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Building Defects Investigation - Two Case Studies on Steel and Reinforced Concrete Structures

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Abstract

The purpose of this paper is to present two case studies involving the initial assessment of potential causes of building structures that are in doubt. The investigation involving a fertilizer-manufacturing building and residential buildings. The corrosion problems that occurred in the industrial building were severe, and necessitating an assessment to gauge the building's safety condition. For the residential building, a visual inspection was conducted not only on the residential structures themselves but also on the surrounding infrastructures, in order to justify whether the nearby construction works were responsible for the problems. From the investigation on the industrial building, corrosion seems to be the primary problem and a potential cause of structural instability. The severity can be seen as most of the steel structural elements exhibited signs of material loss from their surfaces. From the evaluation through visual inspection and tests, the aggressive environment and insufficient maintenance are the main contributors to the corrosion related damage. Concerning the residential building, based on the inspection of the nearest infrastructures, no fractures were identified that could be attributed to the nearby construction works. Therefore, it may seem that the on-going project may not have affected the existing residential housing located nearby.

1. Introduction

Construction failure is an unacceptable dissimilarity between expected and observed performance [1] and forensic engineering is a process investigation of failures. Understanding and recognizing the failure mechanisms is prerequisite for determining the appropriate type of repair for the affected structural elements. In forensic investigation, physical evidence and scientific methods are the crucial factors to be taken into consideration to reasonably identify the cause, effects, and possible remedies for building defects or failures. To understand the failure mechanism of the structural elements and establish the causes of the damage, an evaluation phase should be initiated from the beginning. Understanding the fundamental underlying causes of damage is necessary, as the structures may deteriorate due to more than one symptom. The description of the symptoms can be from the visual inspection and from laboratory evaluation. This paper discusses two cases involving two types of buildings: cracking in residential buildings and corrosion in a fertilizer steel structure building.

Cracks and steel corrosion can significantly impact structural safety, reliability, and serviceability, resulting in substantial economic losses and environmental issues. Such failures will shorten the service life of structures, potentially leading to collapses and endangering public safety and requiring substantial repair costs [2] [3]. Deterioration due to corrosion is a serious problem to steel frame and in addition the aggressive environment conditions and inadequate maintenance are the main reasons for corrosion related damage [4]. Structures in relatively low-risk environments may require minimal treatment, conversely, a steel structure exposed to aggressive environment like the fertilizer building, needs to be protected with a durable system that may necessitate maintenance for an extended lifespan.

There is no direct precise methodology to predict corrosion-based damage effect and structure design codes provide general recommendation and philosophies that mainly concern the use of protective coating systems, assessment of corrosion material resistance, thickness, and maintenance actions [4]. These can be referred to the design such as EN ISO 12944 [5], EN 10025-5:2004 [6] and as explained in clause 2.1.2 BS EN 1993-1-1 [7].

Corrosion in a steel structure can lead to gradual weakening over an extended period, which may eventually result in collapse. Hence, the relationship between corrosion and damage must be carefully assessed, as immediate repair might be essential in certain cases. The BS EN 12500 standard establishes a classification system for evaluating the corrosivity of atmospheric environments which is determined by assessing the mass loss of standard specimens after their first year of exposure [8]. The estimation of the corrosivity will be based on knowledge of local conditions or of specific data that characterize the local conditions. In this case study, corrosion has significantly impacted the building. The loss of material not only results in a thinner structure, but the deterioration is severe and has extended to the point where holes are clearly visible in the structural elements.

Cracks can be caused by several factors and unnerving for the occupants as cracks may have a major effect on structural safety, reliability, and serviceability. Changes in the ground conditions under and around a house can cause it to move slightly, for example foundation movement. Movement on buildings can lead to cracks developing in the structural. Cracks are generally divided into two types: structural cracks and non-structural cracks. Crack shape, number, width and length on the structural surface indicates the earliest degree of degradation and the ability of the concrete frameworks to hold. Active fractures cause a great deal of discomfort and need careful treatment because they are structurally dangerous. Small cracks that look insignificant can also develop and can eventually lead to serious structural failure. Manual visual inspection might not inefficient, however, initial assessment from visual inspection is crucial. Crack detection imaging techniques available

2. Methodology

According to Ratay [9], the scope of work for the forensic analysis may fall into one of the following categories, listed in increasing effort, depending on the client's requirements or the severity of the situation.

a. Simple visual (due-diligence) inspection, oral or written letter-report of observations on.
b. Inspection, quick-and-tentative opinion, report
c. inspection, some analysis, opinion, report

In this study, scope of work in categories b and c were required by clients. For both cases various physical evidence was gathered during the visual inspection. Through visual inspections and, when available, appropriate documentation, the individual and interrelated effects of the building's materials, site, architecture, and maintenance history were taken into consideration.

The primary method of assessment in these two cases was visual inspection. However, for specific evaluations, tests were conducted on particular elements, such as using rebound hammers and Vernier Caliper Measurements. Rebound hammer was used for assessing the quality of hardened concrete and were used to estimate in-place compressive strength of the concrete [10] whereas the vernier Caliper was employed to ascertain the width of crack defects in the concrete specimens. Measurement of crack width is a crucial testing procedure when assessing the integrity and quality of concrete [11].

2.1 Case 1: Fertilizer-Manufacturing Building

The building in Case 1 is a fertilizer steel structure building, where the primary issue is corrosion affecting the structures. When this problem escalates and corrective measures are not implemented, corrosion can indeed lead to a reduction in the capacity of structural members and result in premature failure.

Corrosion is a natural process that leads to the deterioration of metal components, such as steel reinforcement and steel structures, due to chemical interactions with their environment within a building. It arises as an electrochemical reaction, manifesting in various forms like chemical corrosion and atmospheric corrosion. When acidic substances, including water, come into contact with metals, rust starts to form. In industrial building applications, iron (typically carbon steel) stands as the most commonly used metal for structural purposes.

Numerous commercial chemicals are used in fertilizers, and all fertilizer mixtures consist of three core components: nitrogen, phosphorus, and potassium. Additionally, they contain secondary plant nutrients like calcium, sulfur, magnesium, and iron. The exact ingredients and proportions vary across different fertilizer types, making certain fertilizers more corrosive than others. The fertilizer can be more corrosive if it can react to produce aggressive substances such as ammonia or hydrogen sulphide, if chloride ions are present (including potassium or ammonium chloride), or if or if they are exposed to acidic conditions. Moreover, there is evidence indicating that the most significant effects arise in fertilizer solutions containing approximately 15% nitrogen [12]. Table 1 provides examples of typical reactions between liquid fertilizers and steel. While fertilizers remain dry, no corrosion occurs. However, due to their hygroscopic properties, fertilizers can absorb moisture, leading to corrosive effects [12].

Table 1 *Corrosive reactions of liquid fertilizers* [12]

Liquid fertilizers	Chemicals	Reactions with steel
Nitrogenous solutions	Ammonium nitrate, urea	Slow interaction with steel, can be more rapid at weds and bolt holes, etc.
Phosphate solutions	Ammonium Phosphate	Tends to be less reactive, form a protective phosphate coat which can protect metal from subsequent attack by nitrogenous solutions, unless acid conditions prevail.

2.1.1 Visual Inspection on the Steel Structures

To establish the investigation framework, a visual inspection of the building was conducted, covering the bagging and intermediate storage area, storage tank area, and the process areas. Fig. 1 displays the building's layout plan, indicating the specified areas in red.

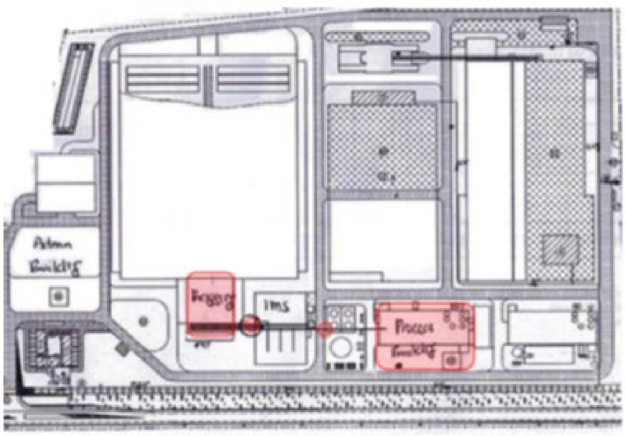
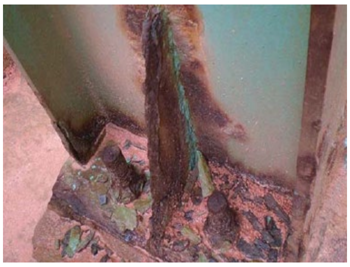


Fig. 1 *Layout of the building compound*

The visual inspection identified corrosion across various structural steel elements, manifesting at varying degrees, site locations, and elemental positions—especially at connections and flanges. This corrosion is attributed to environmental exposure and the deposition of aggressive damp material or chemicals, causing material disintegration and distortion. Material disintegration refers to the deterioration and breakdown of the steel due to the corrosive processes while the distortion can be observed from the deformation or alteration in the shape of the steel elements caused by the corrosion. Several figures are referenced to illustrate specific instances of corrosion and related concerns. As depicted in Fig. 2, the visual inspection further substantiated the widespread corrosion affecting the structural elements of the building.

(a) Steel beam and connection



(b) Column base and connection

(c) Steel beam, connection & services

(d) Steel column and connection

(e) Steel column and connection

(f) Diagonal steel brace and connection

(g) Concrete chipped-off on pedestal

(h) Fragile cover crumbled during testing process at the process building

(i) Water leaking from the roof

(j) Deposition of damp material

Fig. 2 *Observation on structure defects*

Fig. 2 (a) presents the corrosion evident on a steel beam and its connection situated between the bagging and intermediate storage buildings. The severity of corrosion on the column base plate is depicted in Fig. 2(b), which was captured from the same location.

At the upper storey of the process building, corrosion has manifested on various steel elements: beams and steel for services, steel columns as depicted in Fig. 2(c) and Fig. 2 (d). Further signs of corrosion can be seen on the column splice (Fig. 2(e)) and the steel brace (Fig. 2(f))—both located on the upper storey of the process building.

Fig. 2(g) illustrates how corrosion on the column base plate can affect the concrete pedestal. As steel corrodes, it generates iron oxide (rust) as a byproduct. Iron oxide occupies a greater volume than the original steel, resulting in the expansion of corrosion products. This expansion eventually generates internal pressure within the concrete, leading to chipping off the concrete pedestals. Consequently, tests were conducted on the pedestals to assess their current strength and their ability to support the steel elements.

The corrosion's severity is evident as it affects other structural members. Fig. 2(h) illustrates the fragility of the concrete cover during testing, indicating potential integrity concerns. The persistent compromised site conditions further contribute to the deterioration, as illustrated in Fig. 2(i) and Fig. 2(h). The former demonstrates steel elements exposed to rainfall, while the latter highlights the deposition of damp material, exacerbating the corrosive environment.

To address these issues, it is necessary to implement measures for safeguarding and maintaining structural integrity. This might involve corrosion protection strategies, maintenance efforts, potential redesigns, and repair work. Addressing corrosion and concrete spalling, along with mitigating compromised site conditions, ensures the facility's sustained safety and functionality of its structural elements.

2.1.2 Rebound Hammer, Vernier Caliper Measurements and Results

The Rebound Hammer test was performed to determine surface hardness, which provides a loose correlation to material strength. The Schmidt Rebound Hammer is primarily an apparatus for testing surface hardness in concrete. This test was conducted to ascertain the compressive strength property of the concrete structures adjacent to the steel elements being assessed, as illustrated in Fig. 3. In this case, the measurements were conducted on randomly selected elements.

(a) Column concrete pedestal (b) First floor slab

Fig. 3 *Rebound hammer test*

The rebound hammer test was performed on several structure elements and the correlation of the rebound hammer test to the concrete strength are as listed in Table 2

Table 2 *Rebound hammer test*

Results Of Rebound Hammer Test					
Element	Location	Average Compression Strength (N/mm^2)	Element	Location	Average Compression Strength (N/mm^2)
concrete pedestal	Between the bagging & intermediate storage buildings	31.8	Ground floor plinth	Process building	33.40
concrete pedestal	Between the bagging & intermediate storage buildings	28.1	Ground floor plinth	Process building	25.93
concrete pedestal	Storage tank area	30.1	First floor slab	Process building	53.25

Ground floor column	Process building	50.50	First floor slab	Process building	53.25
Ground floor column	Process building	37.00	First floor slab	Process building	46.05
Ground floor column	Process building	42.40	First floor beam	Process building	29.80
Ground floor column	Process building	36.85	First floor beam	Process building	49.90
Ground floor column	Process building	52.75	First floor beam	Process building	16.35
Ground floor column	Process building	17.87			

The results of the rebound hammer test generally indicated that most structural elements had values exceeding 30 kN/m². However, a few cases showed compressive strength below 20 kN/m², suggesting that the concrete strength in those locations might be low.

A pedestal is a crucial component of a compression structure, situated between the footing and column. Its purpose is to evenly distribute the load over the footing. Typically, a concrete pedestal serves as a compression element designed to bear the column or statue's compression load. Therefore, it is concerning that some pedestals have experienced concrete loss, compromising their structural integrity.

It is important to note that there exists significant variation in opinions among researchers regarding the accuracy of strength estimation from rebound readings. The correlation between rebound readings and the probable accuracy of concrete strength estimation in a structure is reported to be within ±25% [4].

In addition to the Rebound Hammer test, Vernier caliper measurements were also conducted as part of this study (Fig. 4). Given that corrosion can occur at varying rates based on the environmental conditions the metal is exposed to, Vernier caliper measurements are essential. These measurements allow us to determine the current thickness of the structural elements and evaluate the extent of deterioration caused by corrosion.

Fig. 4 *Vernier calliper measurements*

The results of the vernier caliper measurements on selected elements are indicated in the Table 3. In general, the steel structures could be seen distorted and its material thinning out occurred due to the expansive corrosive stresses. The results of the vernier caliper measurements on selected elements are as indicated in the Table 2. In general, the steel structures could be seen distorted and its material thinning out occurred due to the expansive corrosive stresses. As the factory building is still in operation facing the problem of directing the structure of the building and repairs need to be done as one of the maintenance routines

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Table 3 *Results of vernier caliper measurement*

Results of Vernier Caliper Measurement Between the banging & intermediate storage buildings						
Element	**Condition**	**Recorded (mm)**			**Average (mm)**	**Different (mm)**
Column flange	Uncorroded (base Value)	15.38	14.95	15.01	15.11	
	corroded	16.01	17.08	15.04	16.04	0.93
	corroded	29.51	29.44	28.22	29.06	13.94
Beam flange	Uncorroded (base Value)	15.04	14.88	15.02	14.98	
	corroded	25.44	24.27	23.18	24.30	9.32
	corroded	31.57	30.75	30.77	31.03	16.05
Column base bracing plate	Uncorroded (base Value)					
	corroded	11.67	11.86	12.04	11.86	
	corroded					
Anchoring bolt	Uncorroded (base Value)					
	corroded	32.06	31.57	34.45	32.69	
	corroded	34.64	31.39	28.10	31.38	
Column web bracing plate	Uncorroded (base Value)					
	corroded	13.71	17.56	15.71	15.66	
	corroded					
Connection plate	Uncorroded (base Value)					
	corroded	25.90	28.74	24.74	26.46	
	corroded					
Connection bolt	Uncorroded (base Value)					
	corroded	43.56	43.76	42.74	43.35	
	corroded	47.70	46.92	49.18	47.93	
Gusset plate	Uncorroded (base Value)					
	corroded	15.68	12.73	26.93	18.45	
	corroded					
Gusset plate	Uncorroded (base Value)					
	corroded	31.91	18.11	18.24	22.75	
	corroded					
Ladder column flange leading to 2nd floor.	Uncorroded (base Value)	9.42	8.32	8.32	8.69	
	corroded	5.80	5.63	5.94	5.79	-2.90
	corroded	19.77	20.07	21.11	20.32	11.63

3. Case 2: Residential Housing

Cracking tends to occur when significant movement affects a building. Not only is this visually unattractive, but if left untreated, it can also compromise the integrity, safety, and stability of the building. Various factors, such as changes in ground conditions, foundation settlement, or defects, can contribute to this movement.

In this case, an investigation was conducted to determine whether the cracks in residential buildings located near a construction project involving four blocks of 9-storey apartment buildings were a result of the nearby construction work. This investigation involves two types of affected residential buildings: single-storey detached houses and single-storey terrace houses. The single-storey detached houses have been resided for almost 2 years, while the single-storey terrace houses were constructed and occupied for over 10 years. Homeowners raised concerns about cracks in August 2017, as the cracks were becoming more noticeable.

The nearby construction project consists of four 9-storey apartment buildings and a single-storey shop-lot. The project commenced in 2015 and is ongoing at the time of the investigation. Piling work for the main building apartments of the project was completed in March 2016, and the piling work for the single-storey shop-lot was finished in April 2017. The piling method used is hammer piles.

Information was gathered from the developer and affected residents to better understand their concerns and complaints in order to determine the cause of the problem. Through interviews with residents of the affected residential buildings, it became evident that the concern revolved around the appearance of cracks during the construction works that commenced near the housing estate.

Visual inspection and preliminary qualitative forensic assessment were conducted on the surrounding construction project, which covers several affected residential properties, electrical substations (TNB 1 and TNB 2), the drainage system surrounding the housing area, and the oxidation pump house adjacent to the TNB substation. The satellite view and the site plan of the project location are shown in Fig. 5

(a) Satellite view (b) Site plan

Fig. 5 *Project location*

The TNB 1 and TNB 2 substations are the closest buildings to the construction project with a distance of about 15m to 20m whereas an oxidation pump house is located next to the TNB 1 substation. As for the residential houses involved in the investigation are located approximately 150m to 200m and to the west of these houses is the Malacca River which is about 50 m away from the very end house. To the east is the other row of residential single houses and the double-storey terrace houses that have long been built.

The TNB 1 and TNB 2 substations are the closest buildings to the construction project, situated at about 15m to 20m. An oxidation pump house is located next to the TNB 1 substation. The residential houses involved in the investigation are located approximately 150m to 200m away. To the west of these houses lies the Malacca River, which is about 50m away from the last house. To the east, there is another row of residential single houses and double-storey terrace houses that have long been built.

3.1 Visual Inspection

Fig. 6 shows the settlement observed in semidetached single-storey houses located directly in front of the construction project. Settlement can be observed at several locations within these houses including the car porch, living room and apron (Fig. 6). According to the homeowners, settlement in the car porch area began once they occupied the house.

(a) (b) (c)

Fig. 6 *Settlement in residential*

Another defect can be seen on the concrete flat roof of the car porch, evident in the form of calthemite stalactites, as shown in Fig. 7(a). Calthemites are concrete, mortar, or lime-derived secondary deposits consisting primarily of calcium carbonate that grow on or under man-made alkaline structures such as concrete. In this case, the condition cannot be related to ground settlement as no cracks were visible. This problem is actually common in concrete flat roofs and is solely caused by waterproofing issues and water ponding.

The brick wall at the car porch has horizontal crack near the floor level as depicted in Fig. 7(b). It is likely the wall was constructed without a ground beam directly above the floor below it. Therefore, as the floor settled, it caused the brick walls to shift and subsequently cracking. Longitudinal cracking along the adjoining beam-brick perimeter is also visible in several sections of the houses, as can be seen in Fig. 7(c) and Fig. 7(d). This cracking is most prominent at the intersection of brick walls and beams, which is expected due to structural movement, excessive vibration, and differences in shrinkage/expansion ratios between various materials such as brick, concrete, and mortar plaster. It's important to note that there were no failures observed in the main building structures.

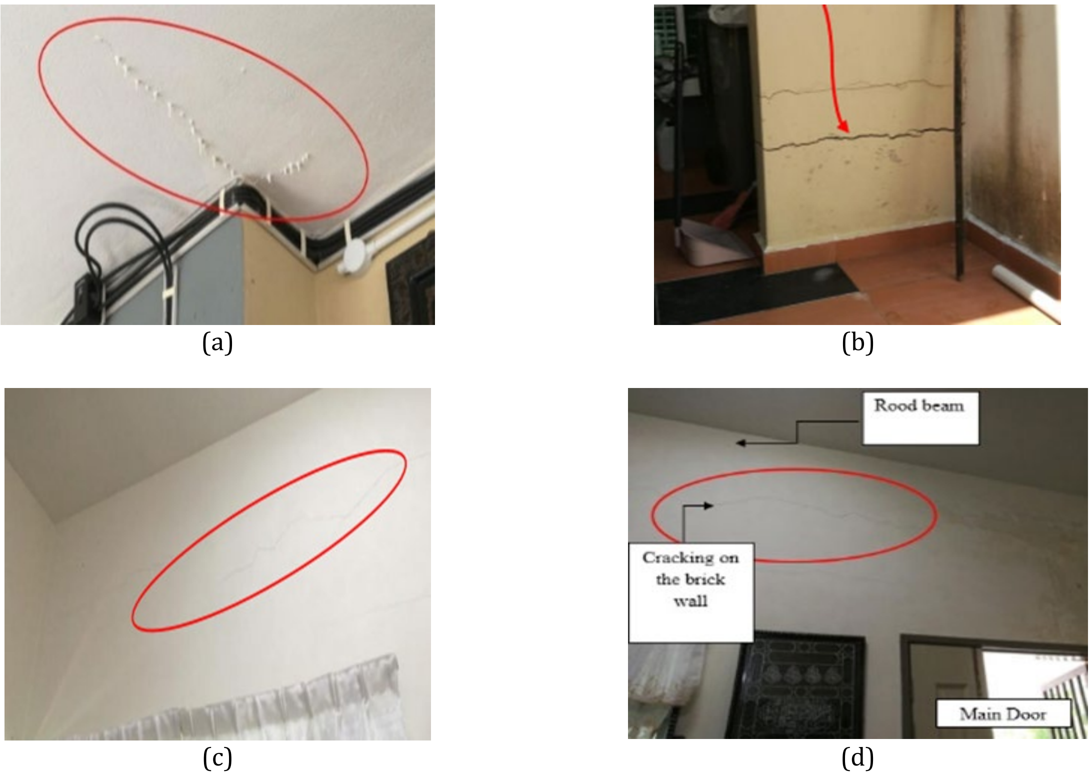


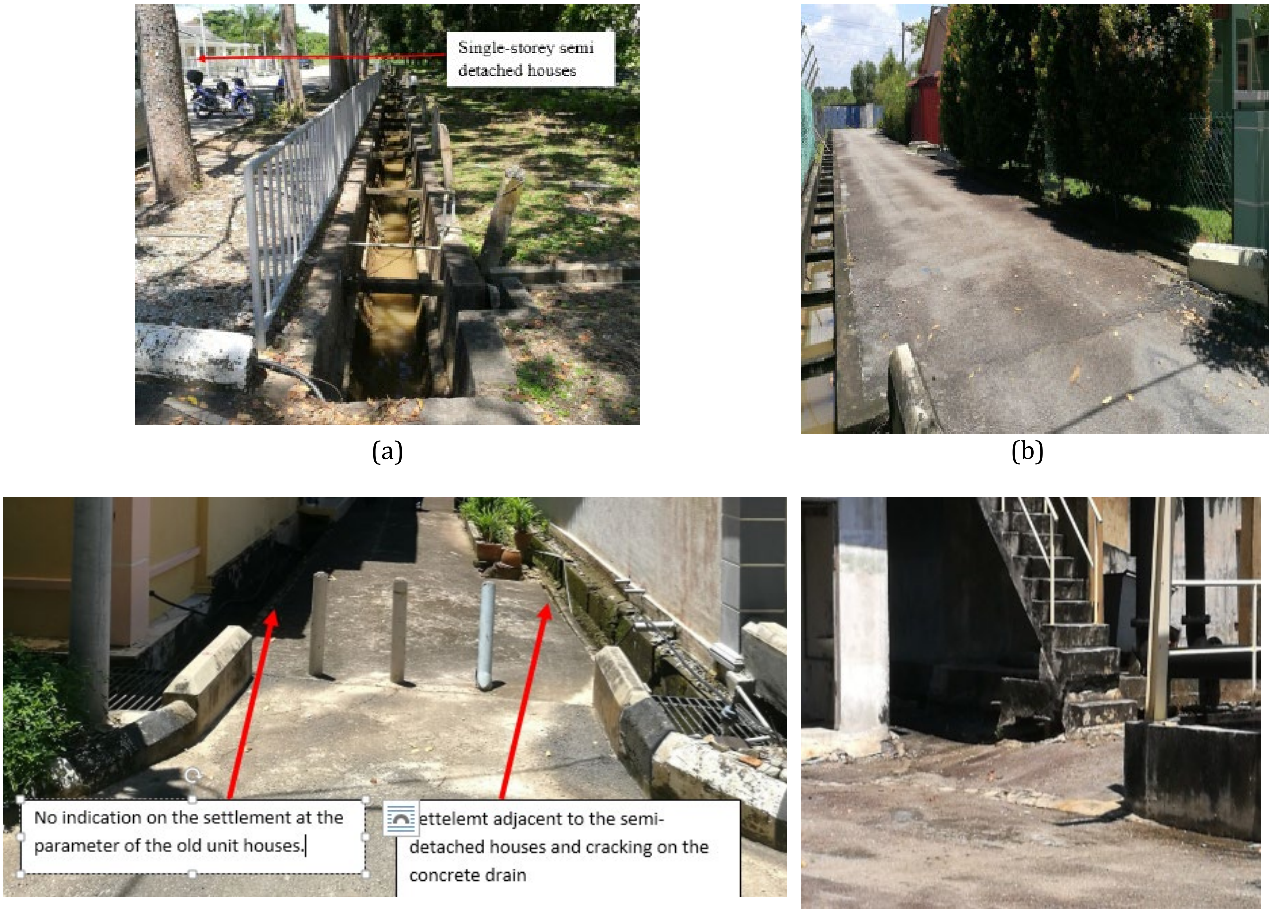
Fig. 7 *Few observed defects in residential*

To investigate whether the defects in semidetached single-storey houses were caused by the construction site, inspections were carried out on the infrastructures surrounding the project. These included TNB sub-stations, existing concrete drains, road, the oxidation pump house, and the oxidation pond. Both TNB substations are the closest buildings to the construction projects and the visual observation on the sub-station could only be made from outside the fence. No significant cracking was observed on the outer structure, outer wall, apron floor (outer perimeter) or concrete trench around the building of both TNB substations, as shown in Fig. 8.

Fig. 8 *Electrical substation TNB 1 and TNB 2*

Inspection of the concrete drain located in front of the construction project and adjacent to the single storey-detached houses was found in satisfactory condition (Fig. 9(a)) with no significant cracking observed on the concrete channel, its walls and the iron barrier. There was also no settlement or cracking observed on the roads and the drains in the small lane between the single-storey houses and the construction site (Fig. 9(b)). However, observation in the other small lane, located between the end of semi-detached houses and double-storey houses, showed settlement and significant crack on the side of the houses. Surprisingly, there was no settlement or significant cracking observed on the old two-story terrace house as shown in Fig. 9(c).

Regarding the pump house and the oxidation pond, a significant settlement, approximately 150mm, was observed on the apron and stairs of the oxidation pump house (Fig. 9(d)). Based on these observations, including the settlement and the discoloration of the structure, it can be inferred that the settlement occurred long before the construction project started. Additionally, these infrastructures were built using an older system and were in place before the project commenced. Since the Melaka River is located less than 100m from the pump house, it could be an indication that the significant settlement may be caused by high water and groundwater levels. The inspection also suggests that this location may be more susceptible to settlement due to soft ground and the presence of water sources. Therefore, soil investigations and suitable foundations are necessary to prevent such phenomena in such locations."



(a) (b)

(c) (d)

Fig. 9 *Defects surrounding the residential area*

4. Conclusion

The most prominent single reason for failures that emerged was a grossly inadequate appreciation of loading conditions or the real behavior of the structure [13]. This conclusion can be applied to case 1. Based on the information gathered in case 1 through the prescribed forensic investigation methods, it can be concluded that corrosion is the primary problem for the fertilizer buildings and the potential cause of structural instability. The facility suffering defects due extreme exposure of the manufacturing material to the steel structure. This corrosion has led to a decrease in structural performance, resulting in deterioration that has affected the desired performance level before the building's service life expired. The aggressive environment and inadequate maintenance are the main reasons for the corrosion-related damage. It is further proposed that rectification works be carried out on affected structural elements in the foreseeable future to arrest further material degradation and mitigate potential structural failures, particularly when the building is still being subjected to the same compromising site conditions.

Regarding case 2, the evaluation was due to the justification on the effect of ongoing construction project from the nearby residential. Based on the inspection carried out on buildings and infrastructures surrounding the construction project and the semi-detached houses, it can be summarized that there is no significant fracture or damage as a result of the piling work on infrastructure surrounding the construction projects of apartments, such as concrete trenches and roads (especially around the old terrace houses). Evidence from the existing TNB substations, which are the closest buildings to the construction site, does not show any fractures on walls, floors, or trenches around the buildings, suggesting that the piling work on apartment construction projects has no effect that could damage the structural and non-structural parts of the two TNB substations. For the new houses, no breaks or damage can be observed on the main structures of the buildings, which suggests that the piling work of the apartment construction project does not have an impact that could damage or jeopardize structural elements (beams and columns) of the building. On the other hand, the fractures that occur on the walls and floors of the houses illustrate that the shading reflects more the occurrence of soil deposits. This kind of fracture phenomenon indicates that there has been land settlement. The same sediment phenomenon can be observed in the oxidation pool pump house where large areas of sedimentation and its conditions indicate that sediments have occurred over a longer period before the commencement of an apartment project.

Cracking in a building element may constitute a defect in a variety of ways. Cracking occurrence may result in more than one type of defect such as structural defect, a serviceability defect, and an appearance defect. The expected consequence of cracking is unknown until further information is obtained. Further information should be obtained by further investigation by a Structural Engineer into the cause of cracking. The information from the visual inspection was used in the hypothesis of the cause of the problem.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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