Jurnal Kejuruteraan 37(3) 2025: 1117-1130
https://doi.org/10.17576/jkukm-2025-37(3)-04

The Need to Investigate the Behaviour of Reinforcement using a Metal Magnetic Memory

Nur Atikah Adila Abdul Mutalib[a], Noorsuhada Md Nor[a*], Azli Arifin[b] & Shahrum Abdullah[b]

[a]*Faculty of Civil Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang,*

Permatang Pauh Campus, Penang, Malaysia.

[b]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment,*

Universiti Kebangsaan Malaysia, UKM Bangi, Selangor, Malaysia.

[*]*Corresponding author: ida_nsn@uitm.edu.my*

Received 14 August 2024, Received in revised form 26 December 2024
Accepted 26 June 2025, Available online 30 May 2025

ABSTRACT

The occurrence of damage in reinforced concrete (RC) beams is influenced by various factors such as the material properties. The localisation of invisible damage and the identification of the critical stress state leading to structural damage or failure of the steel bars are crucial tasks in structural diagnosis. Hence, the main objective of this study is to investigate the behaviour of steel bars using magnetic metal memory (MMM) before any significant stress or load has been applied. Two types of reinforcement were prepared, differing in the tensile part. Steel bars with a size of 12 mm and 16 mm were used for the tensile part. A total of six reinforcements were prepared for each size of steel bars. The MMM was used to scan the behaviour of the steel bars in the tensile section along the scan line of 1150 mm. From the MMM test, two magnetic flux leakage signals were analysed: Component signals, Hp-2 and normal gradient signals, dH(y)/dx. It was found that the larger variations observed in the 16 mm steel bar could indicate a greater susceptibility to defects or stress concentrations in the material. The differences in the signal patterns between the two diameters could also reflect the response of the material. This study is of significant benefit as a baseline measurement to understand the initial condition of the steel and to better monitor and evaluate its performance throughout the life cycle of the reinforced concrete structure.

Keywords: Reinforcement; steel bar; fatigue; metal magnetic memory; component signal; magnetic flux leakage

INTRODUCTION

Many concrete structures like bridges, pavements, highways, airports, flyovers, and other infrastructural engineering structures undergo repeated loading. Therefore, a structural fatigue failure may occur because of this cyclic loading and significant changes on the characteristics of materials such as stiffness, toughness and durability may occur which will in turn affect residual life of concrete member (Simon, and Raj 2021).

The use of reinforced concrete (RC) is extensive, and it is reasonably priced as well. As a result, it is commonly used in many different civil engineering structures, such as tunnels, dams, high-rise buildings, and bridges (Qiu et al. 2019). Because RC structures are composed of both ductile steel and brittle concrete, residual microcrack coalescence of the concrete may occur because of increased steel strain, which weakens the bond between the two materials (Md Nor et al. 2023). The transfer of stress between the concrete and the steel reinforcing bar is the primary concern in the design and analysis of reinforced concrete structures, and it can be ensured by a dependable bond performance (Zhang et al. 2017).

Assessing the behaviour of the RC structures and confirming their safety are critical tasks especially for the bars. For assessments of structural problems, non-destructive testing (NDT) and combinations of various diagnostic techniques are preferred. There are many methods used for detecting the behaviours of steel reinforcement such as Ultra Sonic Testing (UST), Magnetic Particle Testing (MPT), Radiographic Testing (RT), Ground Penetrating Radar Testing (GPRT) and Metal Magnetic Memory (MMM). There are three main categories of assessment methods: non-destructive, partially destructive, and destructive (Pospisil et al. 2021). As the assessment is carried out, the behaviour of the steel bars in the concrete can be identified. However, from the three methods, the non-destructive is more practical as it is easy to handle, and safe for the building. One of the NDTs which can be used to identify the behaviour of the steel bar is metal magnetic memory (MMM). The MMM techniques, has been developed in recent decades due to the development of magnetic detection (Xie et al. 2022). Due to its non-destructive nature, low cost, high efficiency, and other advantages, the MMM proved to be an effective method for assessing the early fatigue damage of ferromagnetic material (Liu et al. 2021, Zhang et al. 2023, Lin et al. 2012). The trend in publications by year shown in Figure 1 shows that many studies were carried out with the help of MMM.

Figure 1 illustrates the number of publications per year from 1990 to 2023. At the beginning, the number of publications was very low, with only 3 in 1990. Over the course of the decade, it gradually increased with slight fluctuations, reaching 25 in 2000. The research conduct by Barnes & Atherton (1993) on the long strips that cut axially from a pipeline show that surface stress alone is insufficient for considering the effects of stress on magnetic flux leakage amplitudes. A more significant increase can be observed between 2001 and 2010, with the number of publications increasing steadily despite some fluctuations, from 20 in 2001 to 110 in 2010. Significant increases were seen in years such as 2005 with 67 publications, 2008 with 90 publications and 2010 with 110 publications. Dubov (2001) presented a technique for monitoring the bends of boiler and steam-line tubes using the magnetic memory of metal. The method was used in examination of blades of the turbine K-300-240 of the first block of the Konakovo hydroelectric power station (Dubov & Matyunin, 2001). The proving experiments of Steel X45 show the maximum error of remaining fatigue life is 4.58% between MMM model calculation and actual life (Haiyan et al. 2006). Another researcher, Yu (2007) has study on the MMM test of stress concentration of weldment in different heat treatment conditions. D. Wang et al. (2008) have been used MMM testing signals on 45 carbon steel during static tension process.

From 2011 to 2023, the trend shows a clear and more consistent increase, starting with 111 in 2011 and reaching the highest number of publications in 2021 with 231 publications. In the following years 2022 and 2023, the numbers remained unchanged with 228 and 231 publications respectively high. There have been notable increases in various years, such as the jump from 40 to 47 publications between 2003 and 2004 and from 88 to 90 publications between 2007 and 2008. In addition, the number increased from 90 to 111 between 2013 and 2014 and from 197 between 2017 and 2018 to 205. According to Ni et al. (2018) metal magnetic memory (MMM) testing was performed on a single edge notched specimen fabricated from structural alloy steel under three-point bending fatigue to monitor crack propagation and forecast the fatigue life of ferromagnetic material. Su et al. (2018) conducted four-point bending experiments on Q235B steel I-beams to determine the strain variation features and the corresponding MMM field Hp (y) under varied bending loads. The experimental results reveal that strain and its accompanying Hp (y) have high regularities under various bending loads. There is a distinct changing pattern between strain and Hp (y) at various measurement sites. The behaviour reflecting the change in Hp (y) with load differs from the behaviour as a function of strain. Hp (y) increases rapidly at initially and then more steadily as strain increases. Strain is more responsive to Hp (y) than load. Strain is more responsive to Hp (y) than load. The quantitative link between strain and the corresponding Hp (y) is established with a high fitting degree, and it may be utilized to assess the strain state of a steel beam. In Liu et al. (2017), the Kp perturbation algorithm is used to study the influence rule of magnetic field intensity on magnetic memory signal. The multi-primary cell magnetic mechanical model is established based on the number of effective Bohr magnetons p in the K space, and the quantitative changing relationship of magnetic mechanics under the action of external magnetic field is calculated. The study's findings demonstrate that when an external magnetic field is applied, electron orbit motion is intensified, the crystal lattice structure is deformed, and the atom's magnetic moment increases. When the magnetic signal is small, the magnetic memory signal grows with a linear increase in the external magnetic field intensity.

Overall, the graph shows a clear and steady increase in the number of publications over the years, with the strongest growth observed from the early 2000s. The increase becomes even more pronounced from 2010 onwards, indicating a growing interest and progress in this range. Despite minor fluctuations in certain years, the overall direction is upward, indicating robust growth in research output. This constant growth rate over the last decade underlines the increasing focus and importance of the research area in question and reflects its growing body of knowledge. Arifin et al. (2022) conducted a fatigue crack growth test on SAE 1045 steel were conducted with a constant tensile load amplitude in the form of single-edge cracks. The experimental results demonstrated that as the fatigue cycle and fracture length grew for each R, dH/dx rose exponentially. The magnetic flux gradient was used to develop the governing equations for the fatigue crack length equation and the fatigue cycle equation, along with the stress ratio.

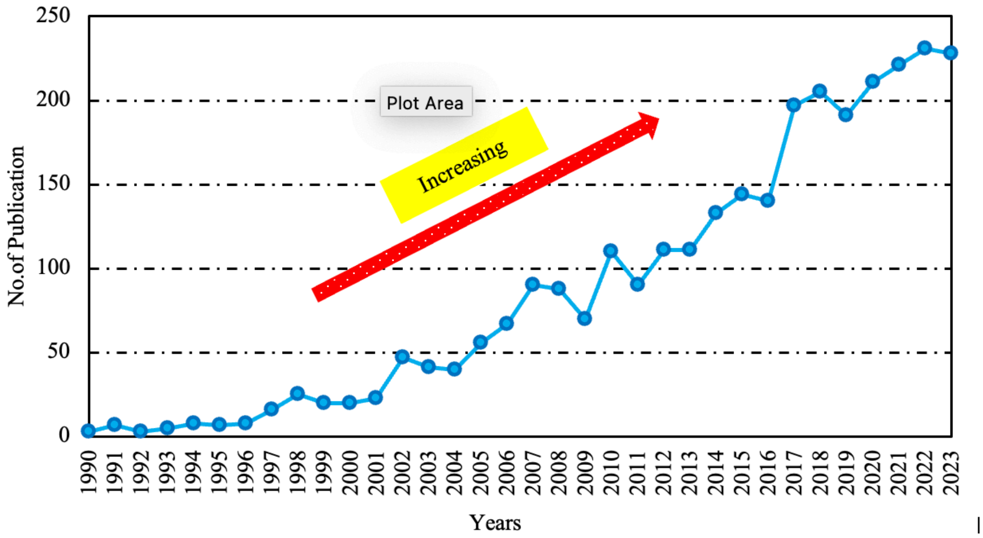


FIGURE 1. The number of publications in relation to the years for the general application of MMM in the engineering field

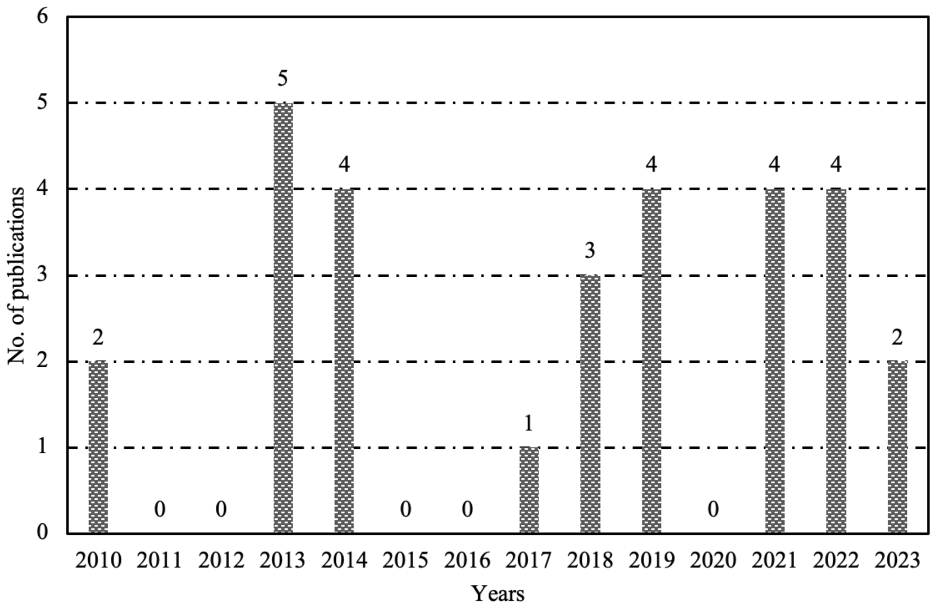


FIGURE 2. The relationship between the number of publication and years

A statistical study of the magnetic flux leakage signals revealed that all the data fell within a 90% confidence interval. Thus, the magnetic flux leakage characteristics could be used to create fatigue crack growth behavior models for ferromagnetic materials, as well as an alternate way for forecasting fatigue life. Md Nor et al. (2023) measured and analyzed the behavior of the steel bar in the concrete beam by using the magnetic flux leakage signal, acoustic emission characteristics, and crack breadth. The magnetic flux leakage signal and acoustic emission energy measurements were consistent with the presence of cracks in the center of the beam. The association between the magnetic leakage flux signal and crack opening was found to be strongly correlated, with an R^2 of 0.969. The center of the beam has a high acoustic emission energy of 1300 nVs. The behavior of the steel in the concrete beam can be determined based on the results of a structure's integrity examination.

From Figure 1, a total of 2967 publications can be found in the respective field. From the reviews found that the MMM was used more on pipelines, steam turbine blade, wet stream generator tubes and bridges compared to the RC structures. Therefore, the MMM has been used extensively for damage assessment of ferromagnetic material. Since reinforced concrete structures are a combination of metal and concrete, Md Nor et al. (2023) stated that the MMM is a useful tool to determine the behaviour of steel bars in concrete.

Gong et al. (2022) and Md Nor et al. (2023), conducted the study on the behaviour of the steel bar, meanwhile Qiu et al. (2019), Zhou et al. (2018) and Li et al. (2023) researched on bending strength of corroded RC. To obtain more precise information about the application of MMM for RC structures, Figure 2 shows the number of publications in relation to the years. A total of 29 publications on the application of MMM for determination of behaviour or assessment of RC structures were found from 2010 to 2023. All data was collected from Scopus.com with the specific keywords. Although few researchers have recently addressed magnetic metal memory in the context of RC structure, it is worth investigating as MMM is useful to identify the behaviour of steel bars in concrete. The increasing study of MMM and RC structures in recent years has shown that research is limited and still in demand. The limited investigation on the use of MMM to identify the behaviour of RC structures can be illustrated by Figure 2. The behaviour of the RC beam can be made clear if the behaviour of the steel bars in the concrete can be assessed without damaging the original condition of the structure. The investigation of steel bars before they are loaded or embedded in concrete for the construction of reinforced concrete structures is still an under-researched area. Therefore, the main objective of this study is to investigate the behaviour of steel bars using the MMM before any significant stress or load is applied. This initial assessment, conducted using MMM, aims to establish a baseline assessment of the condition of the reinforcement, providing crucial insight into the integrity of the material prior to its use in structural applications. This baseline measurement is important to understand the initial condition of the steel and to better monitor and evaluate its performance throughout the life cycle of the reinforced concrete structure.

METAL MAGNETIC MEMORY (MMM)

The MMM method, which is originated in the 1990s, is a new type of NDT technology for identifying the presence of stress concentrations and defects in ferromagnetic materials by detecting and analyzing changes in the self-magnetic leakage field (SMLF) on the surface of materials. This methods is special magneto-mechanical effects produced by ferromagnetic materials under the combined action of a geomagnetic environment, inhomogeneities within the material, and stress concentration zones (SCZs) to diagnose the material state (Su et al. 2023, Han and Huang 2021; Abarkane et al. 2019). It is a non-destructive test that analyzes the SMLF distribution across the surface of an element to identify SCZ, defects, and heterogeneities in the material's microstructure. It thus has a strong potential for detecting existing damage and forecasting damage (SCZ) in materials and buildings.

The magnetic flux leakage (MFL) has been used effectively in detecting corroded steel members. The MFL measuring method can be classified into two types: strong magnetic measurement and weak magnetic measurement (Yang et al. 2023). This method allows for a thorough analysis of the stress status and degree of deformation of ferromagnetic components, which allows an early diagnosis to be made prior to component failure. Compared to other magnetic testing techniques, the metal magnetic memory approach has several advantages. For instance, the self-magnetic-flux-leakage (SMFL) signal of items is monitored using this passive testing technique. A variety of elements, including human factors (lift-off, deviation), specimen form, notch shape, initial magnetization state of ferromagnetic materials, and environmental magnetic field, can affect the weak and complicated magnetic signals known as metal magnetic memory signals (Ren et al. 2019).

PRINCIPLE PARAMETERS OF MAGNETIC MEMORY

By monitoring the surface magnetic field distribution of ferromagnetic metal parts, it can indirectly diagnose parts defections and stress concentration positions because of the magnetic mechanical effect that exists in these parts, whose surface of magnetic field has a corresponding relationship with parts load stress. This is referred to as the magnetic memory detection basic principle.

The largest changes in leakage magnetic field Hp will occur in the stress and deformation clusters when the ferromagnetic workpiece is subjected to the geomagnetic surrounding and load effect. In other words, the component of magnetic field Hp(x) has the maximum value, while the component of magnetic field Hp(y) changes symbols and has a zero point. As stated by Gong et al. (2022) after the working load is removed, the magnetic irreversible state changes will persist. In order to ascertain the dangerous area where parts would defect, it thus precisely infer the stress concentration portions of the workpieces (the defect area) using the leaking magnetic field method to determine component Hp(y) (Lin et al. 2012).

Factors such as heat treatment, cooling, bending, welding, machining, cutting, operating stress, and material corrosion can all have an impact on a material's residual magnetization. The deterioration process resulting from operational stress and environmental conditions that the structure is subjected to is a crucial factor that impacts a material's magnetic memory (Pospisil et al. 2021). The magnetic gradient tensor describes the spatial rate of change of the magnetic field vector in three orthogonal directions. If H is the magnetic field vector, the magnetic gradient tensor can be expressed as the multiplication of two matrices that have three vector elements each (Chen et al. 2017).

Under the influence of the Earth's magnetic field, a new magnetic flexible, magnetic organizational, and irreversible orientation occurs at a location where the defect and inclusion centralized, and stress concentration area occurs. The magnetic mechanical effect is the relationship between mechanical stress and residual magnetic states, as well as the self-magnetized phenomenon of ferromagnetic metal materials. The ferromagnetic workpiece's magnetic field is increased by the magnetic mechanical effect, which stresses the surface area. The magnetic field then "memorizes" the position of the regions where the stress concentrates (Lin et al. 2012).

MMM approach has been extensively employed in welding applications for diagnostics of stress concentration because of its advantages of time-saving, cheap cost, and easy operation in comparison to the traditional magnetic flux leakage methods (Wang et al. 2010).

Arifin et al. (2022) found that the gradient behaviour of the MMM signal resulted in a mathematical correlation that can successfully describe the fatigue crack growth behavior. R increases the stress ratio, which accelerates the formation of fatigue fractures and influences the gradient properties of the MMM signal's normal component, dH/dx. This effect can be incorporated into the mathematical relationships that define the gradient behavior of the MMM signal.

In engineering, the MMM technique has various benefits, including ease of use and effectiveness in identifying early damage. It is suitable for a variety of NDT applications, including bridges, steel wires, trains, and pipelines. The fundamental downside of MMM is its low assessment reliability, which is caused by the difficult magnetization process. Many factors determine the magnetization caused by stress, including the geomagnetic field, the initial stress state, the chemical composition, the microstructure, the geometry, and the size of the samples (Han & Huang 2021).

MMM testing technology has a sensitive property for failure and stress concentration in ferromagnetic materials. Equipment failure condition can be determined by detecting surface magnetic field signals in the failure area and stress concentration region. However, according to the principle of metal magnetic memory testing technology, the MMM sensor must be kept close and constant to the detected surface. In order to achieve exact MMM signal, steady and dependable locomotion and adequate adhesion capacity are necessary and significant (Gao et al. 2020).

METHODOLOGY

The process flow of this study is shown in Figure 3. It began with the preparation of the materials used to make the reinforcement. Details of the reinforcements are shown in Figure 4. From this figure, it can be seen that the reinforcement for the tensile part is of different sizes. Steel bars with a diameter of 12 mm and 16 mm were used for the tension part. For the compression part, steel bars of the same size (10 mm) were used for both reinforcements. For the stirrups, the diameter of the reinforcement was 8 mm with a centre-to-centre spacing of 150 mm.

Once the preparation of the reinforcement was complete, the first measurement was carried out using the MMM to obtain a baseline assessment of the condition of the reinforcement before any significant stress or load was applied. This first measurement is crucial as it provides a reference point against which future measurements can be compared. By assessing the reinforcement at this early stage, potential defects, stress concentrations or manufacturing inconsistencies can be identified before the structure is subjected to the any type of loads. Early detection of such problems enables timely intervention and ensures that the reinforcement is in optimum condition to fulfil its intended function in the structure. In addition, establishing a baseline also helps in the ongoing monitoring of the reinforcement by tracking the progression of detected anomalies over time and under different loading conditions. The tracking of any progression by scanning the reinforcement was performed in one direction.

The focus of the MMM scan was on the tensile part of the reinforcement, as this area is critical to the structural integrity of the element. In reinforced concrete structures, the tensile zone is usually the most stressed when loaded in bending. This makes it more susceptible to damage such as cracking or yielding, which can affect the safety and performance of the structure. By focussing the scanning on this stress zone, the MMM can more effectively detect stress-related anomalies or weak points that could develop under load. The six scanned reinforcements provide a comprehensive understanding of the stress distribution and potential problem areas within the critical stress zones.

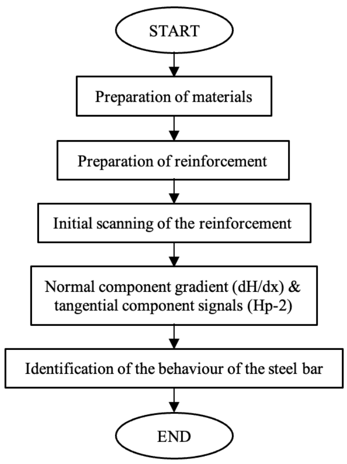


FIGURE 3. Process flow for identification of the steel bar behaviour.

Figure 5 shows the MMM device known as the Test of Stress Concentration (TSCM-2FM), a sophisticated system designed to measure, record and process diagnostic data related to stress concentrations in materials. The TSCM-2FM is equipped with advanced technology to improve the precision of measurements. This includes two flux-gate transducers, Hp-1 and Hp-2, which are essential for detecting magnetic anomalies indicative of stress ranges in the material. These transducers are sensitive instruments that measure the strength and direction of the magnetic field, providing important data on the condition of the reinforcement.

In addition, the device is equipped with a wheel that acts as a length measuring device and ensures an accurate correlation between the position along the reinforcement and the magnetic readings. This function enables precise localisation of detected anomalies and facilitates the identification of specific problem areas within the reinforcement structure.

Figure 4 shows a visual representation of the scan line used during the MMM test. It was strategically positioned to capture data from the centre of the reinforcement, with the read distance set at 1150 mm. This special arrangement ensures that the MMM device scans a large portion of the reinforcement, allowing a thorough assessment of its condition. The data recorded by the MMM signal at this central location provides valuable insight into the stress distribution and possible defects within the reinforcement.

Table 1 presents the summary of the number of reinforcements used in this study and indicates the 12 mm and 16 mm diameter tension bars. This information from assessment of steel bar prior to applied load is crucial as it provides context for the MMM measurements and allows comparative analysis between different reinforcement sizes. Better understanding on how different bar diameters respond to stresses and whether certain sizes are more prone to stress concentrations that could lead to structural failure can be identified.

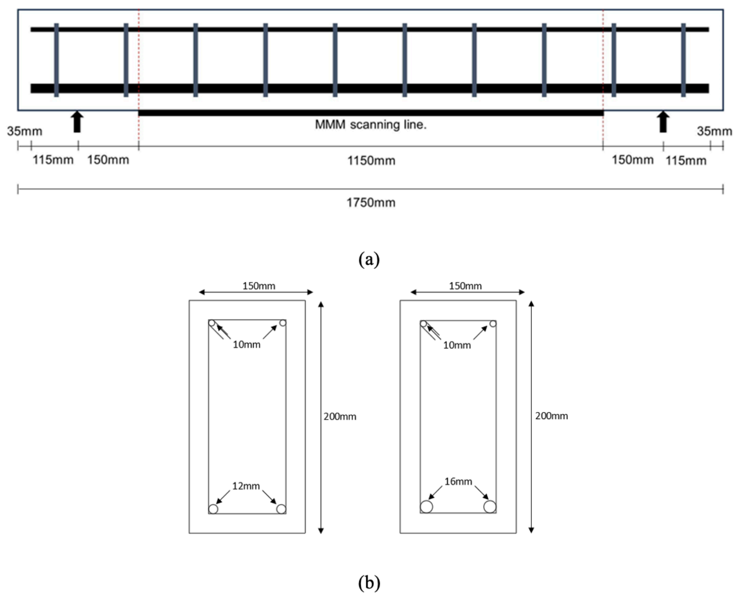


FIGURE 4. Reinforcement used for this study a) side view of the RC beam with detail of the scanning line b) cross sections of the beam

Figure 6 shows scanning with an MMM sensor to detect magnetic anomalies along the rebars. The sensor was scanned at three locations: the left rebar, the right rebar and the centre rebar (between the left and right rebars). In general, as the sensor moves along the three scanning lines, it detects variations in the magnetic field, which are influenced by the structural integrity and stress distribution within the reinforcement. The presence of stirrups along the reinforcement can also contribute to the magnetic anomalies detected when scanning the left and right bars

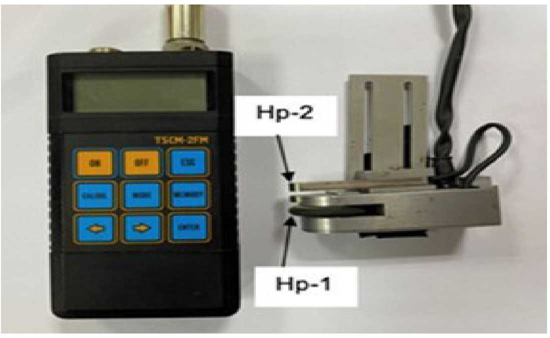


FIGURE 5. Tester of stress concentration magnetometric (TSCM-2FM)

TABLE 1. Number of reinforcements for the MMM test

Reinforcement with size of the steel bar on the tension part	No. of reinforcement
12 mm	6
16 mm	6

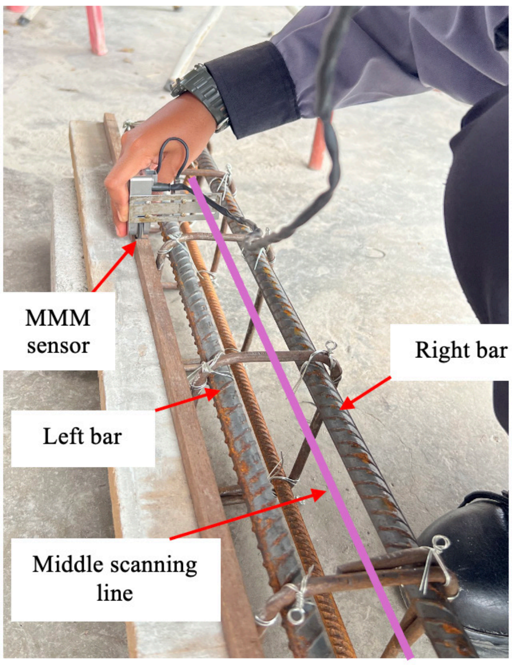


FIGURE 6. Position and location of MMM scanning line

By analysing these anomalies, it is possible to assess the condition of the reinforcement, identify possible defects and evaluate the general structural condition of the bars at these three locations. Placing the scanning line in the centre allows for a comprehensive assessment by capturing signals from both adjacent bars and focusing on the stirrups or connections in between. Two types of signals were analysed; The normal component gradient (dH/dx) and tangential gradient signal (Hp-2).

RESULTS AND DISCUSSION

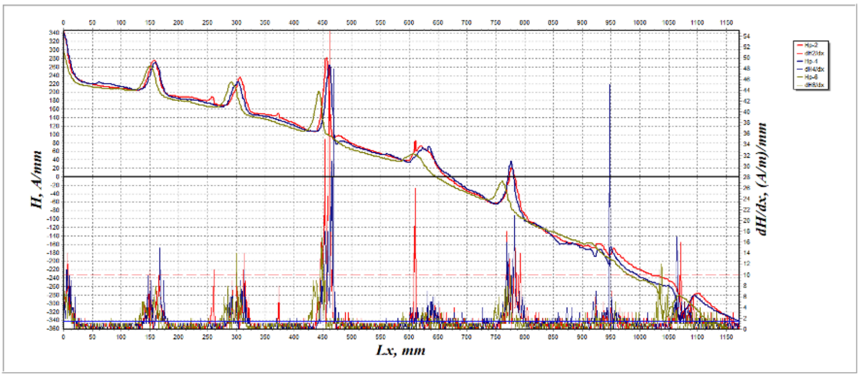
Figures 7 and 8 show the results of the MMM tests carried out on reinforcement with diameter of 12 mm and 16 mm on tension bars respectively. The MMM tests were performed to evaluate the stress distribution and detect possible anomalies within the rebars. The results show that there is a significant increase in the Hp-2 magnetic field component at certain distances along the reinforcement. This increase is attributed to the presence of stirrups associated with the stirrups and reinforcement causing localised changes in the magnetic signal. The regular spacing of these peaks corresponds to the regular spacing of the stirrups along the reinforcement, suggesting a relationship between the physical structure of the reinforcement and the magnetic anomalies observed.

To ensure the reliability of the data, the MMM tests were repeated three times at each location, with the results averaged to account for any variations in the measurements. The results shown in Figures 7 and 8 relate specifically to reinforcement No. 1 and provide a comparative analysis between the two different bar diameters (12 mm and 16 mm). The data illustrates the influence of bar size on the magnetic field distribution, with the 16 mm bar exhibiting different magnetic properties than the 12 mm bar. This comparison is important to understand how different reinforcement sizes respond to loading and to identify potential weak points that could compromise the structural integrity of the material under loading.

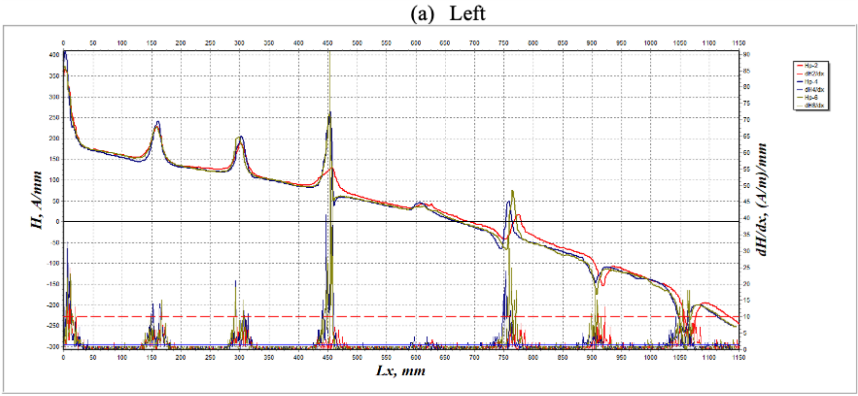
In terms of magnetic flux leakage (MFL), Figure 7 displays the component signal (Hp) and normal gradient signal dH/dX at different positions. From the figure, some peaks on this graph show areas of high and low magnetic field intensities respectively. Notable among these hills are those found at 50, 450, 500, 600 and 750 mm from the presence of stirrups. Some regions, however, have sharper changes in intensity than others which can be seen from sharp peaks shown by dH/dX values. Whereby it appears that there is a general reduction in magnitude with increasing distance, much variation exists as seen from some regions having steep peaks indicating rapid changes.

The above variations indicate that there may be fluctuations associated with different factors affecting the field having probably linkages to material properties under test. These overlapping curves have slight deviations indicating similar but not exactly same magnetic responses for different samples due to influence of various parameters on MFL signal.

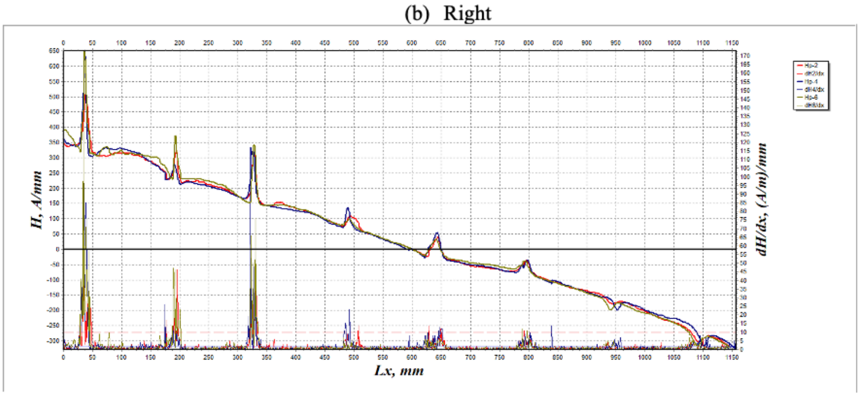
Figures 9 to 13 show the signal of the normal component (Hp-2) for tension bars with a diameter of 12 mm and 16 mm. All figures show data collected along a scanning line of 1150 mm, with measurements taken on six different reinforcements (S1 to S6). The y-axis represents the magnetic normal component signal (H) in A/mm, ranging from -500 to 400 A/mm, while the x-axis represents the position along the tension bar (Lx) measured in millimetres (mm). The data shows the distribution of the normal component signal along the length of the rebars before a load was applied, thus providing information about their initial state. This assessment information is critical to understanding the initial condition of the reinforcement and identifying any potential weaknesses or inconsistencies in the material that could affect performance when under subsequent load. Md Nor et al. (2023) stated that the initial state of the reinforcement is significantly identified so that the state of the reinforced concrete structure can be predicted once a load is applied to it.



(a) Left

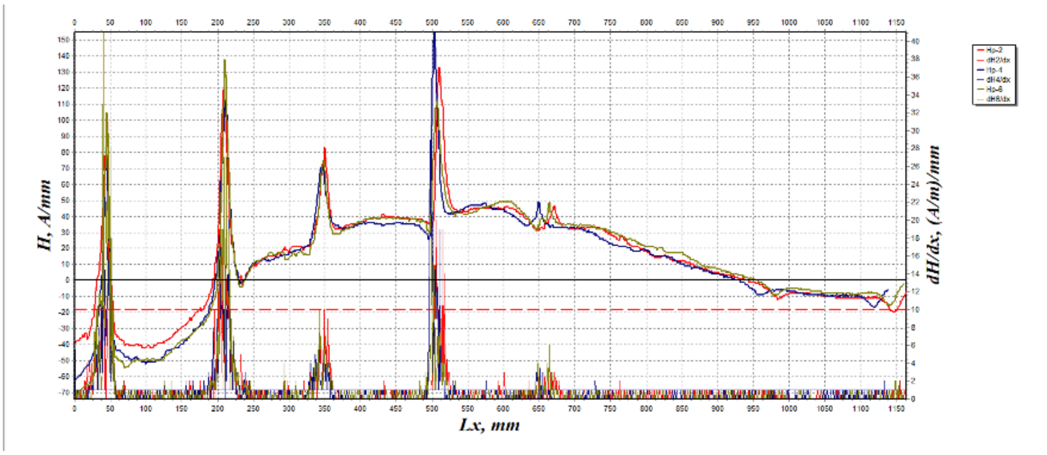


(b) Right

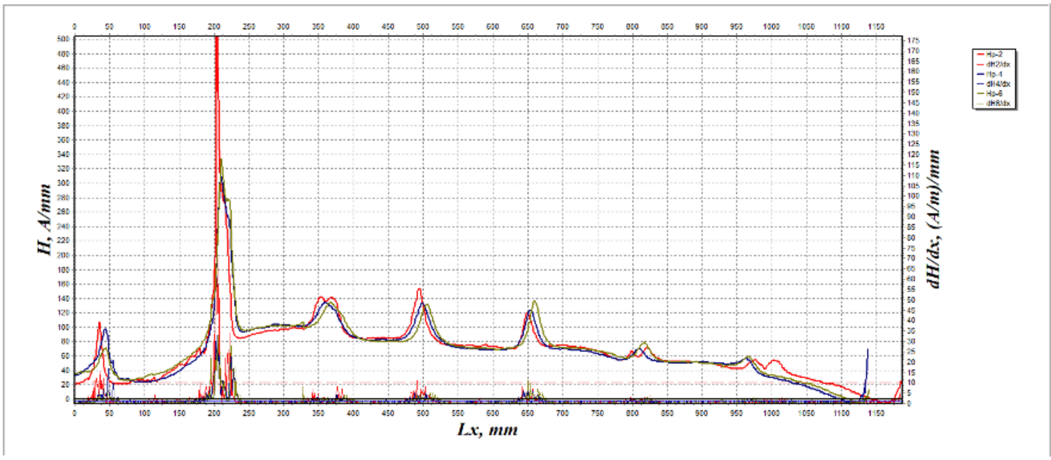


(c) Middle

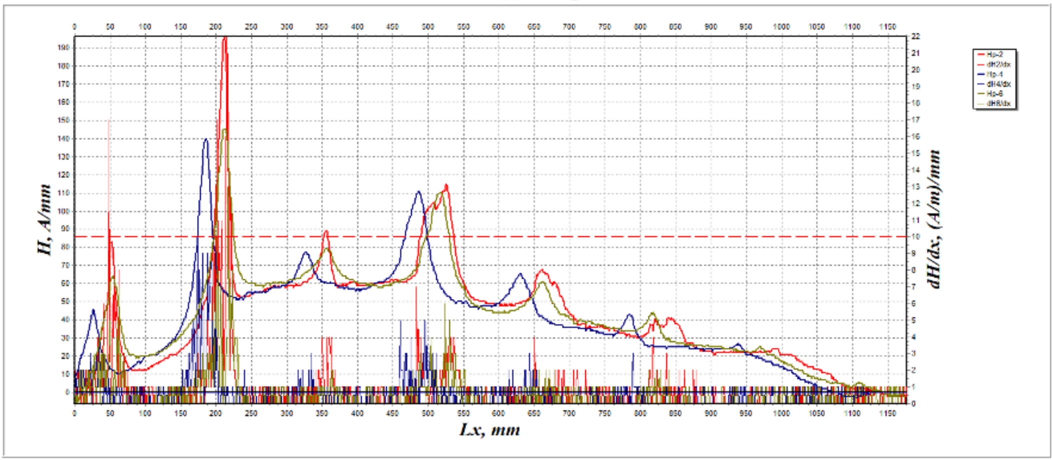
FIGURE 7. Normal component gradient of MMM signal on reinforcement with tension bars of 16 mm



(a) Left



(b) Right



(c) Middle

FIGURE 8. Normal component gradient of MMM signal on reinforcement with tension bars of 12 mm

In this study, the focus was on presenting the results of the Hp-2 signals, which provide valuable insight into the condition of the reinforcement without any damage being present. By analysing the magnetic signals along the reinforcement, it is possible to detect variations in the magnetic field that correspond to changes in the stress state of the material or the presence of defects. This non-destructive testing method enables early detection of problems so that preventative measures can be taken before the reinforcement is stressed. The results of this testing method are critical to ensuring the integrity and longevity of the reinforced structure, as they provide a clear indication of the condition of the reinforcement at an early stage.

When comparing the two graphs of the Hp-2 signal for steel bars with a diameter of 12 mm and 16 mm at the tension part, e.g. in Figures 9 and 10, it becomes clear that the bar with a diameter of 12 mm (Figure 9) generally exhibits fewer magnetic signal fluctuations.

In contrast, the steel bar with a diameter of 16 mm (Figure 10) shows greater fluctuations. Although the signals in Figure 9 show some fluctuations, they are more strongly centred around the zero line, with the peaks and troughs mostly remaining in a narrower range of around, 300 to 300 A/mm. In contrast, the signals in Figure 10 show more pronounced fluctuations, with several signals deviating significantly from the zero line, particularly in the case of S4, S5 and S6, where the fluctuations reach close to the -500 A/mm mark. This suggests that the 16 mm bar may have a higher degree of residual stress or greater material inhomogeneities along its length compared to the 12 mm bar.

The greater fluctuations observed in the 16 mm rod could indicate a greater susceptibility to defects or stress concentrations in the material. The differences in the signal patterns between the two diameters could also reflect the material's response to manufacturing processes such as rolling or cooling, which could have a greater effect on thicker steel bars. The differences in the magnetic signals for both diameters emphasise the importance of non-destructive testing in identifying potential problems prior to loading of the reinforcement.

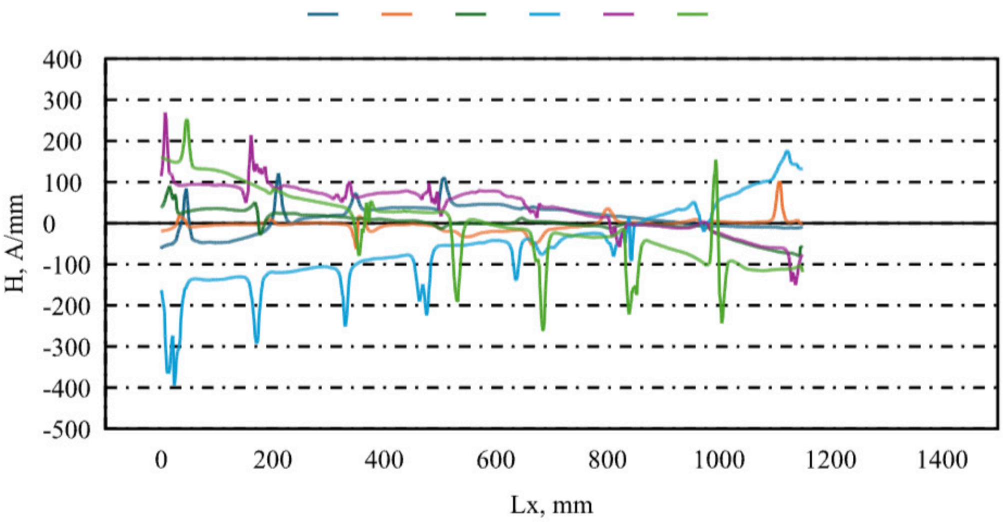


FIGURE 9. Normal component signal along a tension bar with a diameter of 12 mm (Left)

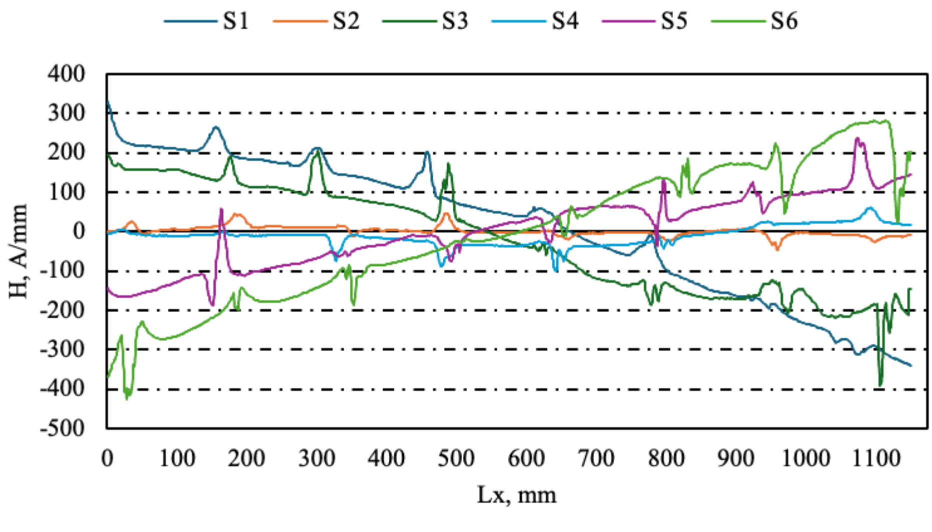


FIGURE 10. Normal component signal along a tension bar with a diameter of 16 mm (Left)

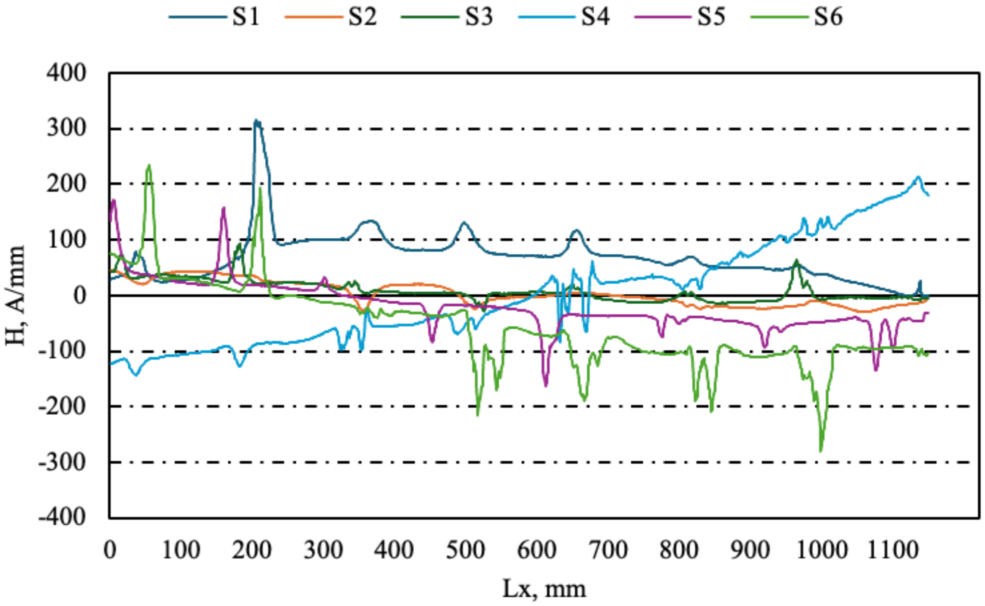


FIGURE 11. Normal component signal along a tension bar with a diameter of 12 mm (Right)

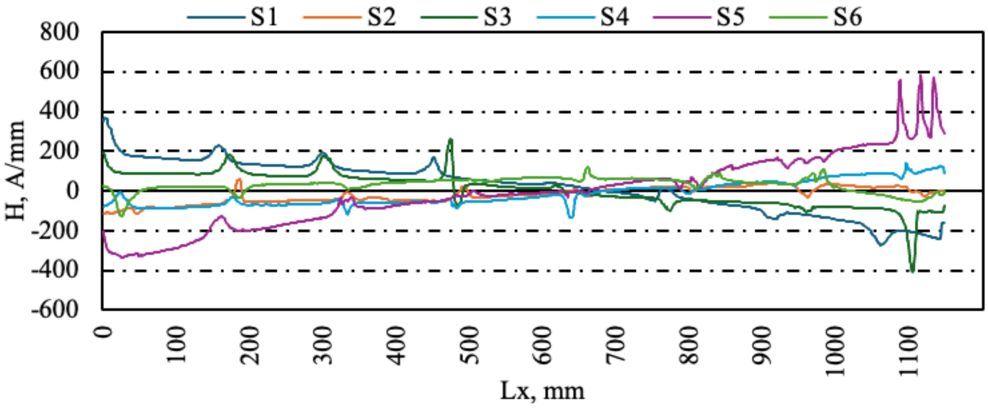


FIGURE 12. Normal component signal along a tension bar with a diameter of 16 mm (Right)

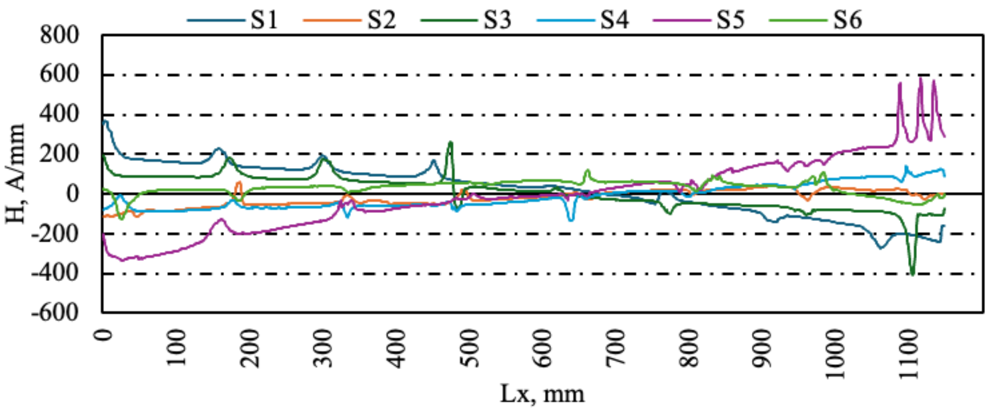


FIGURE 13. Normal component signal along a tension bar with a diameter of 12 mm (Middle)

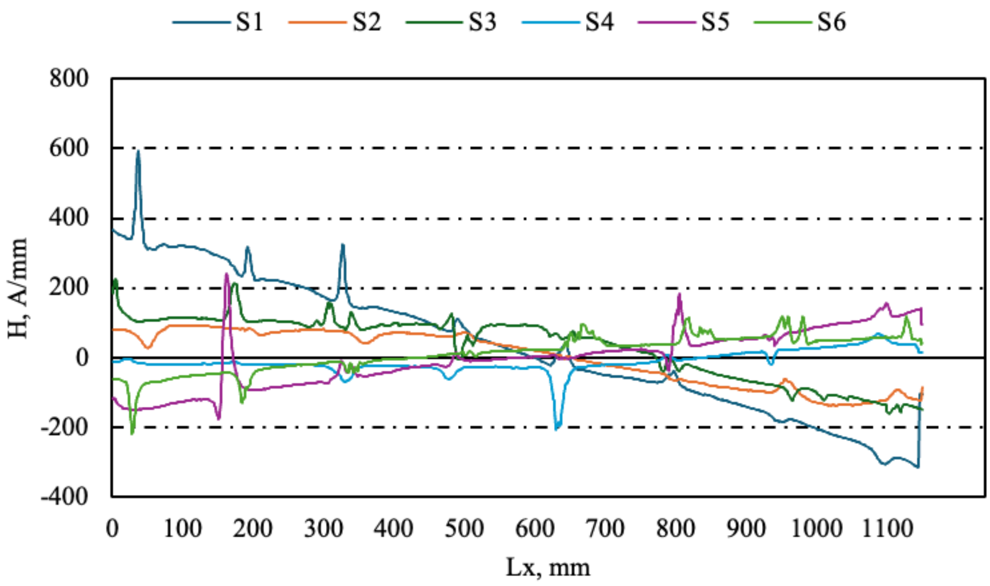


FIGURE 14. Normal component signal along a tension bar with a diameter of 16 mm (Middle)

Figures 11 and 12 show the Hp-2 signal for the steel bars on the right-hand side with a diameter of 12 mm and 16 mm respectively. These figures are similar to the previous ones (Figures 9 and 10), which showed the steel bars on the left side.

In Figure 11, which shows the Hp-2 signal for the 12 mm diameter steel bar on the right, the variations in the magnetic signal are generally moderate, with most signals remaining within the range of approximately -300 to 300 A/mm. There are some notable fluctuations, particularly in signals S4 and S6, where the normal component signal deviates more from the zero line, indicating localised stress or inhomogeneity in the material. However, the overall trend indicates a relatively stable magnetic signal distribution over the length of the bar, similar to the bar on the left with the same diameter.

Figure 12, which corresponds to the 16 mm diameter steel rod on the right, shows more pronounced variations in magnetic signals, similar to the rod on the left with the same diameter (Figure 10). Signals S4, S5 and S6 show clear peaks and troughs, especially around the 1000 mm mark, where the magnetic signal reaches up to 600 A/mm. This indicates that the 16 mm bar on the right may have higher residual stresses or material irregularities compared to the 12 mm bar. The differences in magnetic field behaviour between the two bar diameters observed in both the left and right bars illustrate the potential influence of bar thickness on the distribution of stresses and magnetic properties in the material.

Figures 12 and 13 show the signals of the normal component along tension part in the centre of the reinforcement. It is noteworthy that the scanning was not carried out on the tension rods but on the stirrups. In Figure 12, the signal amplitudes from the sensors for the 12 mm diameter bar generally vary in the range -300 to 300 A/mm, with more pronounced peaks and troughs occurring particularly at the beginning (0-100 mm) and towards the end (900-1100 mm) of the scanned area. This indicates localised magnetic anomalies, possibly indicating areas where the stirrups influence the magnetic signal.

In contrast, Figure 13, which corresponds to the 16 mm diameter bar, shows larger signal fluctuations with amplitudes between -400 and 600 A/mm. The wider range and higher amplitude fluctuations in this graph indicate that the thicker rebar interacts more strongly with the magnetic field, resulting in more pronounced signal fluctuations. The differences between the two figures illustrate the influence of the bar diameter on the detected magnetic signals. The thicker bar (16 mm) causes stronger disturbances in the magnetic field, as shown by the higher amplitude values for all sensors.

CONCLUSION

In a nutshell, the magnetic flux leakage signals detected using the MMM technique were able to identify the defective areas on the reinforcement. The highest Hp-2 for the 16 mm diameter reinforcement is 313.33 A/mm, 586 A/mm and 588.67 A/mm, while for the 12 mm diameter reinforcement, 261.33 A/mm, 309.33 A/mm and 310 A/mm were measured. Remarkable fluctuations were observed in particular for signals S4 and S6, where the signal of the normal component deviates significantly from the zero line. These deviations indicate the presence of local stresses or material inhomogeneity.

DECLARATION OF COMPETING INTEREST

None.

ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Higher Education (FRGS/1/2022/TK0/UITM/02/16) and Universiti Teknologi MARA, Cawangan Pulau Pinang (600-RMC/FRGS 5/3 (045/2022)) for their research funding support.

REFERENCES

Abarkane, C., Ríos-García, G., Gale-Lamuela, D., Rescalvo, F., Gallego, A., & Benavent-Climent, A. 2019. Metallic slit-plate dampers: Damage evaluation with metal magnetic memory technique and application to structures with rocking columns. *Metals* 9(9). https://doi.org/10.3390/met9090953

Arifin, A., Abdullah, S., Ariffin, A. K., Jamaludin, N., & Singh, S. S. K. 2022. Characterising the stress ratio effect for fatigue crack propagation parameters of SAE 1045 steel based on magnetic flux leakage. *Theoretical and Applied Fracture Mechanics* 121: 103514. https://doi.org/https://doi.org/10.1016/j.tafmec.2022.103514

Barnes, R., & Atherton, D. L. 1993. Effects of bending stresses on magnetic flux leakage patterns. *NDT & E International* 26(1): 3–6. https://doi.org/10.1016/0963-8695(93)90158-Q

Chen, H., Wang, C., & Zuo, X. 2017. Research on methods of defect classification based on metal magnetic memory. *NDT & E International* 92: 82–87. https://doi.org/https://doi.org/10.1016/j.ndteint.2017.08.002

Dubov, A. A. 2001. A technique for monitoring the bends of boiler and steam-line tubes using the magnetic memory of metal. *Teploenergetika* 4: 31–36. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035768120&partnerID=40&md5=c4f61b23b510bdd7d48f4b93bd4ab47c

Dubov, A. A., & Matyunin, V. M. 2001. Early diagnostics of blade damages with using the method of magnetic metal memory. *Tyazheloe Mashinostroenie* 10: 32–33. https://www.scopus.com/inward/record.uri?eid=2-s2.0-0035550135&partnerID=40&md5=1a3dcc111753f7d84dad6b93e33aeace

Gao, F., Fan, J., Zhang, L., Jiang, J., & He, S. 2020. Magnetic crawler climbing detection robot basing on metal magnetic memory testing technology. *Robotics and Autonomous Systems* 125: 103439. https://doi.org/https://doi.org/10.1016/j.robot.2020.103439

Gong, Y., Zhou, J., Zhao, R., Qu, Y., & Tong, K. 2022a. Study on stress measurement for steel bars inside RC beams based on self-magnetic flux leakage effect. *Journal of Magnetism and Magnetic Materials* 562. https://doi.org/10.1016/j.jmmm.2022.169784

Gong, Y., Zhou, J., Zhao, R., Qu, Y., & Tong, K. 2022b. Study on stress measurement for steel bars inside RC beams based on self-magnetic flux leakage effect. *Journal of Magnetism and Magnetic Materials* 562. https://doi.org/10.1016/j.jmmm.2022.169784

Haiyan, X., Minqiang, X., Rixin, W., & Jiazhong, Z. 2006. MMM fatigue damage evaluation and life prediction modeling for ferromagnetic materials. *Key Engineering Materials*, *324*-325 *I*: 619–622. https://www.scopus.com/inward/record.uri?eid=2-s2.0-33750925183&partnerID=40&md5=87a4d3ed4c04d3dda3870cd0babbcab7

Han, G., & Huang, H. 2021. A dual-dipole model for stress concentration evaluation based on magnetic scalar potential analysis. *NDT & E International* 118: 102394. https://doi.org/https://doi.org/10.1016/j.ndteint.2020.102394

Li, B., Li, S., Zhang, G., Ying, H., Xia, Q., & Liu, S. 2023. Grading assessment of steel bar corrosion in concrete structures based on naive Bayesian model and spontaneous magnetic flux leakage effect. *Journal of Engineering and Applied Science* 70(1). https://doi.org/10.1186/s44147-022-00170-9

Lin, G. M., Lin, H. Y., & Dong, K. 2012. Analysis of metal magnetic memory testing technology. In F*rontier of Manufacturing Science and Measuring Technology II, PTS 1 and 2* (Vols. 503–504, edited by W. P. Sung, J. C. M. Kao, & R. Chen. Issue 2nd International Conference on Frontiers of Manufacturing Science and Measuring Technology (ICFMM 2012), pp. 1623-+). https://doi.org/10.4028/www.scientific.net/AMR.503-504.1623

Liu, B., He, L., Huo, X., Wang, G., & Zhang, Q. 2017. Study on the MMM signal characteristics in magnetic field based on Kp perturbation algorithm. *Yi Qi Yi Biao Xue Bao/Chinese Journal of Scientific Instrument*, 38(1): 151–158. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85016740470&partnerID=40&md5=b6d21c8b2fe08a7d14bcae428df50ec4

Liu, B., Zeng, Z., & Wang, H. 2021. Study on the early fatigue damage evaluation of high strength steel by using three components of metal magnetic memory signal. *NDT & E International* 117: 102380. https://doi.org/https://doi.org/10.1016/j.ndteint.2020.102380

Md Nor, N., Abdullah, S., Mohamad Halim, M. A. H., & Arifin, A. 2023b. Evaluation of the behaviour of steel bar in the concrete under cyclic loading using magnetic flux leakage and acoustic emission techniques. *Materials* 16(6). https://doi.org/10.3390/ma16062172

Ni, C., Hua, L., & Wang, X. 2018. Crack propagation analysis and fatigue life prediction for structural alloy steel based on metal magnetic memory testing. *Journal of Magnetism and Magnetic Materials* 462: 144–152. https://doi.org/10.1016/j.jmmm.2018.05.019

Pospisil, K., Manychova, M., Stryk, J., Korenska, M., Matula, R., & Svoboda, V. 2021. Diagnostics of reinforcement conditions in concrete structures by gpr, impact-echo method and metal magnetic memory method. *Remote Sensing* 13(5). https://doi.org/10.3390/rs13050952

Qiu, J., Zhang, H., Zhou, J., Ma, H., & Liao, L. 2019. Experimental analysis of the correlation between bending strength and SMFL of corroded RC beams. *Construction and Building Materials* 214*:* 594–605. https://doi.org/10.1016/J.CONBUILDMAT.2019.04.120

Ren, S., Ren, X., Duan, Z., & Fu, Y. 2019. Studies on influences of initial magnetization state on metal magnetic memory signal. *NDT & E International* 103: 77–83. https://doi.org/https://doi.org/10.1016/j.ndteint.2019.02.002

S, A., Simon, K. M., & Raj, B. 202. A Review on Residual Life Assessment of Plain and Reinforced Concrete Members. *Proceedings of International Web Conference in Civil Engineering for a Sustainable Planet*. https://doi.org/10.21467/proceedings.112.33

Su, S., Yi, S., Wang, W., Zhao, X., Sun, H., & Ren, G. 2018. Experimental study on the relationship between the strain and metal magnetic memory field of steel beams. *Insight: Non-Destructive Testing and Condition Monitoring* 60(7): 380–386. https://doi.org/10.1784/insi.2018.60.7.380

Su, S., Zuo, F., Wang, W., Liu, X., Li, J., & Deng, R. 2023. Invisible damage identification and danger warning for steel box girders using the metal magnetic memory method. *Structures*, 54: 704–715. https://doi.org/https://doi.org/10.1016/j.istruc.2023.05.106

Wang, D., Dong, S.-Y., Xu, B.-S., Chen, Q.-Z., & Dong, L.-H. 2008. Metal magnetic memory testing signals of 45 carbon steel during static tension process. *Cailiao Gongcheng/Journal of Materials Engineering* 8: 77–80. https://www.scopus.com/inward/record.uri?eid=2-s2.0-49549118000&partnerID=40&md5=5021857ec6f2410aace4369f68f8de7c

Wang, Z. D., Yao, K., Deng, B., & Ding, K. Q. 2010. Theoretical studies of metal magnetic memory technique on magnetic flux leakage signals. *NDT & E International* 43(4): 354–359. https://doi.org/https://doi.org/10.1016/j.ndteint.2009.12.006

Xie, Z., Zhang, D., Ueda, T., & Jin, W. 2022. Fatigue damage analysis of prefabricated concrete composite beams based on metal magnetic memory technique. *Journal of Magnetism and Magnetic Materials* 544. https://doi.org/10.1016/j.jmmm.2021.168722

Yang, Y., Ma, X., Su, S., & Wang, W. 2023. Study on corrosion damage characterization and tensile strength evaluation for locally corroded bridge steel via metal magnetic memory method. *Measurement* 207: 112406. https://doi.org/https://doi.org/10.1016/j.measurement.2022.112406

Yu, F.-Y. 2007. Metal magnetic memory test of stress concentration of weldment in different heat treatment conditions. *Jinshu Rechuli/Heat Treatment of Metals* 32(9): 86–89. https://www.scopus.com/inward/record.uri?eid=2-s2.0-35248835070&partnerID=40&md5=792ee25ba9fd15a3d4816006f1bc4300

Zhang, X., Ou, J., & Wu, Z. 2017. Effect of Circumferentially Nonuniform Lateral Tension on Bond Behavior between Plain Round Bars and Concrete: Analytical Study. *Journal of Structural Engineering (United States)* 143(12). https://doi.org/10.1061/(ASCE)ST.1943-541X.0001903

Zhang, Y., Hu, D., Chen, J., & Yin, L. 2023. Research on non-destructive testing of stress in ferromagnetic components based on metal magnetic memory and the Barkhausen effect. *NDT & E International* 138: 102881. https://doi.org/https://doi.org/10.1016/j.ndteint.2023.102881

Zhou, J., Qiu, J., Zhou, Y., Zhou, Y., & Xia, R. 2018. Experimental study on residual bending strength of corroded reinforced concrete beam based on micromagnetic sensor. *Sensors (Switzerland)* 18(8). https://doi.org/10.3390/s18082635