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STADIUM VIBRATION ASSESSMENT FOR SERVICEABILITY CONSIDERING THE VIBRATION DURATION

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Abstract: Vibration problems in grandstand structures have been getting more attention due to increasing slenderness of architectural components and the complexity of crowd loading for structural designers. The vibration serviceability checks under these conditions become a challenge in the design and operation stages. Regarding human comfort and tolerance to vibration, excessive vibrations due to occupant activities may affect their comfort or even cause panic, especially passive occupants who do not participate in generating the source of vibrations. Although durations of excessive vibrations have been proved as one of the most important factors affecting occupants' comfort, it remains a big challenge to be solved. In addition, the currently available approaches using raw acceleration, weighted RMS acceleration, Vibration dose values (VDV), etc. are not sufficient for serviceability assessment due to the lack of detailed guidance for obtaining the integration time and taking the duration of vibration into account. Therefore, in this current study, a new parameter and framework are proposed where the duration of vibration is incorporated with conventional data processing. The aim is to better examine vibration levels of structures and the corresponding likely reactions with an emphasis on grandstand structures. The experimental study shows that the proposed framework can successfully address the impact of duration time on determining the levels of vibrations and human comfort levels using the proposed parameter, and perception ranges.

1 INTRODUCTION

Excessive vibrations in stadiums due to crowd excitations have been caused serious serviceability problems recently. The problems arise from the availability of high-strength materials and precise methodologies that allow designers to design lighter stadiums with slender members. Therefore, vibration characteristics should be carefully investigated in terms of serviceability assessments during the useful life of stadiums to prevent disturbing vibrations.

A lot of research related to human comfort in stadiums has been conducted in the last few decades. Traditionally, human comfort and vibration levels of a stadium are analyzed mainly based on the recommendations in the standards and design guides such as ISO2631-1 1997; BS6841 1987; Murray et al. 1997; National Building Code of Canada, (NBC) 2005. The similarity between these standards is that acceleration is a primary input for the assessment process. However, the many researchers have raised their concerns about the applicability of these standardised documents. For instance, Salyards, Hanagan, and Trethewey 2006 evaluate the differences among available vibration serviceability assessment methods using experimental data from a rock concert hosted at a stadium. The authors concerned with the serviceability limits whose perception range should be revised since the range did not reflect accurately the occupant reactions. Moreover, it was shown that the use of different time steps in the calculation of the recommended parameters (ISO 2631-1 1997; BS6841 1987) drastically altered these values. Caprioli, Reynolds, and Vanali 2007 conducted a comparison between the two widely used vibration assessment standards, i.e., ISO2631-1 and BS6841. Dynamic responses of two different stadiums hosting the same event and two different events were utilized to evaluate the assessment parameters. The difference in the weighting functions presented in the two standards resulted in a slight difference in the final results. In addition, there is no detailed guidance on the use of integration time, which can change the resulting parameters. The authors noticed that the occupant comfort limits found in literature were not consistent since there is a poor agreement between the limits, and the actual occupant reactions reported. Nhleko, Williams, and Blakeborough 2009 conducted an experiment on a simulated grandstand to investigate the development of human perception to vibration, and comfort levels. The results showed that perception variables take on its extreme state far sooner than the comfort variables meaning perception variables should be a primary factor in safety assessment. By comparison with the current serviceability limits, it was concluded that there should be a new category of serviceability assessment for stadium structures since comfort levels investigated for this study stood outside the limits recommended for both transportation and building structures. A more detailed review of stadium vibration assessment can be found at a paper conducted by Celik et al. 2016.

1.1 Objective and Scope

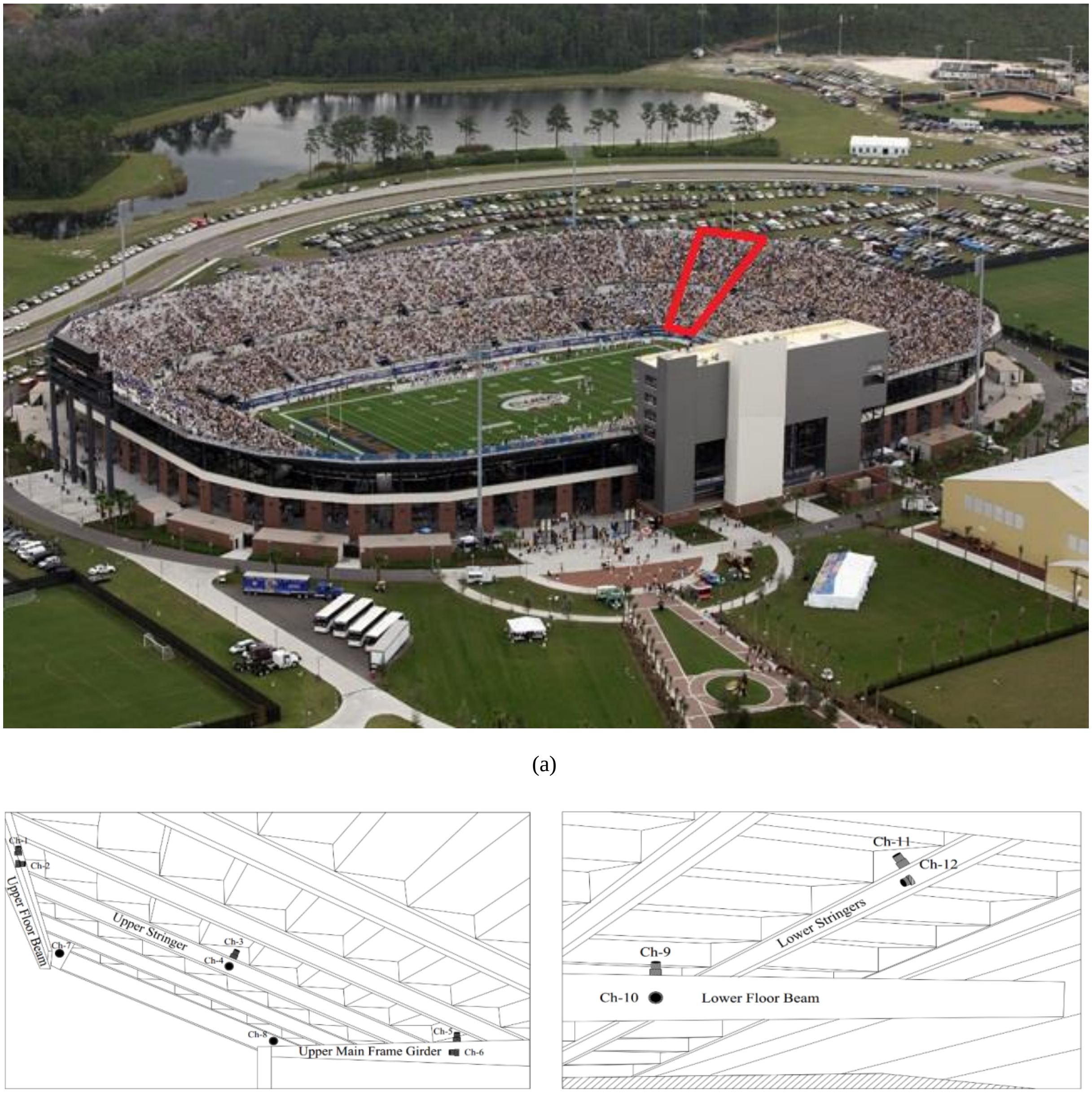
Current related literature has shown that there is a lack of defining the length or duration of excessively vibrating periods caused by occupant activities in stadiums, although it is widely known that this factor is vital for evaluating vibration levels and the expected reactions from the spectators. Therefore, a new methodology for serviceability and human comfort assessments of stadiums is presented where the duration of vibrating episodes due to distinct events during a sporting game is considered along with the application of the frequency weighting functions to explicitly evaluate the severity of vibration against human comfort. The new equation is capable of showing vibrations taken place for longer durations will result in more problems and a higher probability of adverse reactions from the occupants.

2 INSTRUMENTATION AND METHODOLOGY

2.1 Description of the stadium

The stadium under monitoring was constructed using structural steel and has the seating capacity of 45,000 seats approximately. The stadium contains 38 lower-level and 36 upper-level sections. It is decided that the student section located at the rotating corner of the stadium marked in red in Figure 1.a is the monitoring section since it is believed that this section will experience high vibrations due to the student's activities.

The far end of the frame section has 18.29 m opening with 16.76 m height, and the front end has 4.57 m opening with 2.29 m height. Twelve accelerometers were used for the section, eight of which were installed in the upper section while the remaining was installed in the lower sections. Details of the instrumentation are depicted in Figure 1.b, and Figure 1.c. The accelerations in three orthogonal directions were recorded to collect acceleration data in different directions simultaneously. However, the only acceleration in the vertical direction is analyzed and presented in this current study.



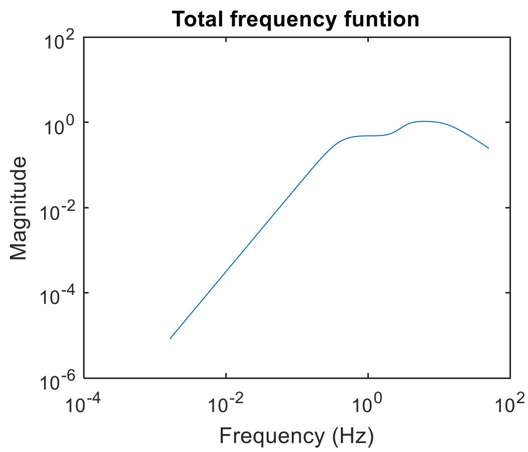
(a)

(b) (c)

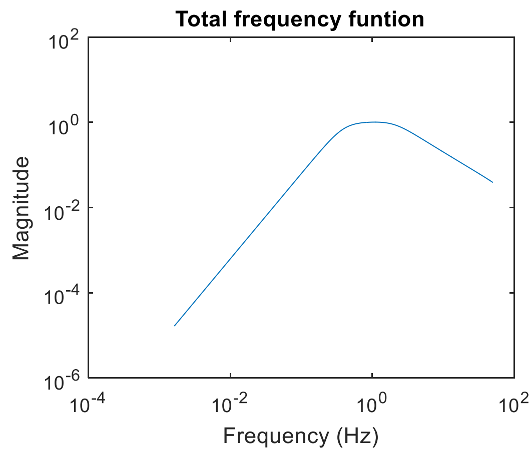
Figure 1. (a) The stadium and the section under monitoring; and the accelerometer instrumentation: (b) Upper section, (c) Lower section

2.2 The Proposed Area of RMS (ARMS) Method

Firstly, the recorded acceleration data are preprocessed using different frequency weighting functions recommended by the ISO 2631-1. The total frequency functions in the vertical and horizontal directions are shown in Figure 2. As the figure shows, the frequency components ranging from 4 to 8 Hz are emphasized, whereas the remaining frequencies are de-emphasized. Essentially, the applications of these filters imply the fact that humans are most sensitive to vibration with the frequencies within 4 to 8 Hz.



(a)



(b)

Figure 2: Total frequency function: (a) vertical, and (b) horizontal directions

Once the filters have been applied to obtain the weighted acceleration, the running Root Mean Square of weighted acceleration is computed using Eq. (1)

$$a_w(t_0) = \left\{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} [a_w(t)]^2 dt\right\}^{\frac{1}{2}} \qquad (1)$$

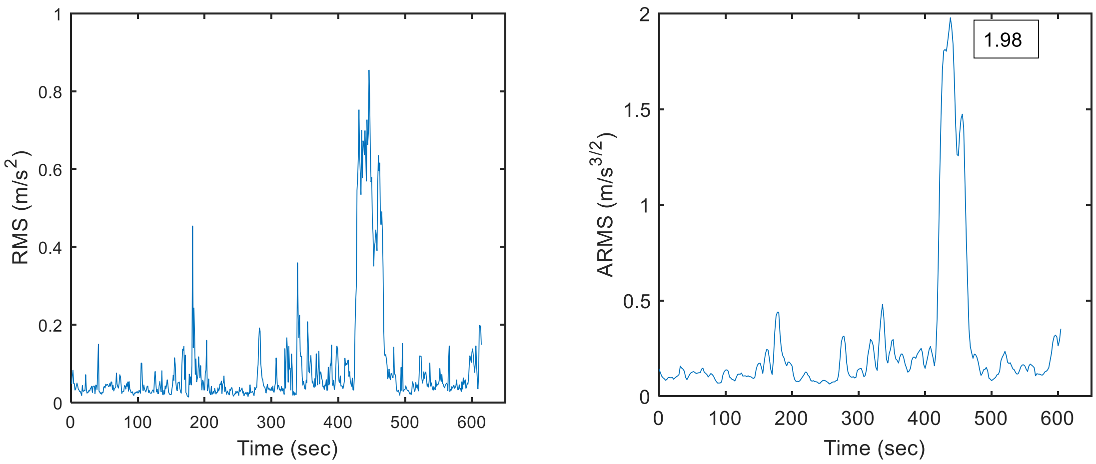
Where, $a_w(t)$ is the instantaneous frequency-weighted acceleration; τ is the integration time which is chosen to be 1 sec in this study; t is the time (integration variable); t_0 is the time of observation.

Subsequently, the proposed Area of RMS (ARMS) is computed based on Eq. (2)

$$\text{ARMS} = \frac{\text{Area of RMS}}{\text{W}^{0.5}} \qquad (2)$$

Where, W is the window length or the duration of the most excessive vibration; Area of RMS is the area of RMS curve under the window length, W. Note that the RMS values are calculated with 1-second integration period.

Regarding the choice of W, the RMS curve and the corresponding ARMS values with W = 10 secs of a typical 10-minute dataset are shown in Figure 3. As can be seen, the maximum value of ARMS is 1.98 $m/s^{3/2}$ which will obviously change when the value of W changes. Also, the value of 10 secs does not truthfully represent the actual duration of the highly vibrating episode in the dataset occurring between the 400^{th} and 500^{th} second since it should be in the range of 40 to 50 secs based on the visual check.



(a) (b)

Figure 3: RMS curve of a typical weighted acceleration dataset and the corresponding ARMS curve

It was interestingly found that the value of the W could be appropriately defined by varying the W up to 60 secs and calculating the corresponding ARMS from the RMS curve with a 0.8 overlap ratio. The optimized value of W is the one that can maximize the ARMS and is close to the actual length of the most excessive episode in the dataset being analyzed. As shown in Figure 4, the maximum value of ARMS is obtained, i.e. 3.54 m/s$^{3/2}$ when using 45-sec window length, which turns out to be an indication of the actual duration of the most exciting episode.

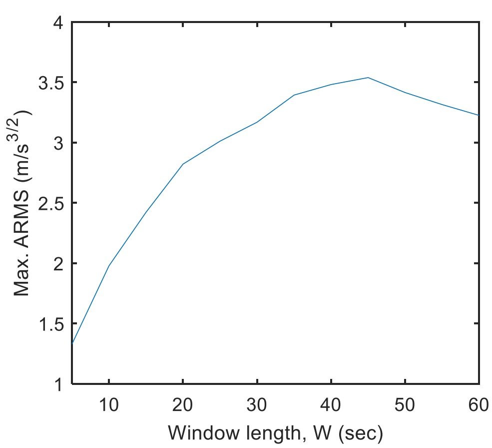


Figure 4: The variation of Max. ARMS under various W values

The observation of W has been thoroughly checked with many dataset and the patterns of W were relatively the same and similar to the one in Figure 4 with a specific value of W that optimizes the ARMS values. Therefore, it can be said that vibrations in stadiums have a clear characteristic which is the extremely vibrating episodes arising from some special events such as scoring, touchdown, to name a few. It is obvious to say that the comfort levels will be greatly affected by such lengthy vibrating events.

2.3 The proposed human comfort levels

After defining the proposed ARMS values for assessing the vibration levels, the next critical step is to define the limits for differentiating comfort levels using the proposed ARMS value. By examining the Motion Sickness Dose Values ($\mathrm{MSDV} = \mathrm{a_w T_0^{\frac{1}{2}}}$) presented in ISO2632-1, it is observed that the MSDV and the proposed ARMS possess the same unit, although the way of calculating these two values are completely different. One of the fundamental differences between the MSDV and the proposed ARMS is that MSDV requires the time exposure T_0, which is not defined easily. The same requirement about the time parameter is expected when calculating the ARMS, but this parameter is defined automatically. Therefore, we start our preliminary analysis by building the limits of ARMS for human comfort on the equation of MSDV, the RMS acceleration ranges presented in the ISO standard, and a reference from Kasperski's perception limits (Kasperski 1996). Note that the acceleration levels in Kasperski's study are considered as RMS frequency weighted acceleration with one-second integration period. The proposed limits using ARMS values are tabulated in Table 1, where there are five levels of expected reactions.

Table 1: ARMS range and the corresponding likely reactions

Levels of ARMS ($m/s^{3/2}$)	Reaction
<1.55	Reasonable for passive persons
1.55-2.78	Fairly disturbing
2.78-5.60	Disturbing
5.60-7.91	Unacceptable
>7.91	Probably causing panic

3 RESULTS FROM THE REAL-LIFE APPLICATION

In 2007, vibration of the stadium was first monitored during a sporting event named Game 1. The stadium was reported to be full with 45,000 spectators. The section was monitored before the game started until 30 minutes after the game was over. While the data was being collected, different events corresponding to the stadium's vibrations were captured. Overall, there were some distinct events being noticed such as kickoff, touchdown (score), interception and playing a popular song. After applying the frequency filtering, the resulting data are analyzed using the proposed framework. The below acceleration plot (Figure 5) shows some events due to the audience's activities, i.e. interception, touchdown and playing the popular song.

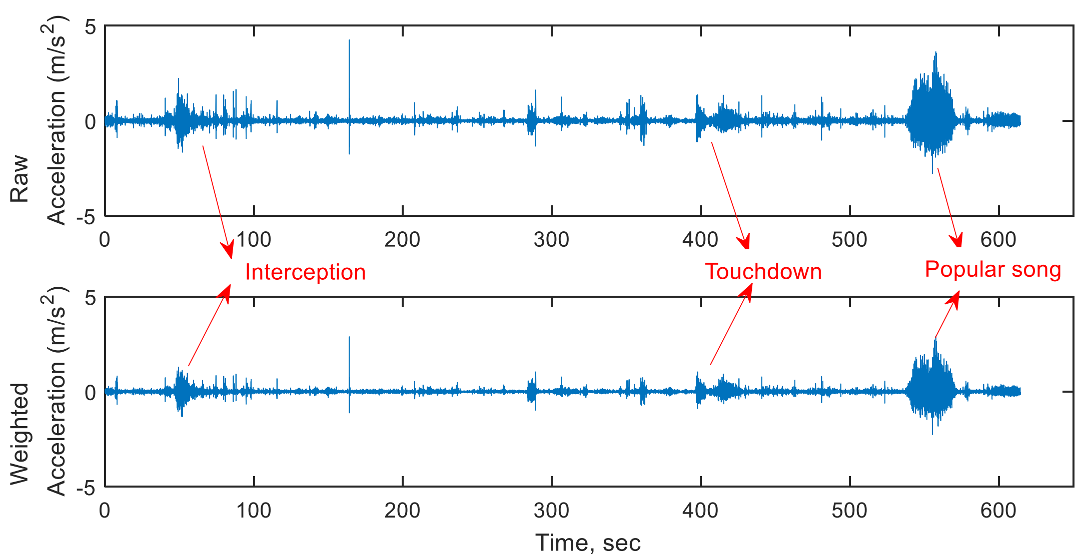


Figure 5: Typical events occurring during the game

Since the sensor referring to channel 11 was installed at the mid-span of the stringer which is directly connected to the seats, this channel is expected to closely represent the vibration and human comfort levels that the audience experiences. Therefore, the results from this channel are primarily discussed as shown in Table 2. Overall, there are five events that caused the most excessive vibrations in the stadium, i.e. touchdown, kickoff, interception, stamping and playing a popular song. The structure vibrates differently during each event with the duration varying from 19 to 50 secs. The weighted acceleration is observed to be highest at 4.485 m/s^2 when the spectators cheered for the touchdown event. In addition, two events, i.e. Score, and Kickoff caused the vibrations to have the longest duration at 40 and 50 secs, respectively. It is obvious that the weighted acceleration and RMS values cannot explicitly indicate the vibration levels in these cases since the vibration length is not addressed.

Table 2: Analysis of data recorded at Channel 11

	Events	Duration (sec) (Visual check)	a_w (m/s^2)	RMS (m/s^2)	Levels of Comfort (Based on ISO 2631-1)	ARMS (m/s$^{3/2}$)	Proposed Perception (Based on the limit of ARMS)	Estimated Duration Using Window Analysis (sec)
Game 1	Score	19	2.470	0.949	Uncomfortable	2.662	Fairly disturbing	15
		50	2.252	0.854	Uncomfortable	3.538	Disturbing	45
	Kickoff	50	2.978	1.381	Uncomfortable	4.922	Disturbing	50
	Touchdown	45	4.485	1.764	Uncomfortable	7.250	Unacceptable	40
	Interception	34	1.654	0.600	Fairly uncomfortable	2.121	Fairly disturbing	30
	Popular song	35	2.927	0.918	Uncomfortable	3.272	Disturbing	30

The ARMS values calculated at channel 11, show very meaningful information. For instance, there are two events of scoring that result in the RMS of 0.949 and 0.854 m/s^2. Even though the RMS value for the latter event is lower, the ARMS values at these two events indicate that the vibration caused by the latter event is more severe than the former counterpart. To be specific, 3.538 m/s$^{3/2}$ is the resulting ARMS value of the latter compared to 2.662 m/s$^{3/2}$, ARMS of the former. This is because the two events have different durations, which are approximately 19 secs for the former and 50 secs for the latter event, respectively. Obviously, longer duration of the latter event is the reason its vibration level is more severe than the former event, although these two events exhibit relatively the same peak acceleration and RMS values. Moreover, the event durations were estimated as 15 secs and 45 secs by using the proposed method, very close to the actual durations (19 secs and 50 secs) of the events as shown in Table 2.

Regarding the comfort levels based on the ARMS values, “Disturbing” was found only at some distinctly vibrating events over long periods when the proposed limit is utilized. To be more specific, vibration levels at channel 11 are reported to cause high discomfort to the spectators. For instance, there are four events during the game, i.e. score, kickoff, touchdown, and playing a popular song from which the reactions are expected to be mostly at “Disturbing.” The reason is that the channel is right under the center of the flooring system of the stadium’s section where students, the most active and exciting audience, stayed to support the home team. From Table 2, the only event that reached the “Unacceptable” limit is the touchdown. This incident caused the vibration level in channel 11 to be the highest at 7.25 m/s$^{3/2}$ using the proposed parameter. Regarding the comfort levels presented in the ISO 2632-1, the perception range reveals a very general statement. For instance, almost all events are categorized as “Uncomfortable” whereas the proposed perception range is very effective as it reflects the fact that different vibration levels due to different events result in different reactions from the occupants.

4 CONCLUSION

Annoying vibrations in civil infrastructure, especially in grandstand structures have been widely studied since it is accepted that maintaining the serviceability limit is a vital requirement for sustainable structures. Available standards and related research provide useful tools; however, their capabilities for evaluating the vibration levels and predicting occupant response are still arguable. In addition, durations of uncontrolled vibrations were not appropriately addressed in these standards and research studies. In this current study, a novel framework is proposed by employing the lengths of excessive vibrations and the frequency weighting functions to comprehensively evaluate the vibration levels and the corresponding levels of human comfort in stadiums. The proposed method can provide better evaluations of vibration levels and human comfort since it can incorporate vibration magnitude and duration at the same time. The results from the real data show that the presented method can effectively address the impact of excessive vibration durations. For future work, it is planned to validate the proposed method using data from different laboratories and real-life structures.

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