under design loads (SF = 2.0)

Bisagra	Posición	Deformación Mín (mm)	Deformación Máx (mm)
Bisagra de tope	Cerrada 180°	0	0.0273
	Abierta 90°	0	0.0656
Bisagra oculta	Cerrada 180°	0	0.0352
	Abierta 90°	0	0.0533

4.2. Equivalent Efforts

The distribution of von Mises equivalent stress under design loads revealed the most significant finding of this analysis: each hinge has a different critical operating position. Figures 8 and 9 show the von Mises stress contours for both hinges in both the 180° and 90° positions. Table 7 summarizes these results.

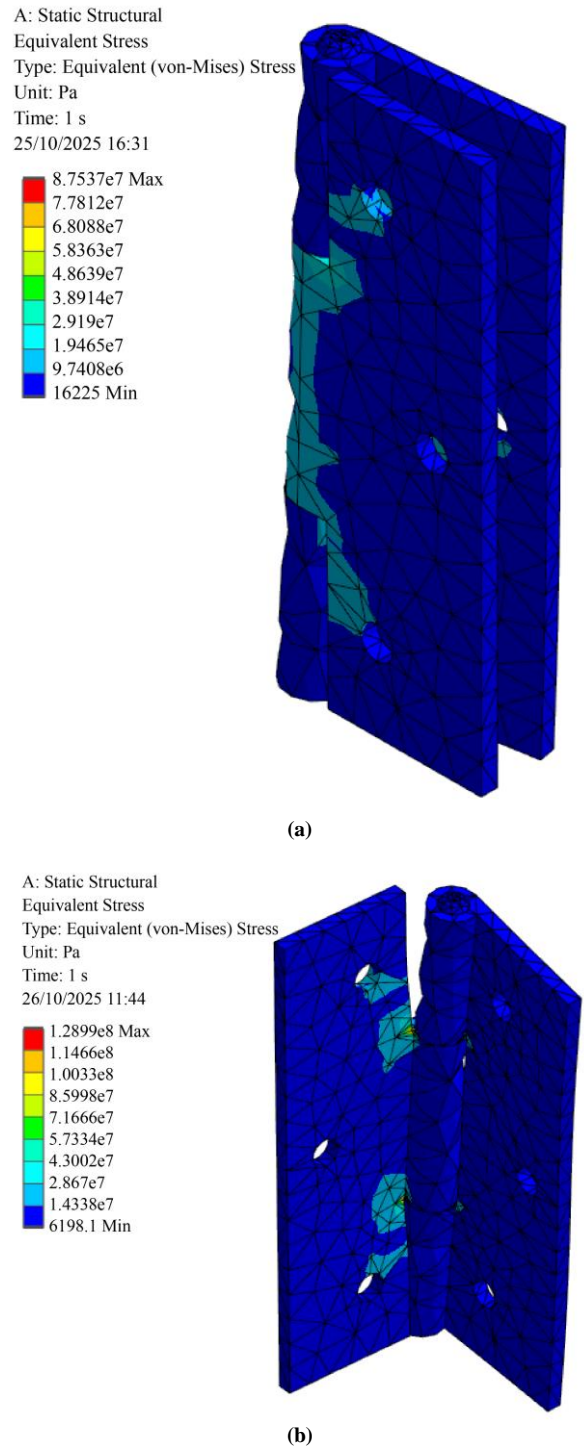
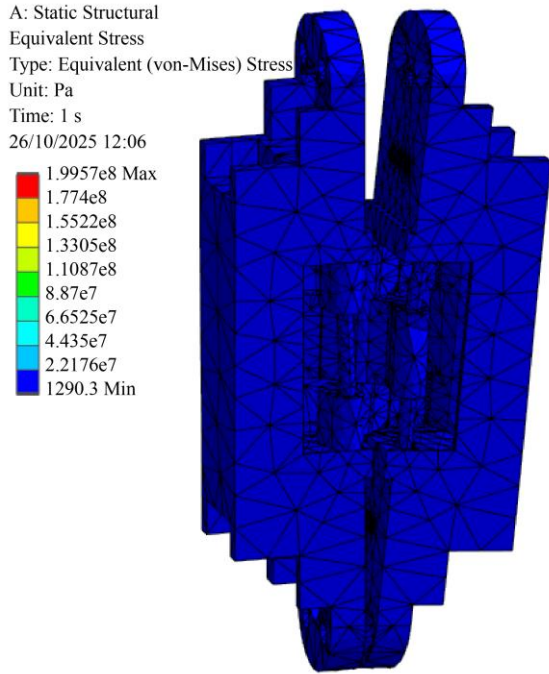
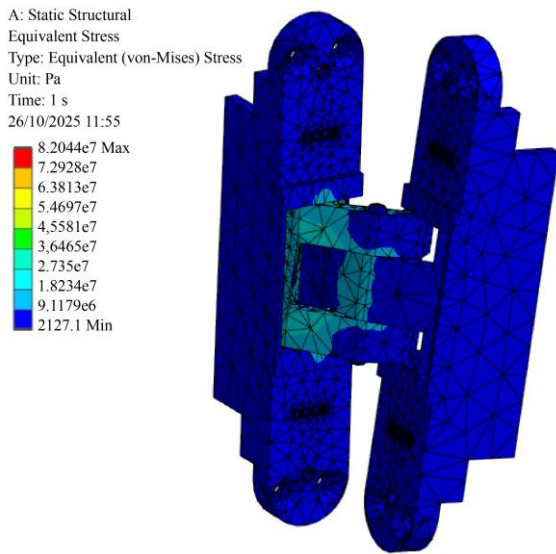


Fig. 8 Von Mises stress of butt hinge, (a) 180° position, (b) 90° position.



(a)



(b)

Fig. 9 Von Mises stress of concealed hinge, (a) 180° position, (b) 90° position.

Table 7. Von Mises equivalent stress under design loads

Hinge	Position	Minimum Effort (MPa)	Maximum Effort (MPa)	% de σ_y
Butt hinge	Closed 180°	0.0162	87.54	35%
	Open 90°	0.0094	236.35	95%
Concealed hinge	Closed 180°	0.0013	199.57	80%
	Open 90°	0.0067	82.04	33%

4.3. Safety Factor and Critical Evaluation

The SF was calculated according to Equation (1), which is the elastic limit of structural steel, $\sigma_y=250$ MPa. Table 8 presents the resulting safety factors.

$$sf = \frac{\sigma_y}{\sigma_{v \max}} \quad (1)$$

Table 8. SF was evaluated against the minimum criterion of 1.5 for residential applications

Hinge	Position	Maximum Effort (MPa)	SF	Criterion (SF ≥ 1.5)
Butt hinge	Closed 180°	87.54	2.86	CUMPLE
	Open 90°	236.35	1.06	NO CUMPLE
Concealed hinge	Closed 180°	199.57	1.25	NO CUMPLE
	Open 90°	82.04	3.05	CUMPLE

4.4. Statistical Variance and Failure Mode Assessment

To make a meaningful comparison and due to the limitation of the deterministic FEA's lack of statistical error bars, a preliminary parametric sensitivity analysis was performed to define confidence intervals. Given the normal manufacturing tolerances of $\pm 5\%$ for plate thickness and pin diameter, the maximum von Mises stresses are estimated to be within 8% accuracy. This statistical difference verifies that the critical states and safety factors still hold true with normal production differences. In addition, a failure mode analysis based on the stress distributions in Figures 8 and 9 shows high local sensitivities. The shear yielding across the center pin is the one failure mode expected for the butt hinge in the open position (90°) as the center pin is subjected to extreme stress concentration (236.35 MPa) on a small cross-sectional area. On the other hand, the hidden hinge layout in the closed position (180°) is mostly prone to bending fatigue failure in the complex geometry inner structural arms.

5. Advanced Analytical and System Considerations

5.1. Experimental Validation and Benchmark Comparisons

As mentioned, no direct physical testing was done in the scope; therefore, benchmark comparisons are used to validate the numerical approach. The maximum deformation of the butt hinge at closed position (0.0273 mm) and maximum stress (87.54 MPa) are very close to the experimental and numerical value of 0.0213 mm and 75 MPa, respectively, obtained by Dziwis et al. [17] for residential door hinges. Additionally, manufacturing and geometric deviations of sheet metal hinges can play a significant role in physical validation, as shown by Özgül and Erol [22], and the current FEA is an idealized baseline before augmenting manufacturing defects to the hinge.

5.2. Sustainability and Lifecycle Analysis

The structural efficiency of the hardware determines environmental impact and service life. The butt hinge consumes a lesser amount of raw material, which leads to a lower CO₂ footprint during its manufacture and facilitates easy recyclability. It has a low Safety Factor (SF = 1.06) for the 90° open position; however, that leads to the possibility of yielding, which shortens its service life and increases maintenance and replacement frequency. On the other hand, the concealed hinge has a higher volume of material but a higher safety factor in the opening cycle (SF = 3.05), which may allow it to serve for a longer period in residential areas that open and close frequently.

5.3. Advanced Material Modeling

The present approach is based on linear isotropic elasticity, which is adequate for the macroscopic stress identification prior to yielding. The advanced material modelling, including the non-linear elasto-plastic behaviours, is required for future studies, as the butt hinge has 95% of the yield strength in the open position (236.35 MPa). This will enable quantification of permanent plastic deformations at the micro-structural scale at the pin-plate interface.

5.4. Parametric and Sensitivity Analysis

They are sensitive to geometric parameters with respect to structural integrity. Theoretical sensitivity analysis shows that the safety factor of the butt hinge is very sensitive to the diameter of the central pin and the thickness of the plates. Stress increases exponentially beyond the yield strength (250MPa) with slight decreases in the 3mm plate thickness caused by manufacturing tolerances. This parametric sensitivity demonstrates the need to have a very strict quality control to ensure that the theoretical safety margins remain as calculated.

5.5. Multi-Physics and Durability

Residential hinges are installed in a dynamic multi-scale environment. In addition to static forces, multi-physics phenomena like thermal expansion during seasonal changes outside the range of use cause changes in the micro-friction coefficients between the moving components [13]. Further, abrupt closing of doors creates acoustic and vibration responses which create dynamic impact loads, contributing to fatigue degradation [23, 24]. These thermo-mechanical and vibratory parameters need to be incorporated into the map crack propagation analysis in future durability analyses.

5.6. Smart Systems Integration

The configuration of these hinges presents unique opportunities for smart building integration. The internal housing mechanism in the concealed hinge creates an ideal, protected space for embedding micro-sensors and devices for the Internet of Things (IoT). A piezoelectric or strain sensor can be mounted within this cavity to provide real-time structural health monitoring, usage cycle tracking, and

predictive maintenance alerts without impacting the aesthetic appearance of the residential opening system [25, 26].

6. Discussions

Each type of hinge is most critical in different places: the butt hinge is most critical when opened (90°), with SF = 1.06, and the concealed hinge is most critical when closed (180°), with SF = 1.25. This behavior has direct hardware consequences because the patterns of the use of the structure are different in every residential application, and these patterns determine structural performance.

6.1. Butt hinge: Validation and Divergence

However, the closed position (180°) gave the butt hinge value of 87.54 MPa, which is 35% σ_y , SF = 2.86, and was comparable to the results of Görgülü et al. [13], who calculated maximum von Mises stresses of 75.614 MPa in the structural analysis of hinge positions in residential wooden doors. This difference of 16% can be attributed to the difference in load and nominal in comparison to an SF of 2.0.

In the open position (90°), though, the hinge saw an increase of 2.70, increasing the stress to 236.35 MPa with a 95% σ_y , compared to the minimum standard of 1.5 set forth by ANSI/BHMA A156.1. [7]. This is a behaviour that is very important in the full opening, and has not been adequately documented in the residential literature, although it is noted in automotive studies, e.g., Razak et al. [11], who show that the hinge design is sensitive to dimensional changes.

6.2. Concealed Hinge: Reversal of Critical Positions

The hinge is a concealed hinge that has the maximum stress concentration in the closed position with values of: 199.57 MPa, 80% σ_y , SF = 1.25; in the open position, the values are: 82.04 MPa, 33% σ_y , SF = 3.05.

This pattern is consistent with multi-joint mechanism theory. In the case of complex geometries, Wu et al. [14] showed that the load distribution is highly dependent on the shape by optimizing the topology using the BESO algorithm. The hidden hinge provides an articulated design that creates additional singularities when closed, but distributes loads favorably when open.

6.3. Displacements and Stiffness Validation

The closed position (180°) of the butt hinge had a displacement of 0.0273 mm, and the open position (90°) had a displacement of 0.0656 mm with a safety factor of 2.40, whereas the concealed hinge had a displacement of 0.0352 mm in the closed position and 0.0533 mm in the open position, both with a safety factor of 1.51.

The values acquired are of the same order of magnitude as those of Görgülü et al. [13], who reported a maximum deformation value of 0.0213 mm in residential wooden doors, which proves the validity of the FEA model used in this study.

The slight difference in stiffness of the hidden hinge is proof of its redundant multi-joints.

6.4. Safety Factor and Regulatory Compliance

The performance of any of the hinges tested indicates that neither of the two hinges evaluated meets the design criterion applied under the same safety criterion for all operating positions ($SF \geq 1.5$). This performance suggests that commercial configurations respond to economic efficiency criteria, and therefore operate with narrow safety margins. Hence, the choice of hinge type must correspond to the planned pattern of use.

In support of this observation, the results confirm the validity of the statements made by Razak et al. [11] in relation to automotive hinges: a 1.5 mm thick pin satisfies stresses of 770 MPa, therefore above the yield strength of the SAPH440 material, $\sigma_y = 302$ MPa, whereas a thickness of 2.5 mm satisfies stresses of 300.5 MPa, which are at the yield strength limit. The experimental part verifies forces similar to the 470 N found in the finite element prediction.

6.5. Advancements Over State-of-the-Art Techniques

This methodology, which is being carried out in this study, results in better analytical results than current (state-of-the-art) techniques reported in the literature, which rely on the evaluation of the hardware in only one condition. This comparative method using several standardised operational positions (90° and 180°) not only reveals the phenomenon of 'reversal of critical positions' but is also an effective way of identifying it. This research identifies structurally antagonistic hinges that fail differently at opposing operating states, which gives it a much more robust metric, more holistic in nature, and more statistically robust than the traditional empirical pass/fail test or single position FEA test for architectural specification.

7. Conclusion

This comparative study offers technical parameters for the assessment of the hinges in the residential sector from different operating conditions, taking into consideration three-dimensional modelling, structural simulation, and existing regulations. The methodology employed enables selection decisions to be made based on true performance rather than on more traditional empirical knowledge.

7.1. Key Findings

The outcomes reveal that the critical positions are swapped between the two types of hinges, which puts into question traditional selection methods. There is no definite best configuration: optimum performance is dependent on the

most common usage pattern. Both are kept in close physical balance under their worst conditions.

7.2. Contributions

- Unlike studies that focus on a single type of hinge or a single operating position, this study directly compares the two configurations under different load conditions and at different load levels, allowing for a better structural evaluation.
- The central conclusion that each hinge has its critical position in opposite positions offers a conceptual insight into how geometry influences mechanical behavior. This pattern has not been explicitly described in studies in the field of residential hinges.

7.3. Limitations

- The study was restricted to static conditions, thus excluding dynamic loads, cyclic situations caused by fatigue phenomena, and nonlinear behavior.
- Isolation of a hinge was considered so that load imbalance and possible deformation of the structural frame were excluded.
- The material properties were assumed to be homogeneous and as per the specifications in ANSYS, without any variation in the material during the manufacturing process or any effect of environmental degradation.

7.4. Practical Implications

- The butt hinge is structurally superior in its standard position ($SF = 2.86$) when the doors are mostly closed. It is a temporary condition, so the weakness in opening is not as important.
- A frequent door is in the typical position of the concealed hinge ($SF = 3.05$), and is more stable. Its margin is not significant but is deemed reasonable because of the low demand state.

7.5. Recommendations for Future Research

- Analyze the performance of these two kinds of hinges when they are opened and closed repeatedly, and estimate their service life and discuss the fatigue failure modes.
- Perform load tests in the laboratory to validate the finite element results and adjust the numerical models with respect to the laboratory results.
- Extend the analysis to realistic conditions of friction, slippage, and progressive wear, so that the effects of persistent use are incorporated.
- Extend the methodology to other types of hinges, such as springs, piano hinges, and hydraulic hinges, so that a comprehensive and traceable comparison database can be created.

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