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Forensic Analysis of Damage in Malaysia Government Structural Assets: Case Studies from JKR Reports

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Abstract

The Public Works Department (PWD)'s primary roles include conducting forensic investigations into structural failures and recommending detailed corrective and preventive measures. It also serves as an expert advisory body, providing expert advice and assessments on structural forensics issues to other government departments and agencies. The department ensures the safety and integrity of government assets through expert forensic analysis and guidance. The research objective is to identify the causes of damage to government-owned structures using forensic reports from the PWD Forensic Division. The scope is focused on forensic reports issued specifically by the PWD building's forensic team. Published forensic reports from the PWD Forensic Division were assessed. The research involved identifying and analysing the findings from these reports to determine the variables associated with damage to different building structures. The data was compiled, conceptualised, and statistically analysed to explore correlations between damage factors. There is a notable increase in the number of forensic reports produced each year. Based on the research results, several variables contribute to the structural damage of government buildings. The most frequently observed factor is material deterioration. An in-depth analysis indicates that cracks in the building structure are a primary cause of material deterioration. These cracks often occur alongside other forms of damage such as delamination, spalling, and corrosion. The conclusion drawn from this research is that the number of forensic examination applications for government buildings is likely to increase. The prevalence of cracks found in the majority of forensic reports indicates significant structural changes that are often only visible through detailed examination. This highlights the need for meticulous attention from all technical stakeholders involved in design, project monitoring, and maintenance. Addressing these issues proactively is essential to ensure the structural integrity and longevity of government buildings.

1. Introduction

The Public Works Department (PWD), established circa 1872, was the first department established by the administration of the "Crown Colony" before the Pangkor Treaty. Major J. FA McNair, a former Colonial Engineer of the Straits Settlements, led the PWD at the start of the establishment of the PWD that year. PWD was established to support the British government's socioeconomic development and political system in the Straits Settlements, which include Singapore, Melaka, Perak (Dinding), Seberang Perai, and Penang. After the union of the Straits Settlements PWD and the Federated Malay States PWD in Singapore, the PWD began to flourish until the formation of Malaysia's administrative centre PWD, which was shifted to Kuala Lumpur. The PWD has been led by 41 experienced Director Generals as of 2021.

PWD is responsible for providing infrastructure across a wide range of construction sectors, including roads, bridges, and public buildings that provide public services to the greatest extent feasible. In 2023, PWD successfully completed 2118 building projects and maintained 9,349 government buildings. It is PWD's responsibility to ensure that all of this infrastructure is always safe for use [1]. The annual periodic inspection is carried out by certified PWD Negeri manpower, where the inspections cover civil, structural, mechanical, and engineering assessments. Minor damages discovered will be repaired, while those that require further investigation will be sent to the PWD Headquarters' forensic department. The PWD forensic team will conduct a "health check" to ensure the building's safety in light of the damage it has sustained, identifying building defects, hazards, and failures, monitoring asset condition, and predicting future deterioration.

Fig. 1 depicts the final phase of life cycle management of asset disposal. Before it is decided to dispose of an asset or structure, it has gone through several stages of maintenance. The maintenance performed aims to extend the service life of the structure, which can provide a guarantee of safety and comfort to the structure's users. This is due to the fact that the structure will experience wear and tear throughout its service life, which will be influenced by three (3) major factors: the structure's age, normal or fair use, and the climate surrounding the structure. When this structure is exposed to these three factors, it will gradually undergo changes such as depreciation, reduction, or a fall in the functional performance or value of a building's services.

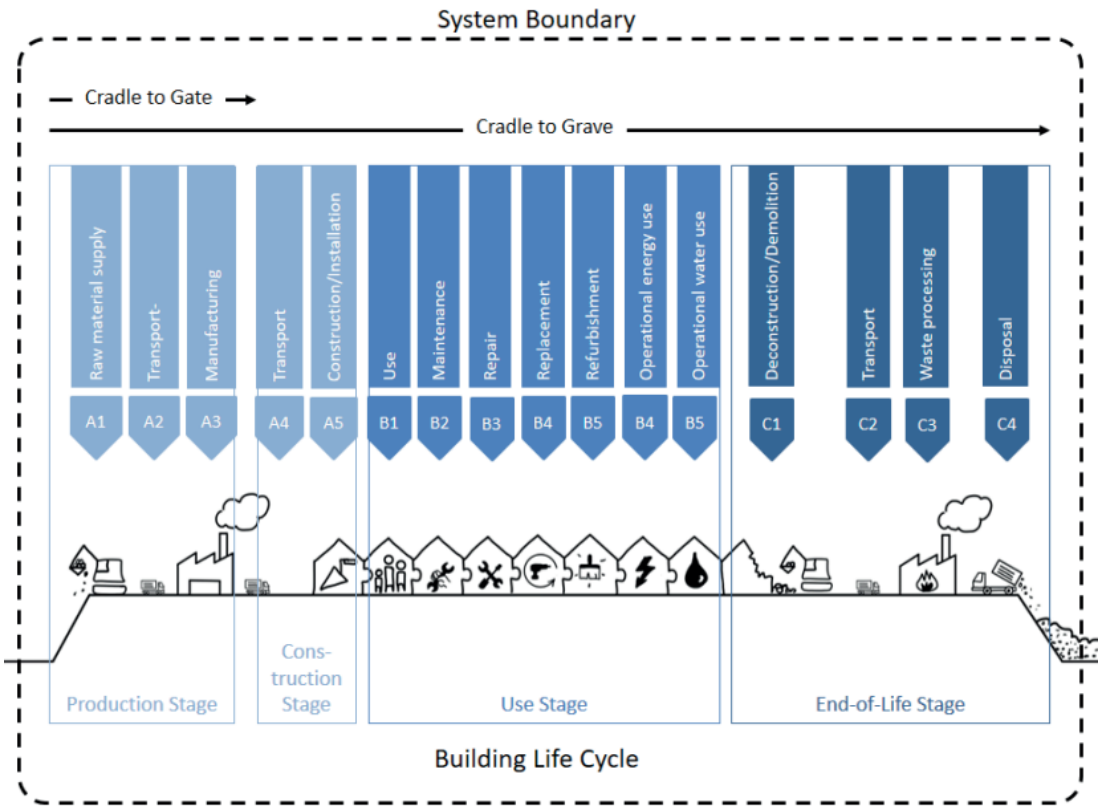

Fig. 1 *The different stages considered in a building life-cycle analysis [2]*

1.1 Structure Maintenance in Malaysia

This maintenance will begin when this structure is ready to be built. About 60 to 80 per cent of the building's operating costs are attributed to maintenance [3], [4], and about 90 per cent of the lifetime of building projects requires maintenance work [5]. Maintenance is essentially required to delay the appearance of defects to ensure that buildings perform optimally throughout their life cycle.

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Referring back to 1971, Malaysia can be seen to have taken early action in maintaining infrastructure assets in this country, with this year's emphasis on the transportation and communication sectors. This was explained in the 2nd Malaysia Plan (1971-1975) [6], where 8.44% of total transport and communication expenditure was allocated for maintenance projects. This maintenance cost rises year after year to ensure that dilapidated structures can be repaired, replaced, and restored while providing users with safety assurance and extending the structure's lifespan. Since then, the government has implemented a number of changes in terms of guidelines, procedures, and circulars to ensure the effectiveness of government asset maintenance. Most recently, "Government Immovable Asset Management Procedures" was one of the regulations that may be applied [7].

1.2 Concepts of Structural Failure in General

It is necessary to first understand what structural integrity entails. The ability of a building structure or a component in a structure to bear loads, including its own weight, without breaking or deforming excessively, is referred to as structural integrity. This shows that the construction that has been implemented realises the function as designed, with the life expectancy period that has been set. All of these structures are designed with structural integrity to prevent catastrophic failure, which could result in injury, severe damage, death and/or financial loss.

Structural failure is defined as the loss of structural integrity or load-carrying capacity in a structural component or the structure itself. When a material is stressed beyond its strength limit, it fractures or deforms excessively; ultimate failure strength is one limit state that must be considered in structural design. A localised failure in a well-designed system should not cause the entire structure to collapse immediately or even gradually. Deterioration in the building structure is identified as a defect that has occurred over a period of time [8]. At this point, the completed building structure is in the same state as it was designed.

The mechanism that causes the deterioration of the structure, which consists of physical and chemical aspects, will begin to affect the structure of the building that stands tall [9]. Physical deterioration can be seen when the structure experiences freeze–thaw loads, non-uniform volume changes, temperature gradients, abrasion, erosion, or cavitation. While deterioration caused by chemicals consists of carbonation, corrosion of steel reinforcement, sulfate and acid attack, or alkali-aggregate reaction. The role of air humidity around the structure and the microstructure of different types of concrete should also be taken into consideration [10].

Each structure is designed based on the design working life as stated in the design manual. In Malaysia, structural design adheres to the Eurocode standards, and the design working life for buildings is 50 years [11]. However, building structural damage often occurs unexpectedly, which occurs during the service life of a building. It can be understood as illustrated in the schematic illustration in Fig. 2 [12]. This graph illustrates how the quality of the structure is changing over time and how it will become less stable. The expected service life as designed can be represented in the sign A during the first stage, which is the time when a structure is created. A building must offer high-quality services without requiring any maintenance. However, there have been numerous instances where this structure has gotten worse during the course of its useful life. Sign B can be used to illustrate this. If this structure has started to deteriorate earlier than planned, repair must be done right away.

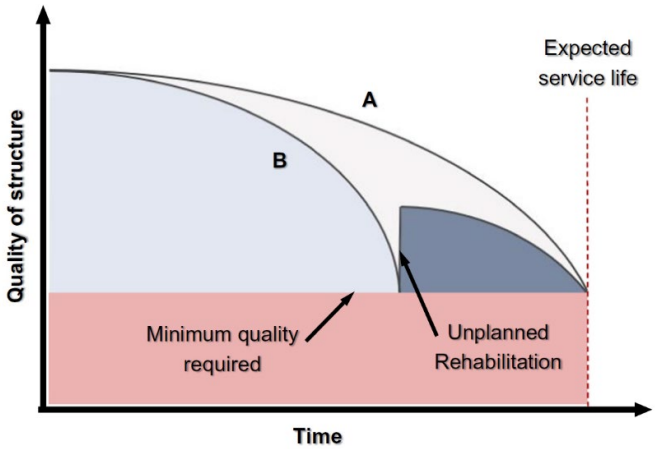

Fig. 2 *Schematic illustration of the concept of 'service life' of a structure*

A structure will continue to be maintained if maintenance is needed at an early stage. This is because the structural damage is similar to silent cancer, as in Fig. 3 [13]. This maintenance will continue to be repeated until the structure can no longer be saved, and finally, demolition will be done.

As can be seen, the government has allocated a large expenditure cost in improving the built infrastructure in Malaysia, which is the main asset of the government in providing services to the public. This infrastructure

includes roads, bridges and buildings. In order to ensure that these government assets are safe to use, PWD has taken the initiative by establishing a forensic team whose role is to carry out a comprehensive and detailed forensic investigation for federal infrastructure and building facilities.

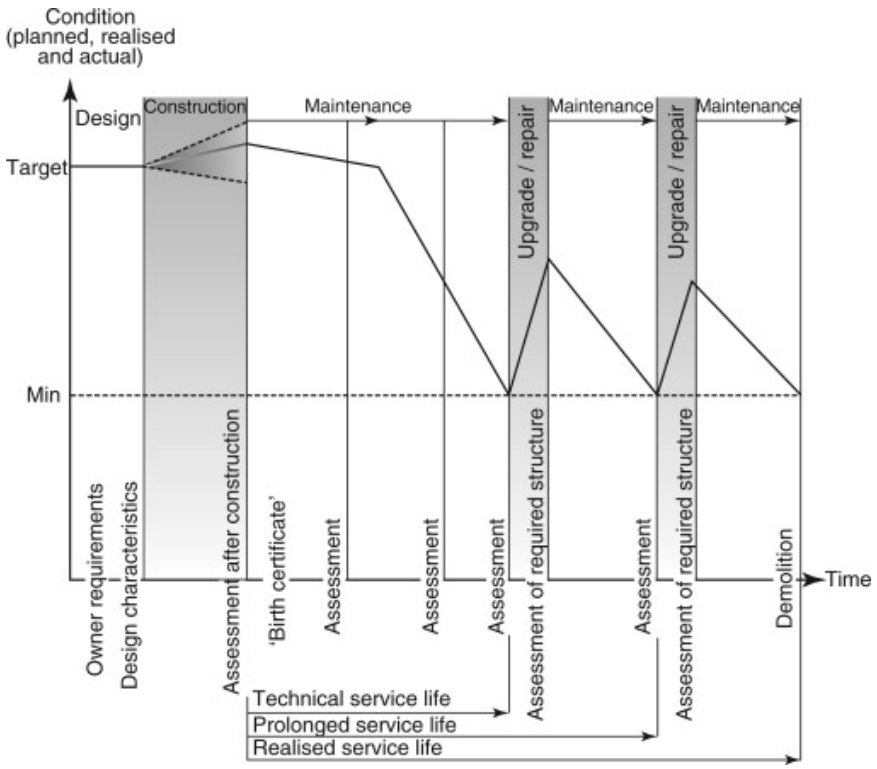

Fig. 3 *Structural service life management as structural flow from birth to exitus (adapted from [13])*

2. Building Inspection Concept

The inspection of this building can be categorised in a number of ways, all of which lead to the same result: identifying the kind of damage that was sustained and determining if it compromises the structural integrity. Three (3) primary authorities in PWD—the District PWD, the State PWD, and the Headquarters PWD Forensic Division—are responsible for conducting the inspection of this building. The only building assets that District and State PWD are involved in are those that fall under their purview.

Each of these authorities has a specialized role when it comes to inspecting the assets of the government, with the District PWD serving as the first response team on the incident in case of building issues as well as the party to carry out any directives from the PWD State or PWD Headquarters regarding the provision of advisory services management advisor in dealing with customers and authorities. While PWD Headquarters offers technical guidance based on research and expertise. The inspection plan is shown in Fig. 4 [14].

The integrity of building materials can be determined based on a destructive test (DT) and a non-destructive test. These tests can be performed during the inspection of the building structure. The details of each test are as follows [15]:

- Non-Destructive Test – (i) Covermeter Measurement, (ii) Rebound Hammer, (iii) Ultrasonic Pulse Velocity Test (UPV), (iv) Penetration Resistance Test (Windsor Probe), (v) Carbonation Test, (vi) Half-cell Potential Measurement, (vii) Initial Surface Absorption Test (ISAT), (viii) Rapid Chloride Penetrability Test (RCPT), (ix) Impact Echo Test, (x) Chloride Ponding Test, (xi) Chloride Diffusion Test (on cores), (xii) Ground Penetrating Radar (GPR), and (xiii) Steel Tensile Test.
- Destructive Test – (i) Compressive Strength Test (cores), (ii) Water Absorption Test (on cores), (iii) Sorption Test (on cores), (iv) Near-Surface Strength Test, (v) Pull-off; Pull-out; Break-off, and (vi) Petrography Test.

The building inspector will have to determine the type of damage that was observed on the structure during the initial phase of the visual inspection. The classification of the damage is decided based on the Handbook for Condition Inspection [16], which is outlined in Table 1. The information gathered will then be recorded on the PWD/Bul/1-06 building inspection form that was brought along, as seen in Fig. 5.

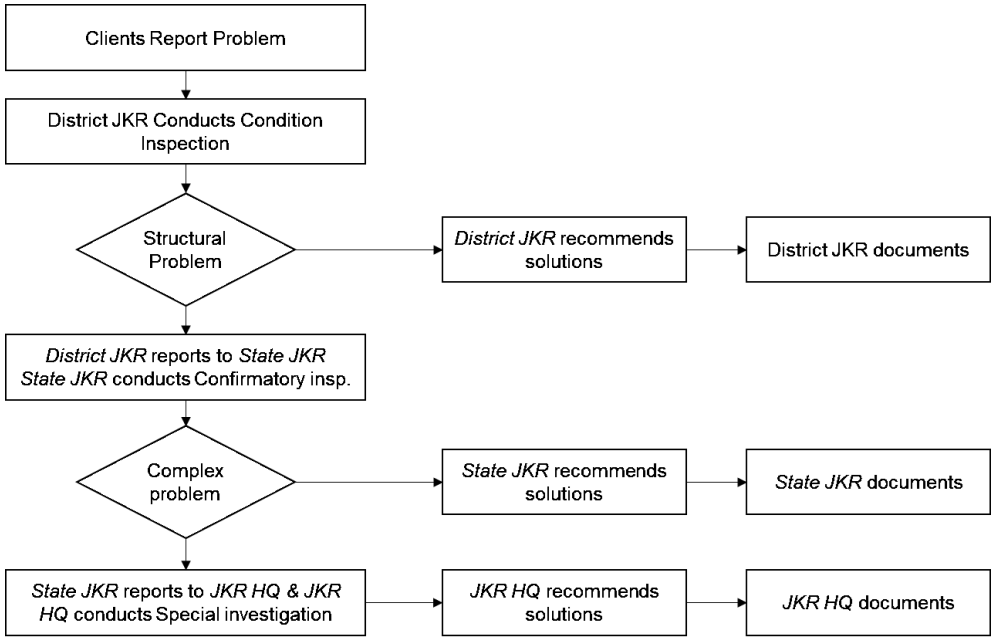

Fig. 4 *Inspection plan*

Table 1 *Types of damage and code numbers*

Damage to the Building	Number Codes
Cracks - intrinsic	6a
Cracks – corrosion-induced	6b
Cracks – load-induced	6c
Cracks - settlement	6d
Spalling	7
Exposed reinforcements	8
Delamination	12
Water leak	14
Tild	15

BUILDING MEMBER		TYPES OF DAMAGE	CODE	DAMAGE		SEVERITY OF DAMAGE				QUANTITY AFFECTED	
COMPONEN	MATERIAL			YES	NO	LIGHT	MEDIUM	SEVERE	V.SEVERE		
BEAM	[✓] CONCRETE	Cracks - Intrinsic	6a		✓						--
		Cracks - corrosion induced	6b	✓							--
		Cracks - load induced	6c		✓			✓			--
		Cracks -settlement	6d		✓						--
		Delamination	12	✓				✓		A	600mm2
		Spalling	7	✓				✓		A	900mm2
		Corrosion of reinforcement	8	✓			✓				--
COLUMN	[✓] CONCRETE	Cracks - Intrinsic	6a		✓						--
		Cracks - corrosion induced	6b	✓							--
		Cracks - load induced	6c		✓			✓			--
		Cracks -settlement	6d		✓						--
		Delamination	12	✓				✓		A	500mm2
		Spalling	7	✓			✓			A	400mm2
		Corrosion of reinforcement	8	✓			✓				--
		Tilt	15								--
FLOOR SLAB	[✓] CONCRETE	Cracks - Intrinsic	6a		✓						--
		Cracks - corrosion induced	6b		✓						--
		Cracks - load induced	6c		✓						--
		Cracks -settlement	6d		✓						--
		Cracks -settlement									
		Delamination	12		✓					A	
		Spalling	7		✓					A	
		Corrosion of reinforcement	8		✓						

Fig. 5 *Structural damage information on form PWD/Bul/1-06*

In the PWD/Bul/1-06 report, the damage condition rating (see Table 2) will be assigned, which states the current condition of the structure. After completion of the inspection, the inspector shall discuss with his engineer the findings of his inspection. Decision shall be made whether the problems can be remedied at the district level or need further inspection by the State PWD. As a general rule of thumb, non-structural problems shall be handled by District PWD, and structural problems shall be reported to State PWD.

Table 2 *Damage condition rating [8]*

Rating	Description
1	No damage found and no maintenance required
2	Damage was detected, and it is necessary to record the condition for observation purposes
3	Damage detected is slightly critical, and thus it is necessary to implement routine maintenance work
4	Damage detected is critical and in large part, and thus it is necessary to implement repair work or to conduct a detailed inspection to determine whether any rehabilitation works are required
5	Being heavily and critically damaged, possibly affecting the safety of the building, it is necessary to implement emergency temporary repair work immediately or rehabilitation work without any delay after evacuating the occupants and cordoning off the area

3. Data Collection and Analysis

This study will be successful in four (4) stages. It is critical to identify structural damage issues that frequently arise in PWD during the initial stage of selecting the study area. The number of complaints received by each forensic team can be used to identify it. When the study area has been determined, the next step is to determine who is responsible for dealing with the problem. This is critical because the PWD is made up of many branches, each with a distinct role. At the same time, there are several branches that frequently collaborate to solve problems.

After gathering the necessary information sources, data collection can begin. This data collection takes the form of a forensic report, which has been implemented in response to complaints received by the forensic department. These reports are then gathered and analysed based on the findings contained within them. These reports' data are analysed, which entails the process of collecting, modelling, and analysing data to generate insights that aid decision-making. The study data were examined using descriptive analysis methods. In the final stage, a conclusion is reached based on the results of the analyses. Fig. 6 depicts the stages of the methodology used to conduct this study.

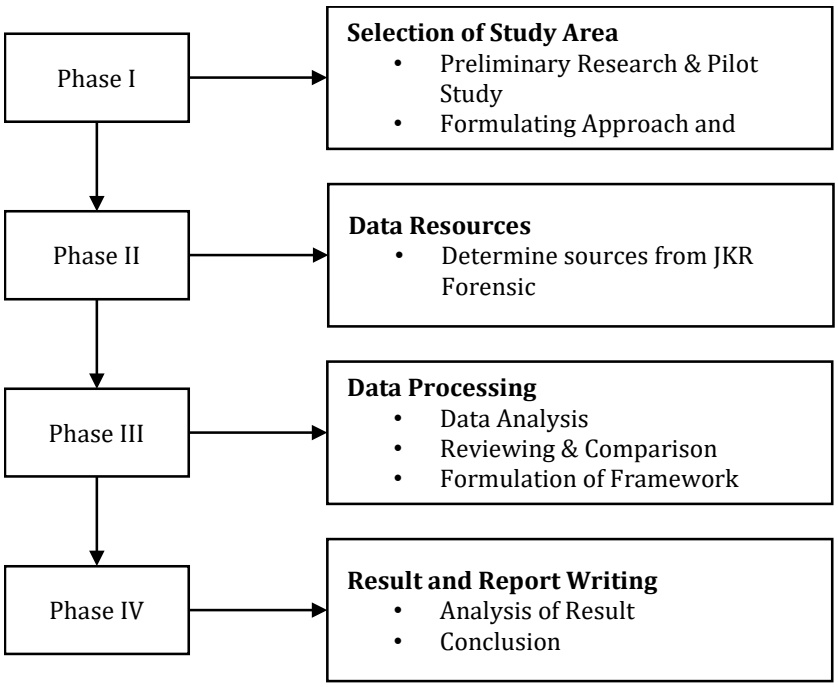

Fig. 6 *Stages in data analysis*

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4. Results and Findings

4.1 Application Trends for Forensic Examination Purposes

This forensic investigation will be carried out when there is an application from the client. Generally, the client makes a request for a forensic examination based on complaints received from users or damage that can be seen visually. According to a summary of reports collected beginning in 2010, the average annual increase in forensic examination applications is 18%, as shown in Fig. 7. This number of applications is a compilation of applications from all Malaysian government agencies that own the building's structural assets. There are two (2) reports prepared, one through a feedback letter and one through an inspection report.

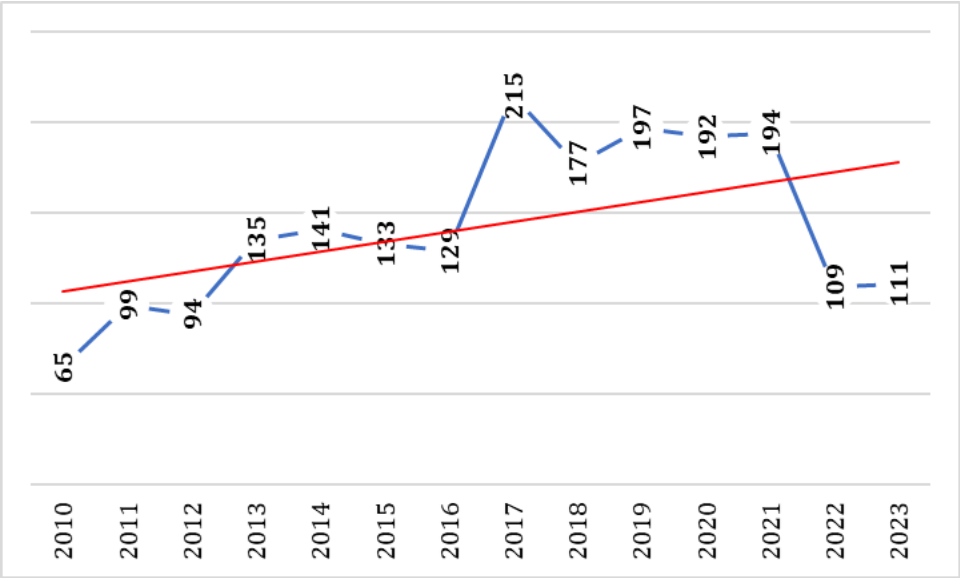

Fig. 7 *Total forensic inspection applications received by the PWD building forensic division*

This inspection report is prepared when a forensic investigator from Headquarters is required to go down to the site for a more detailed inspection to determine damage and defects in the building in question. At the conclusion of this inspection, technical recommendations for the applicant's next steps will be made based on the problems encountered. The amount of reporting provided is depicted in Fig. 8.

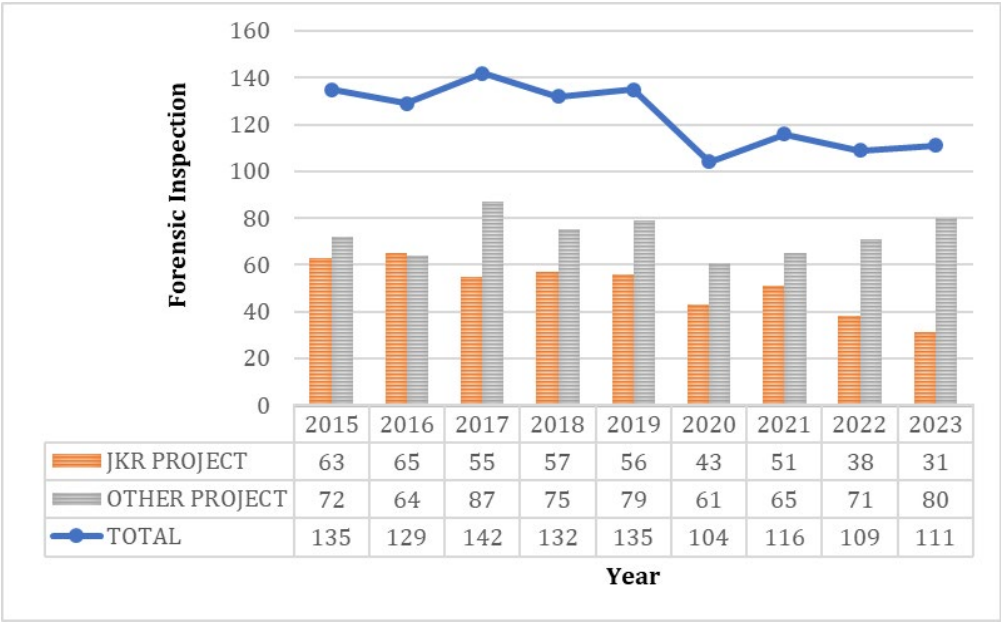

Fig. 8 *Building forensic inspection report statistics-based project owners (construction)*

Fig. 8 depicts the inspection report that was issued following the inspection of the building assets comprised of various Ministries. These building assets are constructed either under the supervision of PWD or by the owner of the asset himself. If it is under PWD supervision, it is referred to as a "PWD Project," and vice versa. As a result, it can be concluded that overall projects built under PWD supervision have a low record when compared to projects not under PWD supervision.

4.2 Causes of Structural Damage to Buildings

The investigating officer will use several methods to determine the cause of the damage during this forensic examination. The first inspection is performed to determine the condition of the building and whether the damage involved structural failure. Furthermore, it seeks to determine whether the structure's use is being abused in such a way that it is causing damage to the structure, as an example of excess load from the permitted use.

Following the completion of the visual inspection, the appropriate test selection will be determined based on the initial report. Non-Destructive Testing is usually preferred to avoid cost increases for each research. After the test results are obtained, the final report of the forensic examination is issued, and this report is submitted to the applicant for further action. Fig. 9 depicts the results of a forensic report for government building structures in Malaysia from 2015 to 2023.

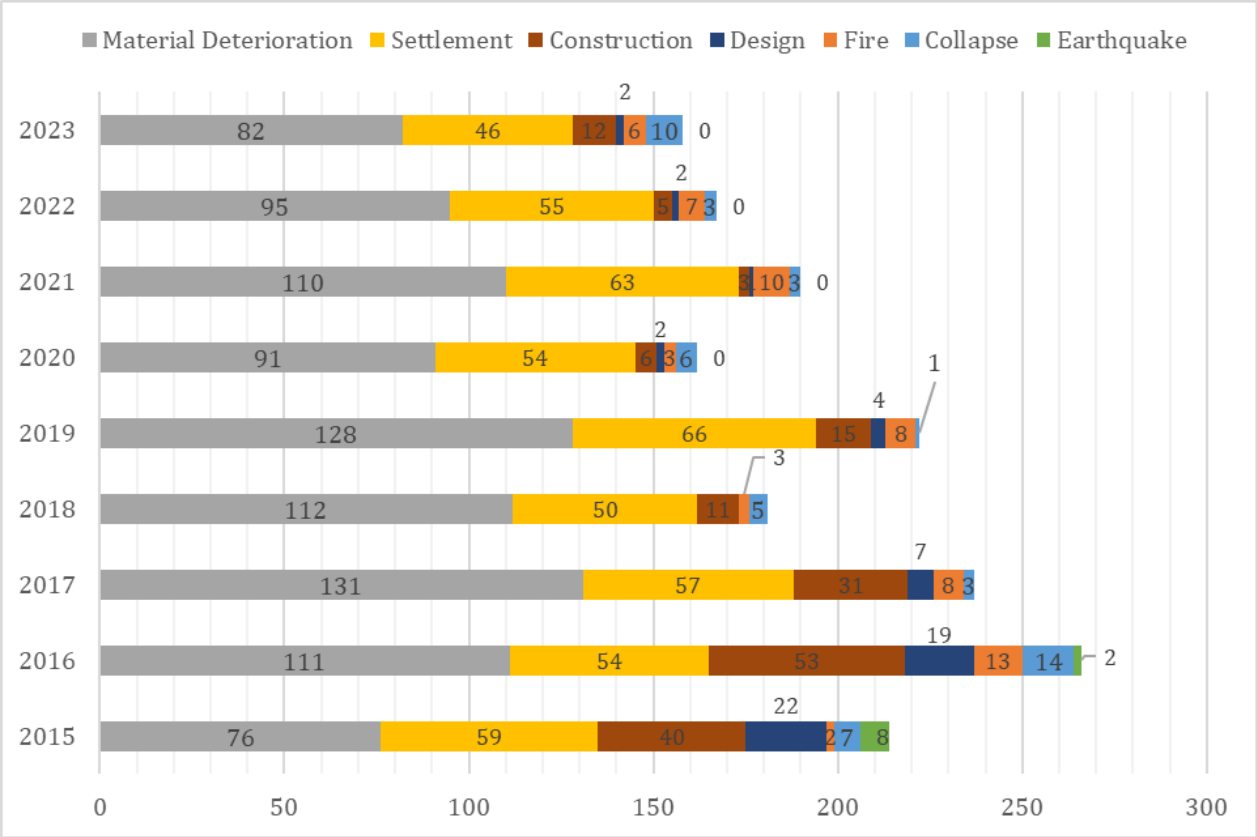

Fig. 9 *Building damage classification based on building forensic reports*

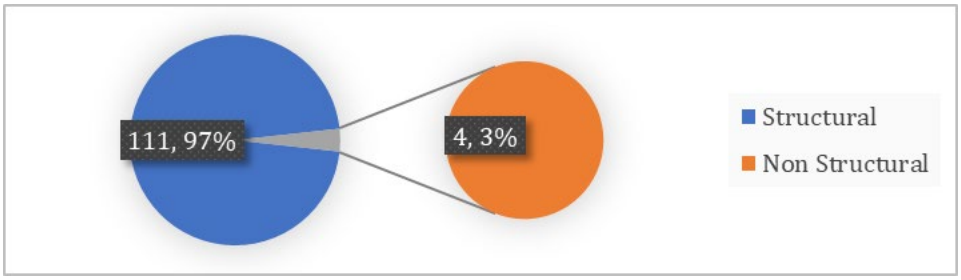

Fig 10 *Inspection reports grouped by damage*

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The diagram in Fig. 9 clearly shows that the main cause of damage to building structures is related to material deterioration, which contributes to an average damage of up to 52% when compared to other damages such as settlement, poor construction quality, design failure, fire, collapse, and earthquake.

Based on the damage that occurred, some of the findings of this inspection concluded that the structural damage did not affect the building's structure. The building's problems include settlement and fires that have no effect on the structure of the building, as well as finishing issues with the installation of windows and doors. Fig. 10 shows the breakdown of structural and non-structural damage, with structural damage accounting for 97% of the inspection report.

4.3 Deterioration of The Material That Occurs

The deterioration of this material is an implication of the physical and chemical phenomena that occur to the structure as described above. There are many types of deterioration that contribute to the deterioration of this material that have been identified through this forensic report, such as cracks, leaking problems, spalling, delamination and settlement. In order to further explain the problem of structural damage to the building in Fig. 10, the approach taken is to analyse the details of the deterioration that occurred in the latest year, which is 2023. After the further details are implemented, the following Fig. 11 is a breakdown of the deterioration that occurred for 111 buildings.

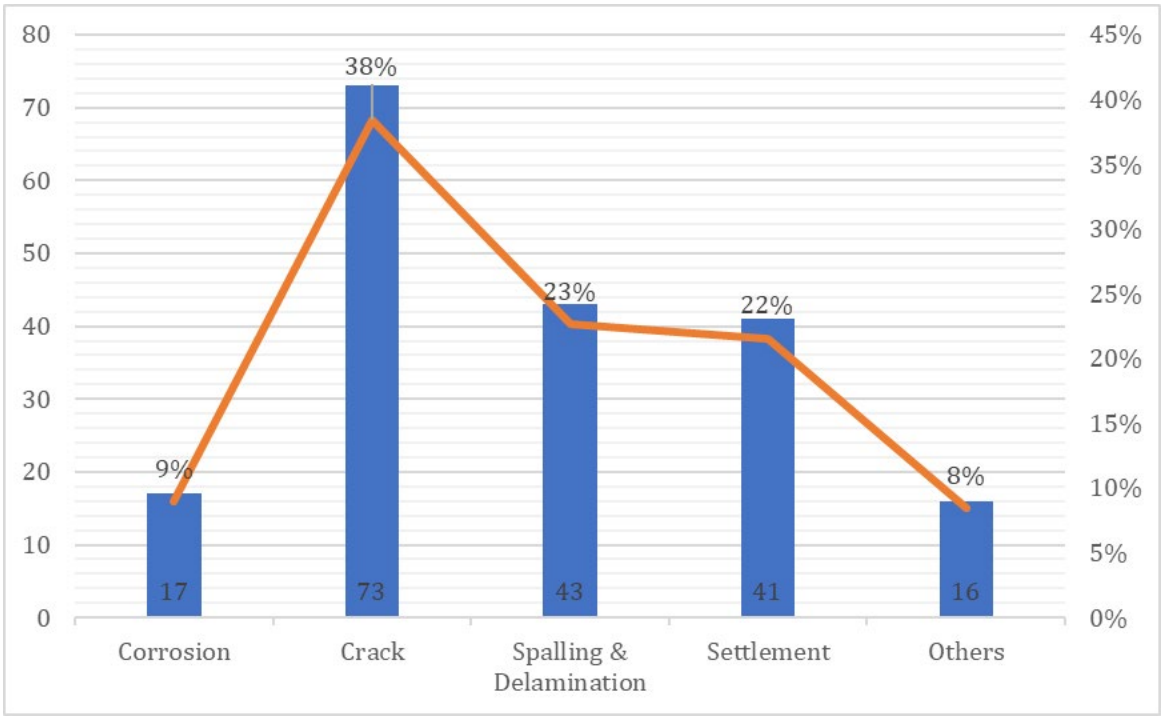

Fig. 11 *The type of deterioration that occurred to 111 building structures for the year 2023*

The main cause of this deterioration is cracking, which accounts for 39% of the total, followed by spalling and delamination (23%), settlement (21%), corrosion (9%), and other factors (8%). Other factors include extensive damage to roof trusses as well as water seepage damage. In accordance with a study by Daud et al. [17], cracking is the primary cause of damage to high-rise government buildings in Kelantan. However, almost the entire structure of this building suffered from multiple types of deterioration at the same time. Cracks in structures, for example, can sometimes be caused by settlement or corrosion in the building's structure. Fig. 12 depicts the number of cracks that occur as a result of settlement and corrosion.

It can be seen that the 33 settlements that occurred had a significant effect on the cracks in the building's structure. These cracks can be clearly seen with the naked eye, including diagonal cracks, interfacial cracks, drying shrinkage cracks, crazing cracks, shear cracks, flexural cracks and horizontal cracks. The corrosion problem that has been discovered occurs concurrently with the presence of cracks in the structure. Several structures have been identified as experiencing corrosion as a result of water infiltration caused by waterproofing damage, stagnant water, or other factors.

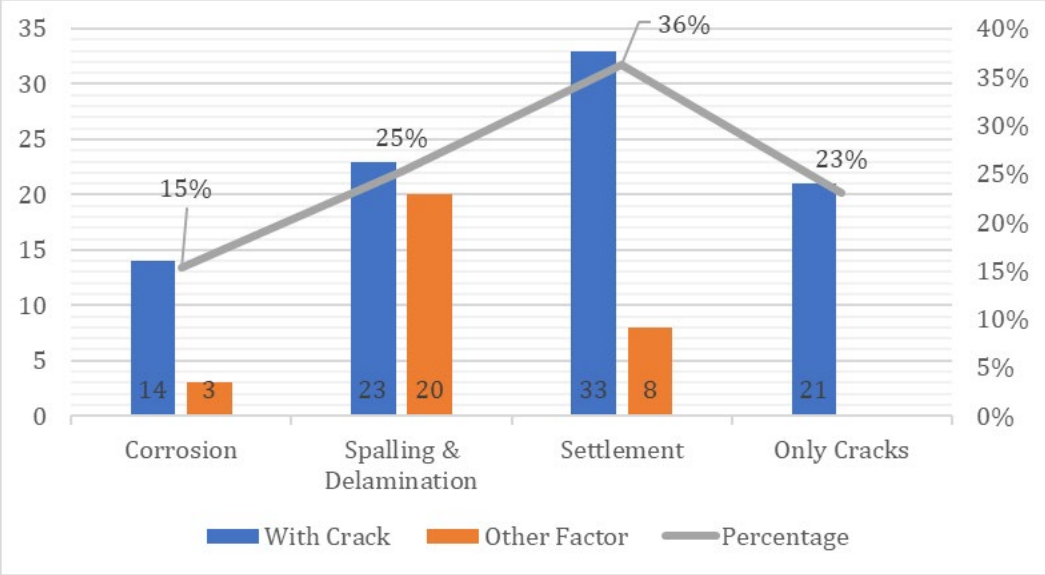

Fig. 12 *Damage that occurs along with cracks*

5. Conclusion

PWD's Building Forensics Division examines the functionality of a building structure that is said to have deteriorated in terms of structural integrity. This inspection is based on reports received from asset owners, which include State PWD, District PWD, and other government agencies. Every year, there is an increase in the number of forensic examination applications received, indicating that many government building structures are beginning to deteriorate structurally.

In accordance with the results of the forensic report for these 1,113 building structures, the cause of the damage can be classified into seven categories: material deterioration, settlement, construction, design, fire, collapse, and earthquake. Material deterioration is the most significant contributor to structural damage among these seven causes. Material deterioration has also been identified in all of these structures, which can be classified as corrosion, cracking, spalling and delamination, settlement, and other damages.

Cracking was the main contributor to damage in almost all of the building structures examined among the structural damage categories. At the same time, the cracks in this structure cause other problems such as spalling and delamination, cracking and settlement. This means that each building will sustain multiple damages. This shows that if the integrity of a building is not addressed from the beginning, the deterioration will continue to worsen with the presence of other damages until the structure of the building is declared to have failed completely.

As a result, this issue must be articulated to the stakeholders involved in order for them to pay special attention to maintaining the functionality of a building structure. This is due to the fact that the structure of this building was developed with a huge allocation while also providing services to the community. When a structure must be demolished, the government suffers a significant financial loss because money must be allocated to rebuild the structure.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Syaherza Senan, Sallehuddin Shah Ayop, Mohd Shamsul Kamarudin;* ***Data collection:*** *Syaherza Senan;* ***Analysis and interpretation of results:*** *Syaherza Senan, Sallehuddin Shah Ayop, Mohd Shamsul Kamarudin;* ***Draft manuscript preparation:*** *Syaherza Senan, Sallehuddin Shah. All authors reviewed the results and approved the final version of the manuscript.*

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