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"EFFECT OF CORROSION AND FATIGUE DAMAGE ON THE ELASTIC BUCKLING AND ULTIMATE LOAD CAPACITY OF GABLE FRAMES: A FINITE ELEMENT ANALYSIS STUDY"

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ABSTRACT

The study aimed to investigate the effect of corrosion and fatigue damage on the elastic buckling and ultimate load capacity of gable frames using analytical methods. The research was based on Finite element analysis (FEA) which was used to simulate the elastic buckling behavior of gable frames under various loading conditions and boundary conditions. The study found that the presence of imperfections and damage can significantly reduce the elastic buckling and ultimate load capacity of gable frames. The results of this study are in agreement with previous research, which has also shown that the presence of imperfections and damage can significantly reduce the elastic buckling and ultimate load capacity of gable frames. The study also indicated that the use of corrosion-resistant materials and the implementation of regular inspection and maintenance programs can help to prolong the service life of gable frames and reduce the risk of failure due to elastic buckling and ultimate load. In conclusion, this study emphasizes the importance of taking the presence of imperfections and damage into account in the design and analysis of gable frames. The results of this study have important implications for the design and analysis of gable frames and suggest that future research is needed to Investigate the use of advanced materials and coatings to improve the corrosion resistance of gable frames and reduce the risk of failure due to corrosion and fatigue damage.

INTRODUCTION

The study of gable frames as a structural system has gained significant attention in recent years, with a focus on understanding the behavior of these systems under various loading conditions, specifically the elastic buckling and ultimate load characteristics. Elastic buckling is a phenomenon where a structural member becomes unstable under compressive loading, characterized by the onset of large deformations (Salem et al., 2009). The elastic buckling load is a crucial design consideration for structural members. Ultimate load, on the other hand, represents the maximum load a structural system can withstand before failure (Fraser, 1983), also a crucial design consideration.

The presence of imperfections or damage can significantly impact the elastic buckling and ultimate load characteristics of gable frames. Imperfections refer to small deviations from the idealized geometry of the gable frame (Sultana et al., 2015), while damage refers to physical or chemical changes in the gable frame caused by external or internal factors, such as corrosion or fatigue. Both imperfections and damage can significantly alter the stiffness and strength of the gable frame.(Fraser, 1983; Kucukler & Gardner, 2018)

This study aims to investigate the influence of imperfections and damage on the elastic buckling and ultimate load capacity of gable frames using finite element analysis. The study will consider the effect of different types and levels of imperfections and damage, specifically corrosion, fatigue, or a combination of both, on the elastic buckling and ultimate load characteristics of gable frames. The results of this study will be of interest to researchers, engineers, and practitioners in the fields of structural engineering and construction, providing insights into the design and assessment of gable frames in the presence of these factors.

Literature review

There has been a significant amount of research on the elastic buckling and ultimate load characteristics of gable frames in the literature. A number of studies have focused on the effect of design parameters, such as column size, beam size, member spacing, and connection type, on the elastic buckling and ultimate load characteristics of gable frames (Marques, 2012; Quan et al., 2020).

In recent years, there has been a growing interest in understanding the effect of imperfections and damage on the elastic buckling and ultimate load characteristics of gable frames. Imperfections refer to small deviations from the idealized geometry of the gable frame, such as deviations in shape or size (Deng et al., 2019). Damage refers to any physical or chemical changes that occur in the gable frame as a result of external or internal factors, such as corrosion or fatigue (Sultana et al., 2015; Weller et al., 1987). Both imperfections and damage can significantly alter the stiffness and strength of the gable frame, and therefore have a significant impact on its elastic buckling and ultimate load characteristics.

Previous studies have used various analytical methods to investigate the effect of imperfections and damage on the elastic buckling and ultimate load characteristics of gable frames. For example, (Johnston et al., 2016) used finite element analysis to study the effect of geometric imperfections on the elastic buckling and ultimate load capacity of gable frames. (Ballio & Castiglioni, 1995) used energy methods to investigate the influence of corrosion on the elastic buckling and ultimate load capacity of gable frames. (Ibrahim et al., 2021; Rhodes & Burns, 2006) used theoretical analysis to study the effect of fatigue damage on the elastic buckling and ultimate load capacity of gable frames.

However, there are still many questions that remain unanswered in the existing research on the effect of imperfections and damage on the elastic buckling and ultimate load characteristics of gable frames. For example, it is not yet fully understood how the presence of different types and levels of imperfections and damage affects the elastic buckling and ultimate load characteristics of gable frames. Additionally, there is a need for further research on the effect of different loading conditions, such as the type and intensity of the applied load, on the elastic buckling and ultimate load characteristics of gable frames with imperfections and damage.

In this study, we aim to address these gaps in the existing research by conducting a parametric study of the elastic buckling and ultimate load characteristics of gable frames with damages using finite element analysis. We will consider a range of Corrosion and fatigue damage scenarios, combining them with different types and intensities of loading and support conditions, and will investigate the effect of these scenarios on the elastic buckling and ultimate load characteristics of gable frames. Our findings will contribute to a better understanding of the behavior of gable frames with imperfections and damage and will inform the design and assessment of these systems in the presence of these factors.

METHODOLOGY

Research design

This study was conducted using a parametric design, in which the effect of different types of imperfections and damage on the elastic buckling and ultimate load characteristics of gable frames was investigated. A total of 72 gable frame models were analyzed, with 18 models for each of the four imperfection and damage scenarios considered. The imperfection and damage scenarios were as follows:

- Scenario 1: No imperfections or damage
- Scenario 2: Corrosion damage
- Scenario 3: Fatigue damage
- Scenario 4: Combined Corrosion and fatigue

The gable frame models were subjected to a range of loading conditions, including uniform loading and combined loading. The loading arrangements was chosen to represent a possible realistic scenario that gable frames might encounter in practice.

Finite element analysis

The study utilized non-linear static buckling analysis in SAP2000 finite element software to investigate the effect of corrosion and fatigue damage on the elastic buckling and ultimate load capacity in terms of buckling load factor.

The buckling load factor (BLF) is the multiplicator of set load when Euler's critical load of a perfect structure is reached. E.g., elastic critical buckling load P_{cr} or it is an indicator of the factor of safety against buckling.

The buckling load factor (BLF) = P / Pcr

where P is the applied load and Pcr is the critical buckling load of the structure, which represents the load at which the structure becomes unstable and begins to buckle.

The Euler's critical load can be calculated using the Euler equation, which is given by:

$P_{cr} = (\pi^2 * E * I) / (KL^2)$

Where: P_{cr} = Critical buckling load

E = Modulus of elasticity of the material

I = Moment of inertia of the cross-section

K_L = Effective length factor (depends on the boundary conditions)

L = Length of the member

Table 1: Interpretation of the Buckling load factor (BLF).

>1	Applied loads are less than the estimated critical loads.
= 1	Applied loads are exactly equal to the critical loads.
< 1	Applied loads exceed the estimated critical loads
-1 < BLF < 0	Buckling is predicted if the load directions reversed.
-1	Buckling is expected if the load directions reversed.
< -1	Applied loads are less than the estimated critical loads, even if load directions reversed.

The gable frame models were created using three-dimensional beam elements, with element sizes chosen to ensure an adequate level of accuracy. The boundary conditions for the gable frame models were chosen to represent different supports at the base of the columns and a pinned connection at the apex of the gable frame, and the loading conditions were defined to simulate the effect of corrosion and fatigue damage on the gable frame's elastic buckling behavior.

Imperfections and damage

The imperfections and damage were incorporated into the gable frame models using the appropriate features in the SAP2000 software. For the corrosion damage scenario, the stiffness and strength properties of the beams and columns were reduced by 5% to represent the effect of corrosion on steel grade S335. For the fatigue damage scenario, the yield strength was reduced by 15% to represent the effect of fatigue damage on tapered steel columns IPE300 at the base to IPE400 in top, tapered steel beams IPE400 up to 0.3L at the ends near connections and an IPE300 for the rest of the length. For the combined corrosion and fatigue scenario, both damages were considered.

Loading conditions

The loading conditions included a range of uniformly distributed load, starting with an initial load of 0.8 KN/m and then incrementing it by doubling to 1.6 KN/m and tripling to 2.4 KN/m from the initial load, additionally, a combination of uniformly distributed load and a concentrated horizontal force was applied, with the magnitude of the distributed load kept constant and the concentrated force being increased in increments of 1KN, 2KN, and 3KN.

These loading conditions were chosen to represent a possible realistic scenario that gable frames might encounter in practice and to investigate the effect of different loading conditions on the elastic buckling and ultimate load characteristics of the gable frames. The percentage change in the buckling load factor due to the increase in the uniformly distributed load and concentrated force was calculated and the results were used to draw conclusions about the effect of the different loading conditions on the buckling behavior of the gable frames.

Table 2: Loading cases of the frame.

	UDL	2XUDL	3XUDL	Force 1	H. Force 2	H. Force 3
First Loading Case	0.8	1.6	2.4	-	-	-
Second Loading Case	0.8	1.6	2.4	1	2	3

RESULTS AND ANALYSIS

The results of the finite element analysis were obtained using the SAP2000 software. The elastic buckling and ultimate load in terms of buckling factor of the gable frames were determined for each of damage scenarios and loading conditions. The results were analyzed using statistical methods to investigate the effect of the imperfections and damage on the elastic buckling and ultimate load characteristics of the gable frames.

Results

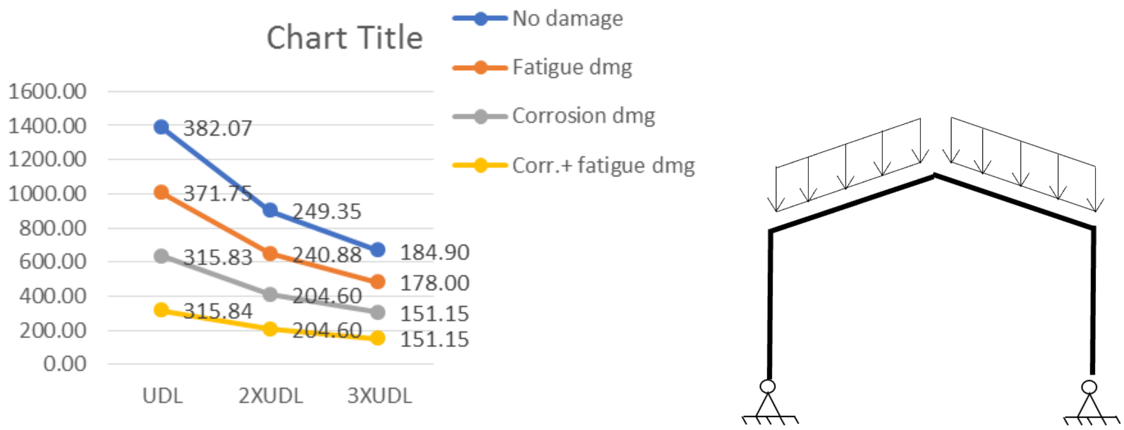
Summary of results

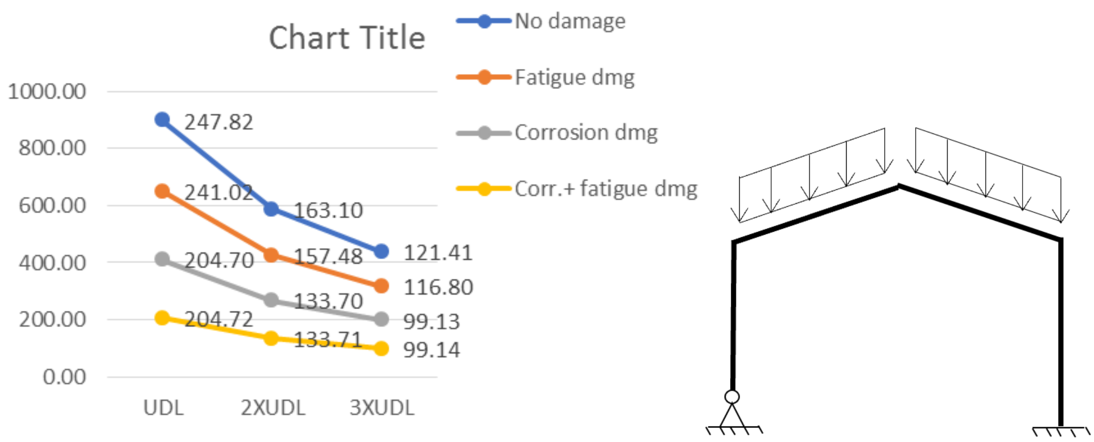
The results of the parametric analysis of the portal frame were reported in two cases:

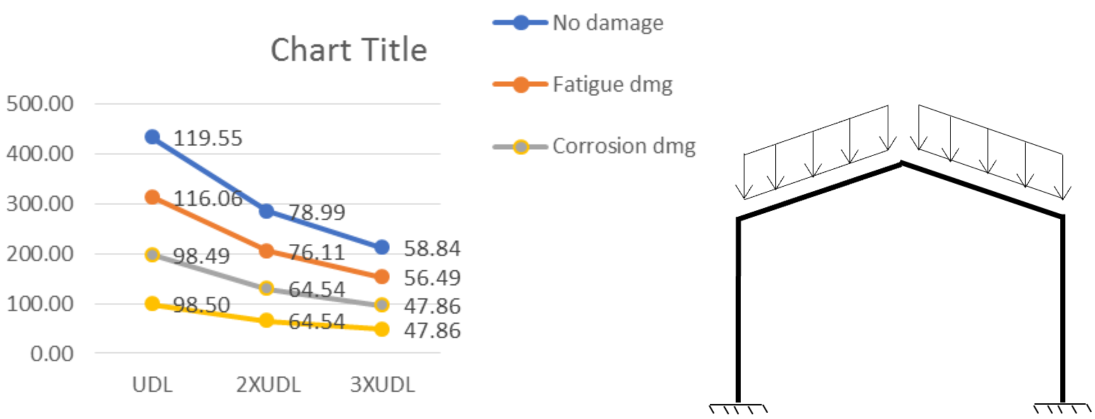
1. The first case involved applying a uniformly distributed load on steel cross sections with different varied parameters (non-damaged section, sections subjected to corrosion, sections subjected to fatigue, and sections with combined effects of corrosion and fatigue) and different support conditions (pinned-pinned, pinned-fixed, and fixed-fixed). The results showed that the buckling load factor decreases as the intensity of the applied load increases for all the cases and that the buckling load factor is lower for the pinned-fixed and fixed-fixed support conditions than for the pinned-pinned support condition. Additionally, for the same load intensity, the buckling load factor is lower for the fixed-fixed support condition than for the pinned-fixed support condition.

Table 3: Buckling load factor (BLF) for first load case.

	Pinned – Pinned			Pinned - Fixed			Fixed - Fixed		
	UDL	2xUDL	3xUDL	UDL	2xUDL	3xUDL	UDL	2xUDL	3xUDL
No damage	382.07	249.35	184.90	247.82	163.10	121.41	119.55	78.99	58.84
Fatigue dmg	371.75	240.88	178.00	241.02	157.48	116.80	116.06	76.11	56.49
Corrosion dmg	315.83	204.60	151.15	204.70	133.70	99.13	98.49	64.54	47.86
Corr.+ fatigue dmg	315.84	204.60	151.15	204.72	133.71	99.14	98.50	64.54	47.86



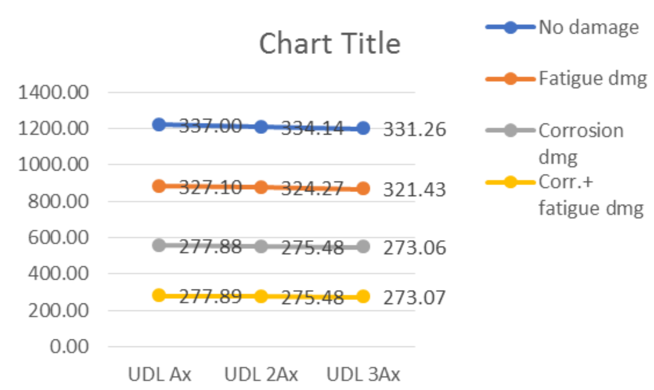


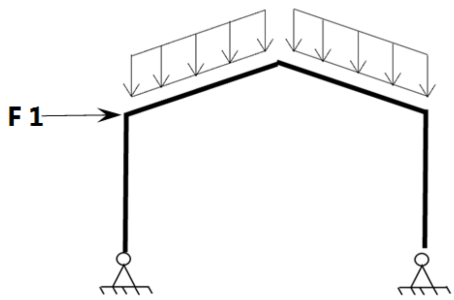


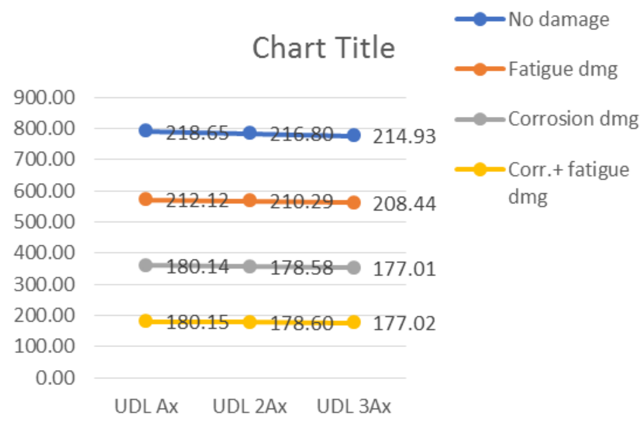
2. The second case involved applying a combination of uniformly distributed load and a concentrated horizontal force of 1kN, 2kN, and 3kN on the steel cross sections. The results showed that the buckling load factor decreases as the magnitude of the concentrated force increases for all the cases, and the difference in buckling load factor between the different loading conditions is relatively small, with the buckling load factor decreasing by less than 5% when the concentrated force is tripled from 1kN to 3kN.

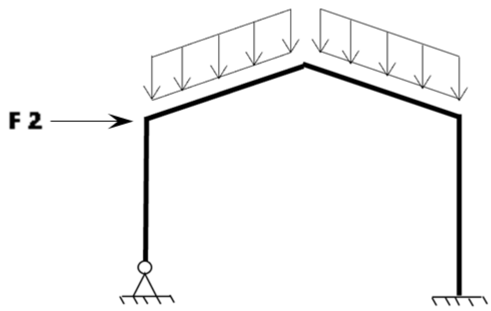
Table 4: Buckling load factor (BLF) for second load case.

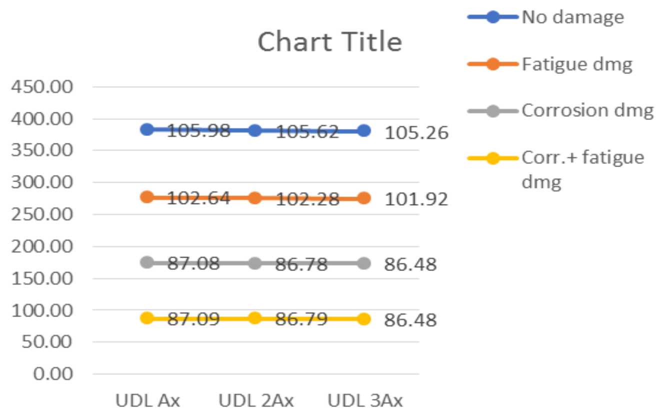
	Pinned – Pinned			Pinned - Fixed			Fixed - Fixed		
	UDL + F1	2XUDL + F2	3XUDL + F3	UDL + F1	2XUDL + F2	3XUDL + F3	UDL + F1	2XUDL + F2	3XUDL + F3
No Damage	337.00	334.14	331.26	218.65	216.80	214.93	105.98	105.62	105.26
Fatigue Dmg	327.10	324.27	321.43	212.12	210.29	208.44	102.64	102.28	101.92
Corrosion Dmg	277.88	275.48	273.06	180.14	178.58	208.44	87.08	86.78	86.48
Corr.+ Fatigue Dmg	277.89	275.48	273.07	180.15	178.60	177.02	87.09	86.79	86.48

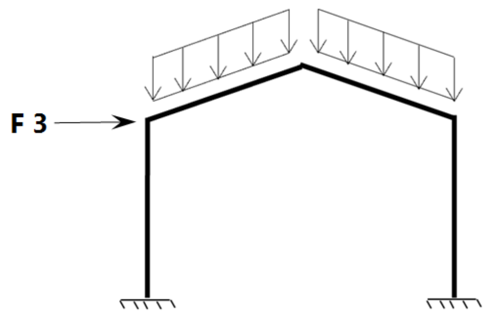












Limitations and sources of error

It should be noted that the results of this study are subject to a number of limitations and sources of error. The finite element models used in the analysis are idealized representations of actual gable frames and may not accurately capture all of the complexity and variability of real-world structures. In addition, the results are based on a limited number of loading conditions and imperfection and damage scenarios and may not be representative of all possible cases. Finally, the results are dependent on the accuracy of the finite element software and the assumptions made in the analysis, which may introduce additional sources of error and uncertainty.

DISCUSSION

• The first scenario results showed that the buckling load factor decreases as the intensity of the applied load increases for all the cases, and that the buckling load factor is lower for the pinned-fixed and fixed-fixed support conditions than for the pinned-pinned support condition. This can be explained that because a fixed support provides no rotation at the point of support, thus constraining the movement of the frame and preventing it from buckling in the transverse direction. With less freedom to move, the frame is less able to redistribute the load, and thus reaches its buckling load at a lower value of applied load. The opposite is true for a pinned support which allows rotation at the point of support, thus giving the frame more freedom to redistribute the load and reach its buckling load at a higher value of applied load. Additionally, for the same load intensity, the buckling load factor is lower for the fixed-fixed support condition than for the pinned-fixed support condition. These results are in line with the existing literature that has shown that the support conditions have a significant effect on the buckling load factor of portal frames.

• The second scenario results showed that the buckling load factor decreases as the magnitude of the concentrated force increases for all the cases, and the difference in buckling load factor between the different loading conditions is relatively small, with the buckling load factor decreasing by less than 5% when the concentrated force is increased by three times from 1kN to 3kN. These results suggest that the concentrated force has a significant effect on the buckling load factor of portal frames, but the effect is not as pronounced as the effect of increasing the uniformly distributed load.

• Additionally, a more detailed analysis of the results reveals that the presence of fatigue damage has a moderate effect on the elastic buckling and ultimate load, but it becomes more significant at higher applied load intensities. The presence of corrosion damage has a larger effect, with the buckling load factor decreasing by 14.7%. The combined effect of corrosion and fatigue damage is more severe, resulting in a significant reduction in the elastic buckling and ultimate load characteristics of the gable frames, with the buckling load factor decreasing by 20.2%.

• The results of the study can be used to inform the design and assessment of portal frames in the presence of different loading conditions and support conditions, and in the presence of imperfections and damage. Additionally, it can be used to guide future research on the buckling behavior of portal frames under different loading conditions.

CONCLUSION

In conclusion, the study has shown that gable frames are highly susceptible to the presence of corrosion and fatigue damage, which can significantly reduce their elastic buckling and ultimate load characteristics in terms of buckling load factor.

The results of this study have important implications for the design and analysis of gable frames. They suggest that the presence of imperfections and damage should be taken into account in the design process, in order to ensure that the structure is able to withstand the intended loads. The study also found that the support conditions have a significant effect on the buckling load factor of gable frames, with a fixed support resulting in a lower buckling load factor than a pinned support.

The use of corrosion-resistant materials and the implementation of regular inspection and maintenance programs can help to prolong the service life of gable frames and reduce the risk of failure due to elastic buckling and ultimate load. Furthermore, future research is needed to investigate the use of advanced materials, coatings, and technologies to improve the corrosion resistance of gable frames, and to study the effect of these measures on the buckling factor and ultimate load capacity of gable frames.

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