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FEASIBILITY STUDY ON AN OPTICAL STRAIN GAGE BASED ON FLUORESCENCE RESPONSE OF GRAPHENE QUANTUM DOTS

Yan-Hao Sun [1], Hai-Tao Liu [1], Bo Yang [1] and Kang Chen [2, *]

[1] *School of Civil Engineering, Chongqing University, Chongqing, China*
[2] *Department of Civil Engineering, Xi'an Jiaotong-Liverpool University, Suzhou, China*
** (Corresponding author: E-mail: Kang.Chen@xjtlu.edu.cn)*

ABSTRACT

In this study, based on the excellent fluorescence properties of graphene quantum dots (GQDs) and their good response to mechanical effects, the GQDs were mixed with epoxy resin to make a coating sensor. Taking this as the research object, the film was coated on the Q235 tensile steel sample, which can dynamically monitor the stress and strain of the steel sample. By investigating the effects of the concentration of the GQDs solution, the synchronization of the film and the steel component, and the residual stress of the epoxy resin, the mechanism of the visual fluorescence signal was analyzed. The response of stress-strain of steel sample and the fluorescence intensity of coating sensor under uniaxial tension and cyclic loading were studied. The test results showed that the synthesized coating sensor had good stability and can produce very sensitive fluorescence response to the stress and strain. The fluorescence intensity of the coating sensor increased with the increase of stress and strain, and decreased with the decrease of stress and strain under cyclic loading, which had the potential to act as a new optical strain gauge. Based on the test results, the stress and strain of the GQDs-epoxy resin composites coated on tensile steel samples with different thicknesses were studied by numerical simulation.

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1. Introduction

Graphene quantum dots (GQDs) are zero-dimensional structure of graphene, belonging to nanomaterials. They can produce stable and bright fluorescence under ultraviolet light irradiation, showing good water solubility, low biological toxicity, chemical inertness and other excellent characteristics [1,2]. The photoluminescence peak position and intensity of GQDs depend on or are independent of excitation wavelength, PH value, solvent, boundary and size of GQDs. Due to its unique characteristics, it has broad application prospects in biosensing [3], bioimaging [4], fluorescent probes [5], optical sensing [6] and so on.

For steel structures, stress and strain monitoring is particularly important. Whether in the basic experimental process or in the specific parts of the actual structure, stress and strain monitoring is required. Especially in harsh environments, it is very valuable to develop a sensor with low cost, good stability, high real-time performance and remote monitoring of stress and strain. The problem of creep strain accumulation of steel structure can not be ignored. At present, there are many methods of strain measurement, including resistance strain gauge [7], optical fiber sensor [8], DIC [9] and so on. Although these methods are currently mature, they are still limited by response time, sample destruction, and cost issues. The quantum dots fluorescence sensor is based on the optical response characteristics of fluorescent quantum dots, which can alleviate the limitations of these problems to some extent.

Liu et al. [10] studied the pressure-induced optical response of InP/ZnS nanocrystals. During the full pressure cycle of 0-2.5 GPa, the photoluminescence blue shift is completely reversible, and the emission color range is from orange to green with a slight intensity enhancement. Wang [11] found that CuInS2/ZnS quantum dots not only showed high photoluminescence intensity, but also showed a reliable and simple relationship between photoluminescence emission peak energy and external pressure. Yin et al. [12] developed a quantum dot-based composite composed of the CdSe@ZnS core-shell quantum dots and bisphenol A epoxy resin. The photoluminescence intensity will change significantly for large engineering strain. Zhao et al. [13] explored a technical means to track the crack propagation of metal materials in real time by using the fluorescence characteristics of quantum dots. It was revealed that the minimum width of the crack that can be detected was 7 μm, which showed a significant improvement compared with the limit that the existing non-destructive testing technology can reach. Zhang et al. [14] found that the luminescence of semiconductor quantum dots can be adjusted by piezoelectric effect. Small mechanical force can cause significant changes in the emission spectrum. Existing studies have found that the photoluminescence properties (fluorescence) of quantum dots do have a more sensitive response to mechanical forces. Therefore, it is very potential to use the fluorescence response characteristics of GQDs to monitor the stress and strain of steel structures.

In this study, the GQDs were uniformly embedded in epoxy resin, and the fluorescence response of the GQDs fluorescence sensor to uniaxial tensile load and cyclic loading was studied. The response mechanism of the GQDs fluorescence sensor was clarified from the influence of factors such as the change of the GQDs solution concentration, the synchronization of sensor and steel sample, and the residual stress inside epoxy resin.

2. Preparation of the GQDs fluorescence sensor

2.1. Selection of the GQDs

According to the preliminary work of the laboratory, three batches of GQDs were synthesized by a similar 'top-down' method [15]. The fluorescence color and fluorescence effect are shown in Fig. 1. The fluorescence colors are blue, green and light blue, respectively. The fluorescence spectra of three batches of the GQDs with different production processes were measured by fluorescence fiber spectrometer (Ocean Insight, FLAME-S-XR1). As shown in Fig. 1, The fluorescence wavelength of the GQDs1 is 501 nm, the fluorescence intensity is 51713 Counts, the fluorescence spectrum is smooth and has only one fluorescence peak. The fluorescence wavelength of GQDs2 is 483 nm, and the fluorescence intensity is 51303 Counts. Although the fluorescence intensity is good, its fluorescence spectrum has two peaks, which is not conducive to the development of later sensors. The fluorescence wavelength of GQDs3 is 486 nm. Although the fluorescence spectrum is smooth, its fluorescence intensity is only 38075 Counts, and the fluorescence effect is poor.

After comparing the fluorescence spectra and fluorescence intensity of the above three batches of GQDs, GQDs1 was used to develop a fluorescence sensor.

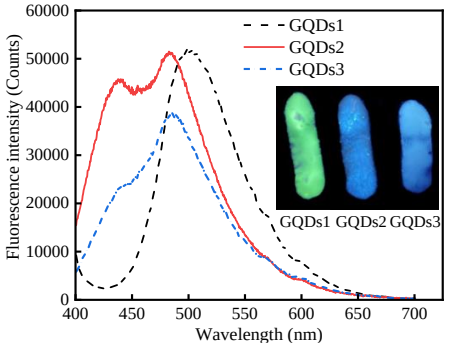


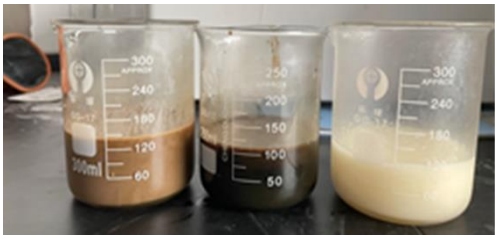
Fig. 1 Fluorescence spectra and fluorescence effect of three batches of GQDs

2.2. Selection of the GQDs carrier matrix

Considering the characteristics of GQDs, it is difficult to be directly used for actual monitoring, so it is necessary to select a suitable bearing matrix, which can not only protect GQDs, but also meet the practical application without affecting its fluorescence characteristics. The epoxy resin is easy to cure and has high strength, which can well protect GQDs from oxidation. And it has good light transmittance, and the fluorescence of GQDs can be well transmitted and almost no attenuation. In addition, the epoxy resin has good adhesion and can be firmly bonded to the structural surface in specific applications.

Considering the need to fully disperse the GQDs into epoxy resin, so epoxy resin must have a small viscosity and good fluidity. After screening and investigation, two epoxy resins were selected, which were 6002-type epoxy resin with 572-type curing agent as well as 664-type diluent, and high transparent epoxy resin with matching curing agent. The ratio test of two epoxy resins was carried out.

For the 6002-type epoxy resin, it belongs to thermosetting epoxy resin. The reference curing volume ratio is: epoxy resin : curing agent : diluent = 1 : 1 : 0.2. The curing temperature and time are : 90 °C 2h + 160 °C 2h + 180 °C 4h. Fig. 2 shows the curing conditions of three different ratios of epoxy resin. The volume ratios from left to right are (epoxy resin：curing agent：diluent) 3：3：1, 3：1：1 and 1：1 (without diluent). The group without diluent was basically uncured. Although the first two groups were cured, the curing effect was poor and the surface was not smooth. According to the curing effect, the shortcomings of this epoxy resin were obvious. The high curing temperature, long curing time and poor curing effect were not conducive to the practical application of the later sensor.



(a) Three different ratio of epoxy resin

(b) Curing condition

Fig. 2 Curing condition of three different ratio of the 6002-type epoxy resin

For the highly transparent epoxy resin, it has the advantages of good transparency, less bubbles, high hardness and low curing conditions. According to the previous multiple blending tests, the curing volume ratio of epoxy resin：curing agent = 2.5：1 was finally determined. Under this ratio, the curing time of epoxy resin was the shortest and the strength was the highest.

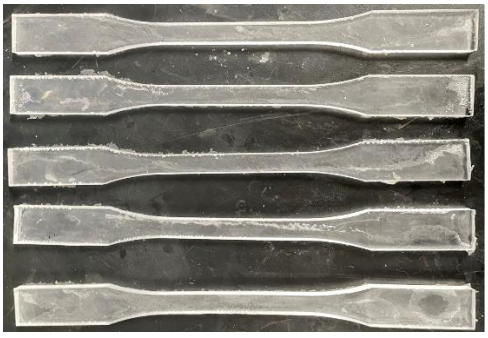


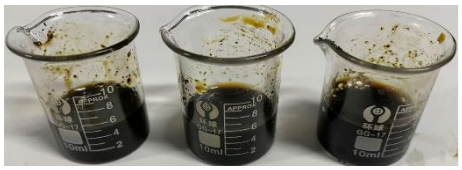
Fig. 3 Cured epoxy resin tensile specimen

As shown in Fig. 3, the cured epoxy resin had a smooth surface and good light transmittance. It was found in tests that the highly transparent epoxy resin can be completely cured at 85 °C for 2h, and can also be completely cured at room temperature for 24 h. So the epoxy resin is superior to the 6002-type epoxy resin in terms of curing performance and practicality. The high-transparent epoxy resin was finally selected as the carrier matrix of the GQDs for subsequent experiments.

2.3. Selection of the solvent

Due to the need to uniformly disperse the GQDs into the epoxy resin in the later stage, it is necessary to select a solvent that can fully dissolve the GQDs, and can be mutually soluble with the epoxy resin, while being volatile. The following three solvents were selected: N-methylpyrrolidone (NMP), anhydrous ethanol and water. The GQDs were dissolved in different solvents at a concentration of 30mg/ml, and the dissolution was observed after full stirring and dispersion. As shown in Fig. 4, the solubility of the GQDs in three solvents was good, and the GQDs can be fully dissolved.

The three solvents dissolved with GQDs were mixed into the epoxy resin in proportion, and the corresponding proportion of curing agent was added to fully stir and then put into the ultrasonic dispersion instrument for ultrasonic dispersion for 5min. The three composite solutions were poured into petri dishes to observe the situations before and after curing for 24 hours. As shown in Fig. 5, the fusion of NMP, anhydrous ethanol and epoxy resin before curing was good, whereas it was difficult for water to fuse with the epoxy resin. Besides, a large number of bubbles were generated after stirring and dispersing. After curing for 24 hours, the epoxy resin in the culture dish added with NMP and anhydrous ethanol had been cured well. However, only a part of the epoxy resin with water as solvent had been cured, resulting in the stratification of water and epoxy resin. Considering that anhydrous ethanol can be completely volatilized during the curing process of epoxy resin, it had little effect on the strength of epoxy resin after curing, so anhydrous ethanol was finally selected as the solvent.



(a) Dissolution of GQDs in solvents

(b) Before curing

(c) After curing

Fig. 4 Three different solvents (from left to right: NMP, anhydrous ethanol and water)

2.4. Optimal concentration of the GQDs solution

The fluorescence intensity of GQDs solutions with different concentrations is different, and the GQDs have fluorescence quenching characteristics [16,17] (the fluorescence intensity of graphene quantum dots decreases, the luminescence time is shortened, and even fluorescence quenching occurs). So it is not the higher the concentration of GQDs, the greater the fluorescence intensity.

Table 1
Different CQDs solution concentration

Concentration (mg/ml)	10	20	30	40	50	60
Anhydrous ethanol (ml)	40	40	40	40	40	40
GQDs (g)	0.4	0.8	1.2	1.6	2.0	2.4

To achieve the best fluorescence performance of the composites, it is necessary to determine the optimal concentration of the GQDs solution. The GQDs were dissolved in anhydrous ethanol. The following six concentration gradients were designed, as shown in Table 1.

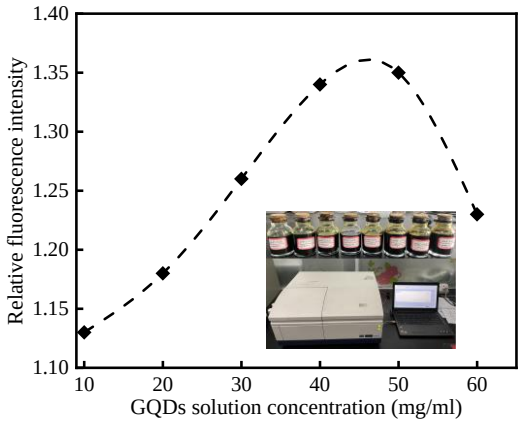


Fig. 5 Optimal concentration curve of GQDs solution

After uniform dispersion, the fluorescence intensity of the six groups of solutions was measured by a fluorescence spectrophotometer (F-7000). The measurement results are shown in Fig. 5. The relative fluorescence intensity was used to compare the fluorescence intensity of each concentration of GQDs solution. It can be seen that the relative fluorescence intensity of the GQDs solution increased with the increase of concentration before 45 mg/ml, and reached the maximum when the concentration of the solution reached 45 mg/ml. After that, the number of the GQDs per unit area increased, whereas the fluorescence intensity decreased due to the fluorescence quenching phenomenon of quantum dots. Considering the amount of the GQDs and the convenience of the later ratio, 40 mg/ml was used as the optimal fluorescence concentration of the GQDs solution.

2.5. Preparation process of the GQDs fluorescence sensor

The preparation of the composite material was carried out in the following three steps. (i) The GQDs were dissolved in the anhydrous ethanol and mechanically stirred for 3 minutes. And then the GQDs solution was placed in an ultrasonic disperser for 5 minutes to disperse the agglomerated GQDs in the solution. (ii) The GQDs solution, epoxy resin and curing agent were mixed at a volume ratio of 0.9 : 2.5 : 1, and the mixed solution was stirred with a glass rod for 3 minutes to fully integrate the three. The stirred solution was placed in an ultrasonic dispersion instrument for another 5 minutes of ultrasonic dispersion, so that the GQDs can be uniformly dispersed into the epoxy resin. (iii) The prepared composite solution was cured in two ways. One is to put the composite solution into a drying oven and cure at 85 °C for 2h. The other is cured at room temperature for 24 h. The preparation process is shown in the Fig. 6.

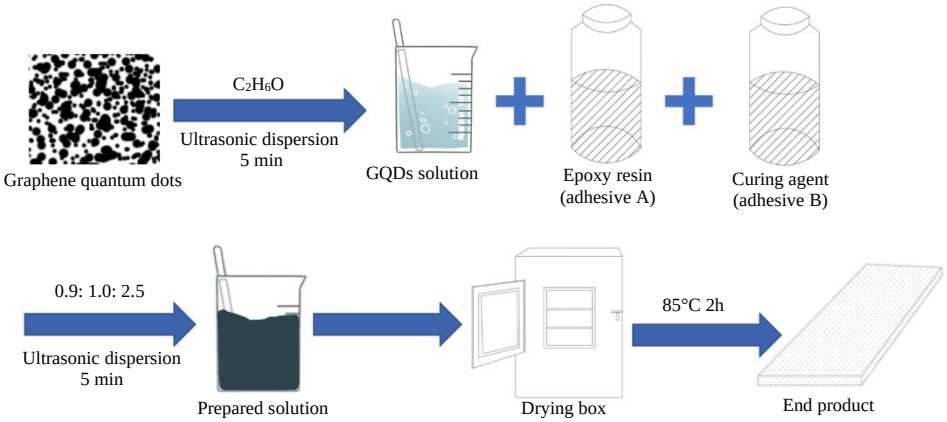


Fig. 6 GQDs fluorescence sensor preparation flow chart

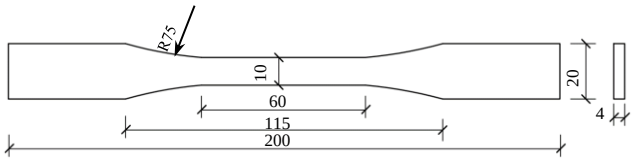
3. Tensile strain monitoring of the GQDs fluorescence sensor

3.1. Tensile fluorescence response of the GQDs fluorescence sensor

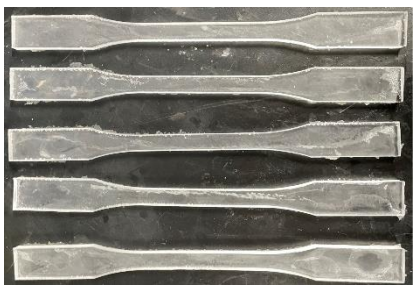
3.1.1. Sample design

According to the Chinese standard GB/T 2567-2021 [18], the tensile sample of the epoxy resin was designed, as shown in Fig. 7(a). Considering the late demoulding, the silica gel mold was customized in the size of Fig. 7(a). Two batches of epoxy resin tensile samples were poured, one batch was blank epoxy resin tensile samples, and the other batch was the GQDs-epoxy resin composites tensile samples.

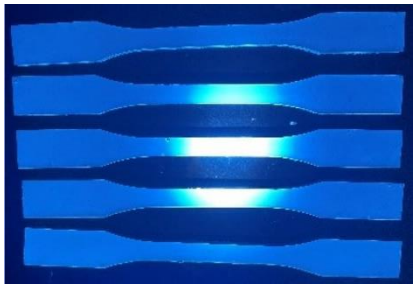
According to the preparation process in Section 2.5, two batches of samples were prepared. The prepared composite solutions were poured into silica gel molds for curing, and the curing method was selected to cure at room temperature for 24 hours. This curing method can greatly reduce the bubbles inside the composite after curing, and the surface after curing is smooth and flat, without uneven stress. The cured blank epoxy resin tensile samples are shown in Fig. 7(b), and Fig. 7(c) shows the GQDs-epoxy resin composites tensile samples. It can be seen that under the irradiation of ultraviolet light with a wavelength of 365 nm, the tensile samples exhibited photoluminescence.



(a) Tensile sample size of epoxy resin



(b) Blank epoxy resin tensile sample



(c) Tensile samples of the GQDs-epoxy resin composites

Fig. 7 Epoxy resin tensile sample

3.1.2. Test device and loading scheme

Fig. 8 shows the test device composed by the universal material testing machine and fluorescence response monitoring system. The fluorescence response monitoring system was built by fluorescence fiber spectrometer, LED 365 nm ultraviolet light source and Y-type fiber. The fluorescence response changes of tensile test were recorded by fluorescence fiber spectrometer. In the experiment, the GQDs fluorescence sensor can achieve photoluminescence under local irradiation of ultraviolet light at 365 nm wavelength.

The loading device was universal material testing machine (SANS), and the loading rate of epoxy resin tensile specimen was set to 1 mm/min.

When measuring the sample each time, it was necessary to keep a certain distance between the optical fiber probe and the measured sample, so that the measured fluorescence spectrum data was more accurate. Through the previous experiments, it was found that the distance between the optical fiber probe and the sample was most suitable in the range of 0.5 cm to 1 cm. This distance range can ensure the accuracy of the measured fluorescence spectrum, and can effectively collect the real-time change of fluorescence intensity. The change of the fluorescence intensity was collected every 1 s.

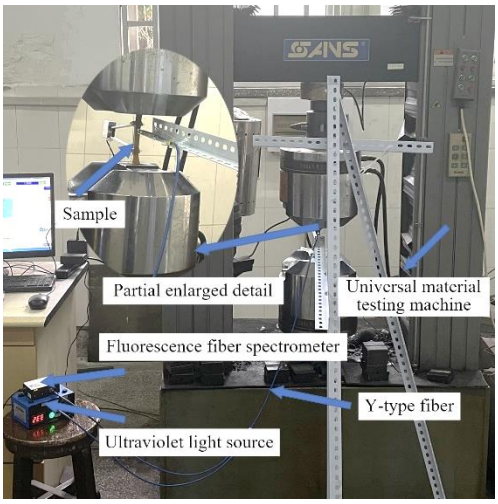


Fig. 8 Test device

3.1.3. Test results and analysis

As shown in Fig. 9, the maximum stress of the blank epoxy resin tensile samples was basically maintained at about 40 MPa, and the maximum strain was maintained at about 6 %. The stress-strain curves of the two blank epoxy resin tensile samples were similar, and the stability during stretching was good, which can serve as a matrix for carrying GQDs.

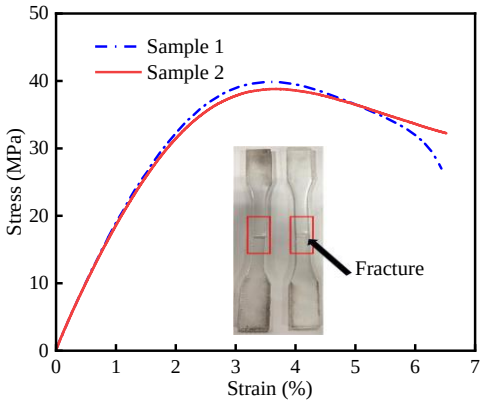
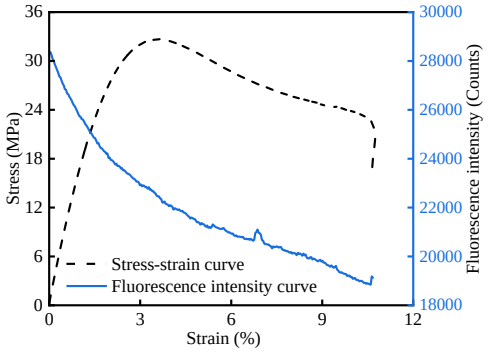
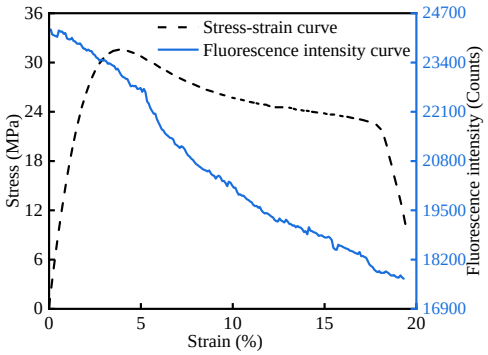


Fig. 9 Tensile stress-strain curves of blank epoxy resin tensile samples

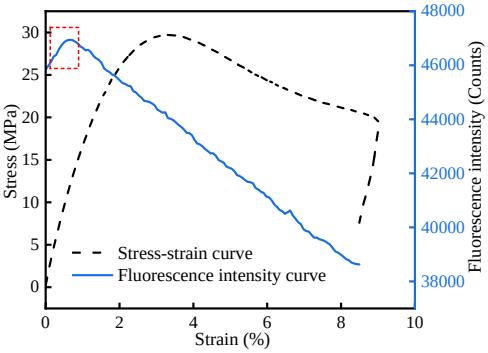
As shown in Fig. 10(a)-(b), the fluorescence intensity of the GQDs-epoxy resin composites tensile samples changed in real time with the tensile strain during the tensile test, and the fluorescence intensity decreased with the increase of the tensile strain. The two curves showed an approximate linear relationship. It was also observed in the tensile experiment that the fluorescence intensity of some tensile samples increased with the increase of strain in the early stage (Fig. 10(c)). Compared with the blank epoxy resin tensile sample in Fig. 9, the maximum strain has been greatly improved, but the maximum stress has been reduced by about 10 %. This showed that the incorporation of GQDs increased the toughness of epoxy resin to a certain extend. Fig. 11 shows the photo of the GQDs-epoxy resin composites tensile samples after fracture, it can be seen that the samples produced a large strain.



(a) Composites smple 1



(b) Composites smple 2



(c) Composites smple 3

Fig. 10 Stress and fluorescence intensity of GQDs-epoxy resin composites samples

Fig. 11 Tensile samples after fracture

As shown in Fig. 12, as the tensile strain increased during the experiment, the number of the GQDs per unit area decreased, which led to a decrease in fluorescence intensity. At the same time, when the GQDs were dispersed into epoxy resin, some quantum dots may agglomerate. During the stretching process, the agglomerated GQDs were pulled apart to expose more GQDs to ultraviolet light, which led to an increase in fluorescence intensity as the tensile strain increased. In the tensile experiment, the change of the number of GQDs per unit area may be one of the reasons for the change of fluorescence intensity.

However, the strain-induced separation of the GQDs aggregates did

increase the number of GQDs exposed to ultraviolet light, resulting in an increase in photoluminescence intensity (fluorescence intensity), which was also observed in the tensile experiment.

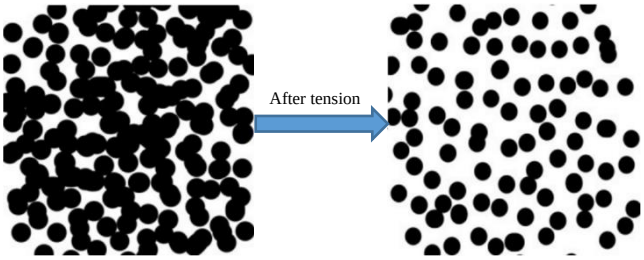
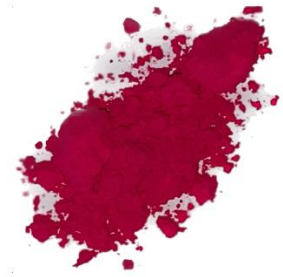


Fig. 12 Comparison of the number of GQDs unit area after tensile experiment

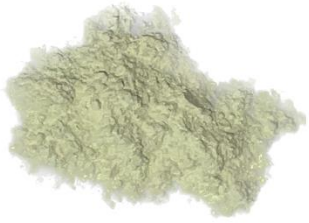
In general, the photoluminescence intensity of the rated number of graphene quantum dots may be related to its quantum yield, that is, the lower the quantum yield, the lower the photoluminescence intensity of graphene quantum dots. Carrión et al. [19] believed that the photoactivation process depends on many factors, including atmospheric conditions (oxygen, humidity), light intensity, the presence of water, and the polarity of the solvent. It can be considered that the tensile strain causes the change of related factors in the photoactivation process of graphene quantum dots, which leads to the decrease of photoluminescence intensity.

3.1.4. Contrast experiment

To prove that the fluorescence response to tensile strain is a unique phenomenon and characteristic of GQDs material, two groups of contrast experiments were set up to investigate whether the common fluorescent material will have a fluorescence response to tensile strain after it is mixed with epoxy resin to make tensile samples. Two representative fluorescent materials [20] were selected. One was a red ultra-bright phosphor with a red fluorescence color, and the other was a yellow phosphor with a green fluorescence color, as shown in Fig. 13.



(a) Red phosphors

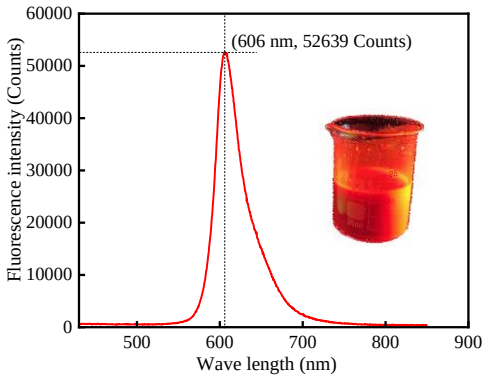


(b) Yellow phosphors

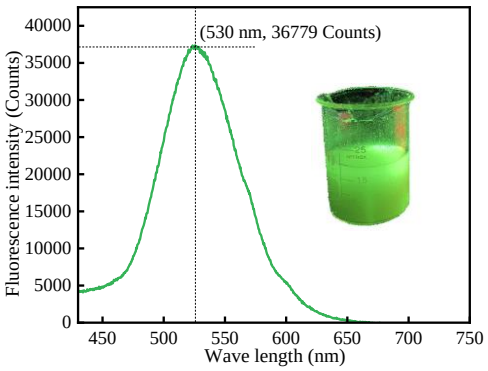
Fig. 13 Two groups of phosphors in contrast experiments

The two phosphors were also mixed into anhydrous ethanol at a concentration of 40 mg/ml, and the fluorescence spectrum was measured by fluorescence fiber spectrometer after fully stirring and dispersing, as shown in Fig. 14. The peak wavelength of the fluorescence spectrum of the red phosphor was 606 nm with a fluorescence intensity of 52639 Counts, and the fluorescence color was red (Fig. 14(a)). Fig. 14(b) shows the fluorescence spectrum of the yellow phosphor. The peak wavelength was 530 nm with a fluorescence intensity of 36779 Counts, and the fluorescence color was green. It can be seen that the fluorescence effects of these two phosphors were excellent and representative.

The dispersed two groups of phosphor solutions were prepared into tensile samples of the epoxy resin doped with phosphor according to the Section 2.5 preparation process, as shown in Fig. 15. The tensile test was carried out after 24 hours of curing to explore whether the samples in the contrast test would have a fluorescence response during the tensile process.



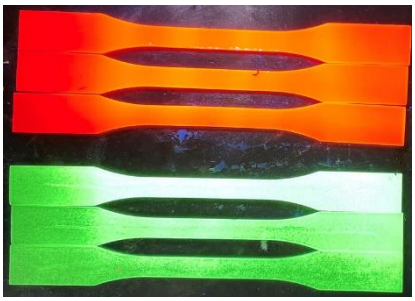
(a) Red phosphors



(b) Yellow phosphors

Fig. 14 Spectrogram of two groups of phosphors

(a) Tensile samples with phosphors



(b) Fluorescence effect after 365 nm UV excitation

Fig. 15 Tensile samples of the epoxy resin doped with phosphor

The test device in Fig. 8 also was employed in the contrast test, and the tensile rate was consistent with the tensile samples of GDQs-epoxy resin composites (1mm/min). The experimental phenomena of the two phosphors were consistent. Taking the red phosphor as an example, as shown in Fig. 16. No regular increase or decrease of the fluorescence intensity with the change of tensile strain was observed during the tensile process. The fluorescence intensity-loading time curve was basically a constantly changing broken line

without any regularity, and the fluorescence stability was very poor. After comparison, it was found that the tensile strain fluorescence response of the GQDs was a unique characteristic of such materials, while other traditional fluorescent materials did not have this characteristic.

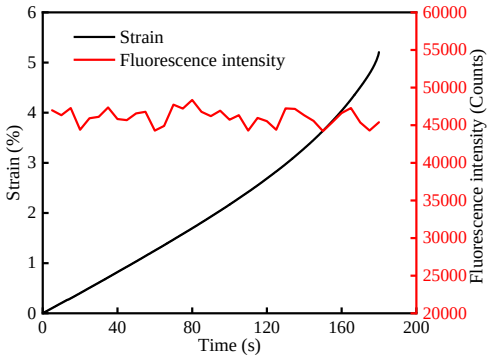


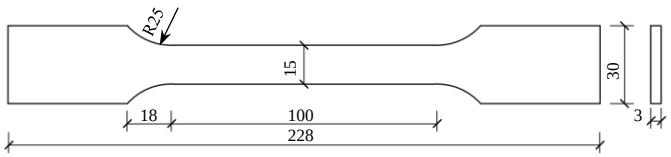
Fig. 16 Strain-fluorescence intensity response curves of tensile samples with phosphors

3.2. Fluorescence response of the GQDs fluorescence sensor to cyclic loading

In reality, the strain of steel structure always changes in real time, and large building structures are basically under cyclic loading during the long run [21]. In this section, the GQDs-epoxy resin composites was coated on the surface of the steel sample to investigate their ability to maintain a consistent fluorescence response under cyclic loading.

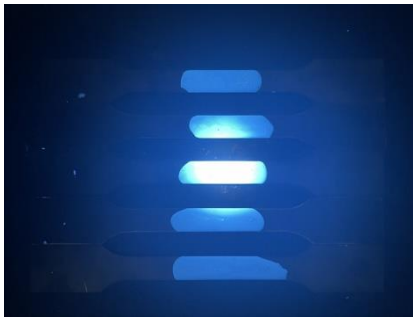
3.2.1. Sample design

According to the Chinese standard GB/T 6398-2017 [22], the tensile steel sample was designed, as shown in Fig. 17(a). To make the test more representative, the most widely used Q235 steel in the building structure was selected to make the steel sample.



(a) Tensile steel sample size

(b) Steel samples coated with the GQDs-epoxy resin composites



(c) Fluorescence effect after 365 nm UV excitation

Fig. 17 Tensile steel sample

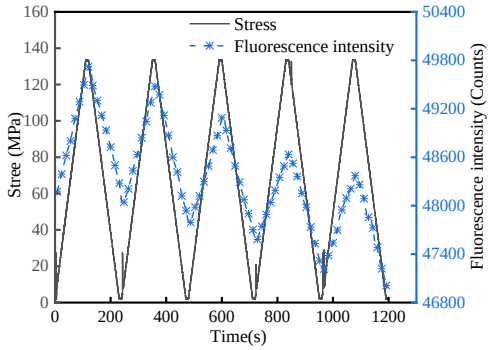
The surface of the tensile steel sample was scrubbed with alcohol to remove surface dusts and make the surface clean and smooth. Through the preparation process in Section 2.5, the prepared composite material mixed solution was dropped onto the gauge section of the Q235 steel sample, and a uniform and smooth film was formed by the gravity of the liquid itself. After being placed at room temperature for 24 hours, the film can be cured on the Q235 tensile specimen, as shown in Fig. 17(b). When the Q235 steel sample was irradiated with 365 nm ultraviolet light, it can be seen that a strong blue fluorescence was generated at the coating, as shown in Fig. 17(c).

3.2.2. Loading scheme

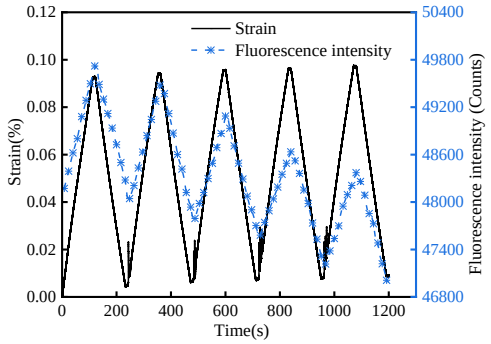
The tensile steel sample coated with GQDs-epoxy resin composites were placed in the universal material testing machine in Fig. 8 for cyclic loading and unloading. The steel sample was installed in the fixture on both sides, and the two ends of the sample were clamped by the rotating handle. The loading and unloading can be realized by moving the fixture on the upper side. During the loading process, the steel sample was kept within the elastic range.

The loading system adopted force-controlled loading, the loading rate was 50 N/s, and the fluorescence intensity was collected every 400 N. Until the load reached 6 kN, the loading was stopped and held for 10 seconds (maintained the stability of the load, facilitated the collection of fluorescence intensity data). Then unloaded from 6 kN, and the unloading process was consistent with the loading process. When unloaded to 100 N, stopped unloading and held for 10 seconds. The fluorescence response of the GQDs-epoxy resin composites to cyclic loading was investigated by repeated cycles.

Fig. 18 shows the response of the GQDs-epoxy resin sensor fluorescence intensity to stress and strain. the Q235 steel specimen had been in the elastic range under cyclic loading. The photoluminescence intensity (fluorescence intensity) of the GQDs-epoxy resin sensor had a good synchronization with the stress and strain of the steel sample. The fluorescence intensity increased with the increase of stress and decreased with the decrease of stress (Fig. 18(a)). The fluorescence intensity increased with the increase of strain and decreased with the decrease of strain (Fig. 18(b)). The curves of fluorescence response were basically linear, indicating that the GQDs-epoxy resin sensor had a high sensitivity to the change of stress and strain.



(a) Response of the sensor fluorescence intensity to stress



(b) Response of the sensor fluorescence intensity to strain

Fig. 18 Response of the sensor fluorescence intensity to stress and strain

It can also be seen from Fig. 18 that the fluorescence response accuracy and stability of the GQDs-epoxy resin sensor were better in the first three cycles. At the fourth and fifth cycles, the fluorescence response effect began to be less stable, and the overall attenuation of the fluorescence intensity began to increase, but the trend of increase and decrease with stress and strain still existed. There may be two reasons for this instability. The first is that the epoxy resin is not a linear elastic material, and residual stress occurred inside the epoxy resin during

multiple loading and unloading. The second reason is that the adhesion between the GQDs-epoxy resin sensor and the steel sample was weakened, and the phenomenon of asynchrony occurred, which led to the instability of the fluorescence response.

The change trend of the fluorescence intensity of the GQDs-epoxy resin sensor indicates that there is an interaction between the GQDs and the epoxy resin, which may be related to internal stress, strain, time dependence of epoxy resin, creep, residual stress and so on [23]. At present, the potential mechanism of this interaction is not clear, and further research and discussion are needed. This may be related to the separation of GQDs aggregates during the tensile process in small strain cyclic loading, resulting in a change in the number of GQDs per unit area.

4. Numerical simulation

4.1. Modeling method

To more clearly investigate the stress of the GQDs-epoxy resin composites when it is coated on the tensile steel member, the numerical simulation of the tensile steel sample coated with the GQDs-epoxy resin composites was carried out. Abaqus/Implicit was adopted for modeling, and the modeling parameters are as follows in Table 2. Since the loading of the steel sample is in the elastic the numerical simulation.

The tensile pressure of 200 MPa was set at both ends of the model as the load. Considering that it is difficult to realize the thin film thickness in practical application, the thinnest thickness of the simulation analysis is controlled at 0.5mm. The coating thickness of the GQDs-epoxy resin composites was set to three groups: 0.5mm, 1mm and 2mm. The FE model is shown in Fig. 19.

Table 2
Abaqus modeling parameters

Component	Density (t/mm^3)	Young's modulus (MPa)	Poisson ratio	Mesh size (mm)
Steel sample	7.9×10^{-9}	206000.0	0.3	1.0
Composites	9.5×10^{-10}	1500.0	0.4	0.1

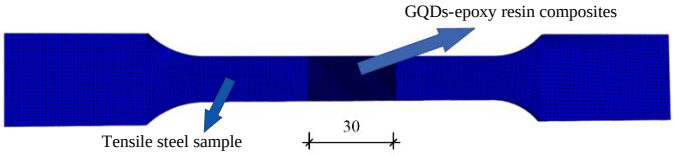


Fig. 19 FE model of steel sample coated with the GQDs-epoxy resin composites

(a) 0.5mm-thickness of the GQDs-epoxy resin composites

(b) 1 mm-thickness of the GQDs-epoxy resin composites

(c) 2 mm-thickness of the GQDs-epoxy resin composites

Fig. 20 Mises diagrams of composites with different thicknesses

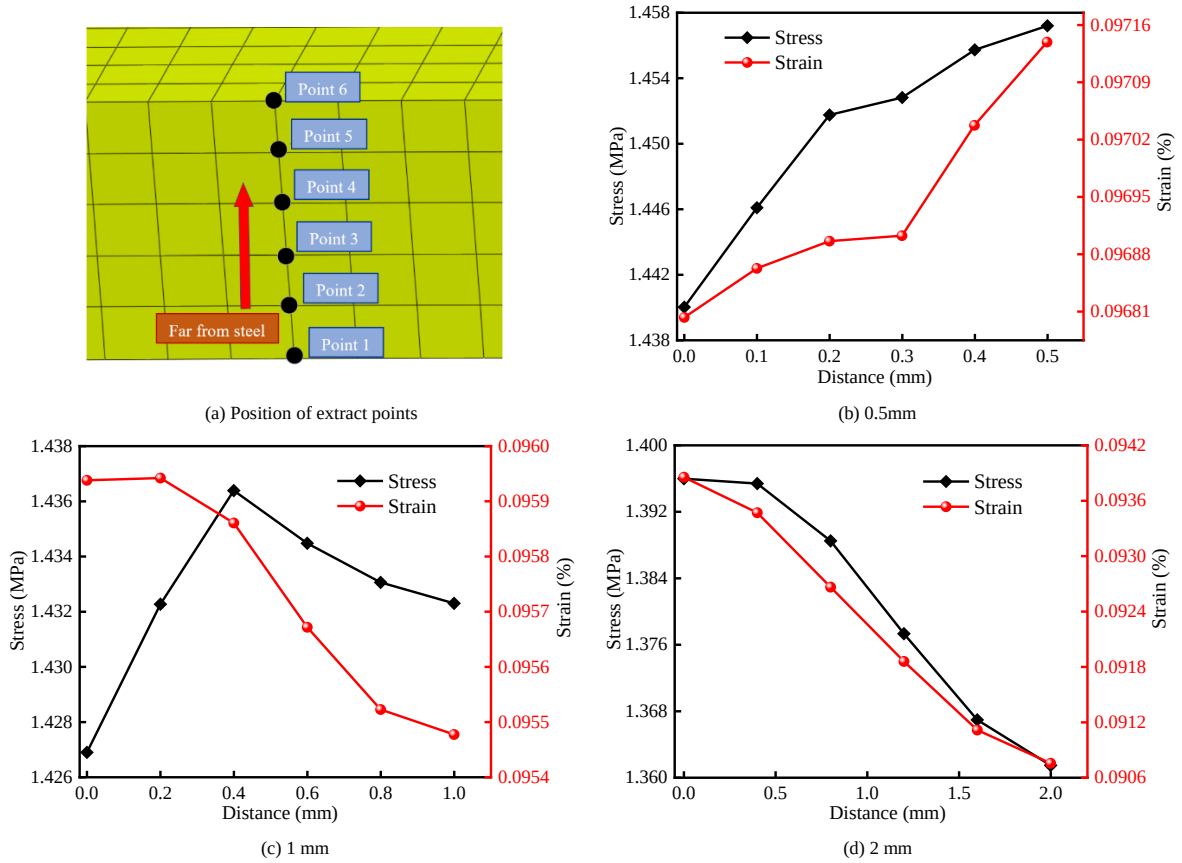
4.2. Numerical simulation results and analysis

During the tensile process of the steel sample, the GQDs-epoxy resin composites will also be subjected to different stresses. To make the stress of the composites uniform, it is necessary to study the stress and strain of the composites on the steel sample under different thickness. Fig. 20 shows the Mises diagrams of composites with a thickness of 0.5 - 2 mm. The stress distribution of the composites with a thickness of 0.5 mm is relatively uniform. However, when the thickness becomes 1 mm, the stress along the thickness direction begins to appear non-uniform phenomenon. When the thickness reaches 2 mm, the non-uniform distribution of stress along the thickness direction is aggravated. It shows that the increase of thickness will lead to the aggravation of stress non-uniform, and the deterioration of stress-strain synchronization will affect the fluorescence response accuracy of the GQDs fluorescence sensor. To select the appropriate coating thickness, it is necessary to further investigate the effect of composite thickness on stress and strain.

As shown in Fig. 21(a), the stress and strain values of six points are extracted at the same spacing along the thickness direction. As shown in Fig. 21(b), the stress and strain of the 0.5 mm-thick composites along the thickness direction show an increasing trend, and the stress and strain at the end far from the surface of the steel sample reach the maximum. For the composites with a thickness of 1 mm (Fig. 21(c)), the strain shows a decreasing trend along the thickness direction, while the stress increases first and then decreases. As shown in Fig. 21(d), when the thickness changes to 2 mm, the attenuation of stress and strain along the thickness direction increases, and the stress and strain at the end far from the surface of steel sample are the smallest. Fig. 22 compares the stress and strain of each thickness at the ends near and far from the steel surface, it is found that as the thickness increases, both of the stress and strain at the ends

near and far from the steel surface decrease.

The reason for the phenomenon of Figs. 21-22 is that only one side of the composites is bonded to the surface of the steel sample, and the stress and strain of the composites are transmitted through the bonding force. Due to the stress and strain development inside the epoxy resin and the characteristics of the viscoelastic material, the excessive thickness of the composites will affect the synchronization of stress and strain, resulting in stress and strain reduction and uneven distribution. Therefore, through the comparative analysis, it is found that the stress and strain synchronization and distribution of the composites with a thickness of 0.5 mm are the best when subjected to tensile load. With the increase of thickness, especially when the thickness changes to 2 mm, the stress and strain of the whole composite layer will be unevenly distributed and the synchronization will become worse.



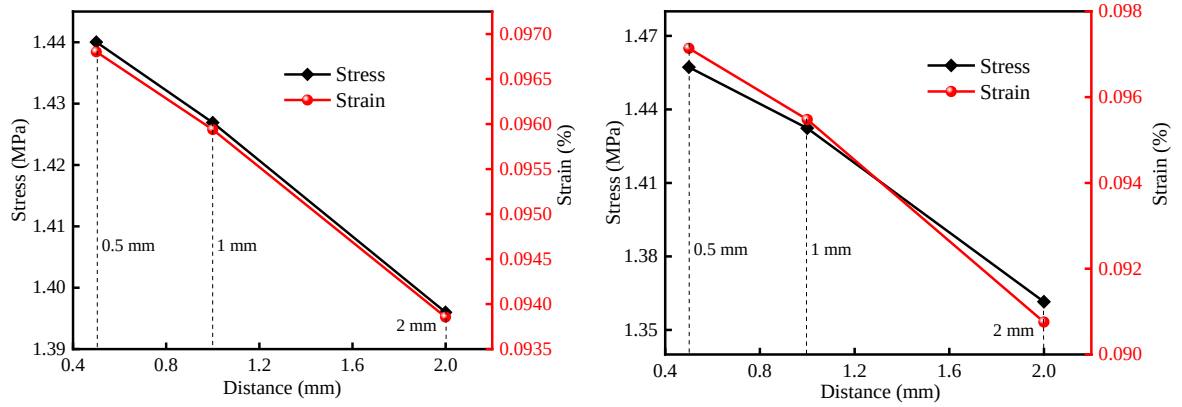
(a) Position of extract points

(b) 0.5mm

(c) 1 mm

(d) 2 mm

Fig. 21 Position of extract points and stress-strain comparison of composites from the near end to the far end



(a) Near the steel sample surface

(b) Far from the steel sample surface

Fig. 22 Stress-strain comparison of composites near and far from the steel sample end

5. Conclusions

In this study, through a series of preliminary deployment experiments, a GDQs fluorescence sensor was successfully synthesized. It was poured into a standard tensile sample, and the uniaxial tensile experiment was carried out by the pouring method. After that, the GDQs fluorescence sensor was uniformly applied to the Q235 standard tensile steel sample by drop coating method, and the cyclic loading experiment was carried out. Furthermore, the stress and strain of the GQDS-epoxy resin composites coated on tensile steel samples with different thicknesses were studied by numerical simulation. The following conclusions can be drawn:

(1) Through the compounding test, it was determined that the highly transparent epoxy resin and anhydrous ethanol were emplyed as the carrier matrix and the solvent of the GQDs. Considering the fluorescence quenching phenomenon of GQDs, the optimal concentration of GQDs solution was 40 mg/ml. The preparation process of the GQDs-epoxy resin composites was standardized. And two curing methods of composites were selected, which were curing at 85 °C for 2h and curing at room temperature for 24h.

(2) The GQDs fluorescence sensor has a good fluorescence response to the tensile strain. After the tensile sample was made, the fluorescence intensity

decreased with the increase of the tensile strain, showing an approximate inverse relationship. The incorporation of the GQDs in the will tensile sample improve the toughness of epoxy resin to a certain extent.

(3) Cyclic test was carried out on the tensile steel samples coated with the GQDs fluorescent sensors. The fluorescence intensity of the the GQDs fluorescent sensors increased with the increase of steel stress and strain, and decreased with the decrease of steel stress and strain. The fluorescence response accuracy and stability were better in the first three cycles, whereas at the fourth and fifth cycles, the fluorescence response effect began to be less stable, and the overall attenuation of the fluorescence intensity began to increase, but the trend of increase and decrease with stress and strain still existed.

(4) Numerical simulation shows that the increase of thickness will lead to the aggravation of stress non-uniform, and the deterioration of stress-strain synchronization will affect the fluorescence response accuracy of the GQDs fluorescence sensor. Through the comparative analysis, the stress and strain synchronization and distribution of the composites with a thickness of 0.5 mm are the best when subjected to tensile load.

References

[1] Zheng X. T., Ananthanarayanan A., Luo K. Q. and Chen P., "Glowing Graphene Quantum Dots and Carbon" Dots: Properties, Syntheses, and Biological Applications", Small, 11(14), 1620-1636, 2015.

[2] Zheng P. and Wu N. Q., "Fluorescence and Sensing Applications of Graphene Oxide and Graphene Quantum Dots: A Review", Chemistry-an Asian Journal, 12(18), 2343-2353, 2017.

[3] Shi J. Y., Chan C. Y., Pang Y. T., Ye W. W., Tian F., Lyu J., Zhang Y. and Yang M., "A fluorescence resonance energy transfer (FRET) biosensor based on graphene quantum dots (GQDs) and gold nanoparticles (AuNPs) for the detection of mecA gene sequence of Staphylococcus aureus", Biosensors & Bioelectronics, 67, 595-600, 2015.

[4] Kortel M., Mansuriya B. D., Santana N. V. and Altintas Z., "Graphene quantum dots as flourishing nanomaterials for bio-imaging, therapy development, and micro-supercapacitors", Micromachines, 11(9), 2020.

[5] Li M. X., Chen T., Gooding J. J. and Liu J. Q., "Review of Carbon and Graphene Quantum Dots for Sensing", ACS Sensors, 4(7), 1732-1748, 2019.

[6] Kalkal A., Kadian S., Pradhan R., Manik G. and Packirisamy G., "Recent advances in graphene quantum dot-based optical and electrochemical (bio) analytical sensors", Materials Advances, 2(17), 5513-5541, 2021.

[7] Kalpana H. M. and Prasad V. S., "Development of the invar36 thin film strain gauge sensor for strain measurement", Measurement Science and Technology, 25(6), 2014.

[8] Murray M. J., Murray J. B., Ogden H. M. and Redding B., "Dynamic temperature-strain discrimination using a hybrid distributed fiber sensor based on Brillouin and Rayleigh scattering", Optics Express, 31(1), 287-300, 2023.

[9] Khoo S. W., Karuppanan S. and Tan C. S., "A review of surface deformation and strain measurement using two-dimensional digital image correlation", Metrology and Measurement Systems, 23(3), 461-480, 2016.

[10] Liu H., Zhao X. H., Yang X. Y., Wang Y. X., Wu M., Jiang J. T., Wu G. R., Yuan K. J., Sui L. Z. and Zou B., "Piezochromic luminescence in all-inorganic core-shell InP/ZnS nanocrystals via pressure-modulated strain engineering", Nanoscale Horizons, 5(8), 1233-1239, 2020.

[11] Wang J. D., Ning H. R., Wang J., Kershaw S. V., Jing L. H. and Xiao P., "Effects of repetitive pressure on the photoluminescence of bare and ZnS-Capped CuInS2 quantum dots: implications for nanoscale stress sensors", ACS Applied Nano Materials, 5(4), 5617-5624, 2022.

[12] Yin S. F., Zhao Z. M., Luan W. L., and Yang F. Q., "Optical response of a quantum dot–epoxy resin composite: effect of tensile strain", RSC Advances, 6(22), 18126-18133, 2016.

[13] Zhao Z. M., Luan W. L., Yin S. F. and Tu S. D., "Real-time monitoring of crack propagationin metals based on quantum dots", China Mechanical Engineering, 26(17), 2374-2377, 2015.

[14] Zhang Y., Nie J. H. and Li L. J., "Piezotronic effect on the luminescence of quantum dots for micro/nano-newton force measurement", Nano Research, 11(4), 1977-1986, 2018.

[15] Ghaffarkhah A., Hosseini E., Kamkar M., Sehat A. A., Dordanihaghighi S., Allahbakhsh A., Kuur C. and Arjmand M, "Synthesis, Applications, and Prospects of Graphene Quantum Dots: A Comprehensive Review", Small, 18, 2102683, 2022.

[16] Achadu O. J. and Nyokong T., "Interaction of Graphene Quantum Dots with 4-Acetamido-2,2,6,6-Tetramethylpiperidine-Oxyl Free Radicals: A Spectroscopic and Fluorimetric Study", Journal of Fluorescence, 26(1), 283-295, 2016.

[17] Das R., Rajender G. and Giri P. K., "Anomalous fluorescence enhancement and fluorescence quenching of graphene quantum dots by single walled carbon nanotubes", Physical Chemistry Chemical Physics, 20(6): 4527-4537, 2018.

[18] Chinese Standard GB/T 2567-2021: Test methods for properties of resin casting body, Standards Press of China, Beijing, China, 2021.

[19] Carrión C., Cárdenas S., Simonet B. M. and Valcárcel M., "Quantum dots luminescence enhancement due to illumination with UV/Vis light", Chemical Communications, 35, 5214-5226, 2009.

[20] Hong G. Y., "Research progress of rare earth luminescent materials", Journal of Synthetic Crystals, 44(10), 2641-2651, 2015.

[21] Ge H. B. and Kang L., "Ductile crack initiation and propagation in steel bridge piers subjected to random cyclic loading", Engineering Structures, 59, 809-820, 2014.

[22] Chinese Standard GB/T 6398-2017: Metallic materials - Fatigue testing - Fatigue crack growth method, Standardization Administration of China, Beijing, China, 2017.

[23] Karimi B. and Ramezanzadeh B., "A comparative study on the effects of ultrathin luminescent graphene oxide quantum dot (GOQD) and graphene oxide (GO) nanosheets on the interfacial interactions and mechanical properties of an epoxy composite", Journal of Colloid and Interface Science, 493, 62-76, 2017