ŌTAUTAHI CHRISTCHURCH AOTEAROA NEW ZEALAND
35TH AUSTRALASIAN ASSOCIATION FOR ENGINEERING EDUCATION ANNUAL CONFERENCE
8-11 DEC 2024
THE ENGINEER AND THE WORLD

Reflection on the use of real-life situations and analogy in collaborative teaching and learning of the undergraduate course Structural Dynamics

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ABSTRACT

CONTEXT

Civil engineering students consider Structural Dynamics the most challenging third-year course. Similar perceptions were observed among students in mechanical and aerospace engineering. Students find it difficult as it is the only course that teaches how to deal with vibrating structures due to dynamic loads such as earthquakes or extreme wind. All other undergraduate courses deal with stationary structures under static loadings. The students find the course challenging because they have learnt little of this subject matter from previous courses. Hesterman et al. (2011) analysed the difficulties students face when studying the "killer subjects" Engineering Dynamics. This paper describes an approach to help students master Structural Dynamics at the University of Auckland.

PURPOSE OR GOAL

The objective is to overcome students' apprehension of the complex behaviour of structures under dynamic loads in the third-year STRCTENG 300 course in Civil Engineering at the University of Auckland by using analogies and real-life situations that students are already familiar with. The intensive two-way classes and laboratory interaction enable students to learn actively. The collaborative environment encourages students to discuss freely with each other and with the lecturer. Through continuous discussions emphasising the physical meanings, students develop their understanding of the relationship between dynamic loading and structural response.

APPROACH OR METHODOLOGY/METHODS

As clear as it is, the mathematical description of the dynamic behaviour of structures provides only limited success. Using real-life situations and analogies coupled with facilitated collaborative learning environments allows students to grasp the core of the materials more easily. They can immediately link with what they are familiar with. This facilitates the ability to express their thoughts without fear of embarrassment and removes these common barriers in active learning.

Two ACTUAL OUTCOMES

Most of the anonymous feedback from students is promising, see e.g., below:

"*I liked the interactive teaching style. How the lecturer forces us to think about the answer instead of giving it to us. The in-class demonstration strongly supported my understanding of the concept as it enhanced my learning by visualising the rather abstract concept, which left a strong impression on me.*"

CONCLUSIONS/RECOMMENDATIONS/SUMMARY

The interactive teaching, with frequent use of real-life situations, analogies and physical experiments in class, clearly encourages students to discuss and ask questions. By asking additional questions as the lecturer, with time for student response, gives the students a deeper understanding.

KEYWORDS

Collaborative learning, real-life conditions, interactive learning and teaching, structural dynamics

Introduction

In traditional engineering classes, lectures are often one-way explanatory in nature. The primary focus is to convey information to create a theoretical foundation. The concepts are conveyed to students in the lectures by mathematically describing the relationship between the load and the structural response with calculation-based examples. In the tutorial sessions, students are asked to solve problems using the formulae they obtain from the lectures. Students take mainly a passive role. This learning environment may not support students' understanding as class discussion, let alone student-led discussion, was not intentionally encouraged. Over time, students believe that they only need to be able to apply the formulae correctly to understand the materials.

Several studies (e.g., Bonwell, 1991; Coulshed, 1993; Freedman et al., 2014; Meyers & Jones, 1993) have shown that involving students actively in their learning by providing opportunities to discuss and reflect on what they have learnt is crucial for developing their deeper understanding. The active involvement of students in their learning can be conducted in many ways, e.g., through hands-on numerical simulations with computer software (Dau et al., 2021) or hands-on physical experiments (Lee and Haritos, 2022).

This course focuses on the students' understanding of real-life problems. By incorporating real-life situations into the lectures, students accept the teaching materials and do not see them as a burden. Frequent discussions between lecturers/tutors and students and between students are intentionally encouraged. The mathematical formulation of structural behaviour is not the core of learning but a necessary learning tool. The goal is the ability to think and analyse critically, which students can later apply in any life situation. Indeed, they will also have a good understanding of dynamic structural behaviour from the course, and the learning materials are there for the student's development and growth.

To help students with their course preparation, I wrote and presented a Primer. It provides a succinct description of the physical meaning of technical terms related to statics and structural dynamics. It is mainly for supporting international and domestic students unfamiliar with the numerous technical terms since they are learning structural dynamics for the first time.

Use of real-life situations and analogies

The course starts with determining the wind and earthquake design load according to the standard AS/NZS 1170.2 (2023) and NZS1170.5 (2004), respectively. Although the loadings due to wind and earthquakes are dynamic loadings, for simplicity, they are considered quasi-static loadings.

In the 2nd year, students learnt how to calculate the displacement of a structure due to a static load using moment-area and unit-load approaches. They perceive that when they can calculate, they understand the underlying principles. However, they do not develop the ability to sense and justify the correctness of their calculation. To guide students to realise the significance of this ability and, at the same time, introduce them to structural dynamics, I use a metal ruler to describe the static and dynamic behaviour of structures (Figure 1(a)). By incrementally pushing the top end of the vertical ruler while clamping the lower end to the edge of a table, students see the increasing bending with the largest displacement at the top end due to the slowly applied load $P(\mathrm{t})$. When the load is gradually released, the ruler returns to its original position due to the restoring force. No vibration occurs. What students see in the experiment does not reflect the constant static load they used to consider in statics, i.e., how the load increases and reaches the maximum considered load P_{o}.

In courses that consider only static conditions, the load is assumed to have the constant value P_{o} at any instant (Figure 2(a)). In reality, the load cannot have a value of zero and P_{o} at the beginning but needs time t_{rise} to reach P_{o} (Figure 2(b)). Depending on how slow/fast the load reaches P_{o} and how short/long the total load duration t is, will dictate the extent of the dynamic effect. How slow/fast t_{rise} and short/long t are, is relative and can only be answered when we know how slow/fast the considered structure will freely vibrate. The time the structure needs to complete one cycle of free vibration is called the natural period T_{n} of the structure. Dynamics is always relative, not like statics. It is like a banker who decided not to continue his life because he lost more than $100M and had only $3M left. Relative to what he once had, it is a huge loss. For others, $3M is enough for an entire life. In contrast to statics, students need to consider the dynamic properties of the structure and the load simultaneously.

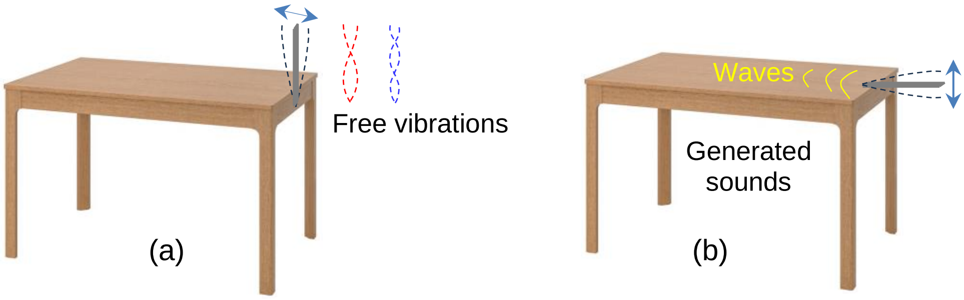

Figure 1. Effect of boundary condition. (a) Static and dynamic behaviour and (b) leak of vibration energy

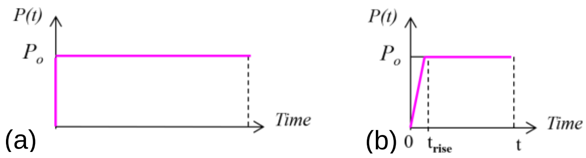

Figure 2. Load assumptions. (a) Static and (b) dynamic loads

If the total load duration is short relative to the natural period T_n of the structure, then accelerations will be activated. These accelerations will trigger inertial forces that act in the opposite direction of the activated accelerations. Together with the restoring forces, they will cause the structure to vibrate.

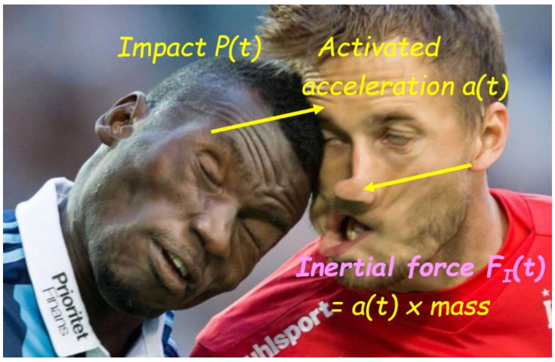

Figure 3. Activation of inertial forces due to an impact load

Figure 3 shows the activated acceleration *a*(t) due to the impact *P*(t) of the left head. Both football/soccer players were trying to “head” the football. The activated inertial forces F_I(t) act in the opposite direction. Both skulls are stiff. Consequently, their tiny inward movement is invisible. The facial muscles are much more flexible. Thus, their movement due to the inertial forces, especially of the head on the right, is clearly visible. The stiffness of the brain relative to the skull is very low; consequently, the sloshing of the brain, although we cannot see it, can cause concussion due to the impact of the brain on the bony skull. It is like an accidental impact of a fighter plane on a nuclear power station, which has a very thick, heavily reinforced wall. The induced extreme vibrations can cause a meltdown of the reactor.

We continue the experiment with the ruler, shown in Figure 1. Instead of pushing, we pull the top end of the ruler and release it. The restoring force due to the sudden release of the top end causes accelerations throughout the ruler, with the maximum acceleration at the top end resulting in the activation of spatially distributed inertial forces. This interplay between restoring and inertial forces causes the ruler to vibrate freely with a shape, as displayed by the black dashed lines. The red and blue dashed lines show only the other two free-vibration shapes. To initiate the second vibration shape, we need another hand to pull the ruler's middle in the opposite direction simultaneously. In reality, there are infinite numbers of vibration shapes because of the mass along structural members. The assumption of fixed support implies that the vibration energy remains in the structure and dies out due to the damping mechanism of the structure. This fixed-support assumption, however, does not reflect the reality. If the ruler is held down at the edge of the table surface (Figure 1(b)), after releasing the top end from an initial displacement, the free vibrations will cause sounds due to the excited cavity beneath the table surface. This sound confirms that some vibration energy leaks to the table in the form of waves that excite the cavity at the bottom of the table. In contrast to traditional teaching approaches that guide students step by step from calculations of the response at one structural location due to a simple dynamic load and continue with more complex loads, this course introduces students from the beginning to the entire aspect of structural vibrations, including the consequence of the boundary condition. Since students know the complexity of real-life cases, they perceive the mathematical formulations as necessary tools to describe structural behaviour with those many simplifying assumptions. The degree of complexity in the mathematical formulations remains; only by knowing the real-life situations can the students' perceptions change.

To further show students the complexity of real-life situations not discussed in traditional teaching, I asked one student sitting in the front row to help me by holding the top and bottom of a piece of A4 paper. I asked the student to close his eyes and explained that I would stick a pen through the paper after counting to three. The paper and impacting pen simulate a wall and projectile, respectively. To be uninfluenced by his anticipation, I stuck the pen through the paper after just counting to two. We repeated the test; however, this time, the student should only hold the paper at the top end. The pen just slid down the paper. The contact force at the paper-pen interface, i.e., the dynamic load, changed due to the different responses of the paper under different boundary conditions. I asked this student his name and then requested other students in the class to thank him for participating in the experiment. Students should appreciate what others have done for them. I told students that the name itself is irrelevant. However, we need a name to be able to communicate sincerely. Without a name, that person will become blurred with time. Students are also encouraged to know their neighbour's name. I need to know their name because I respect them. At the end of the semester, I knew the names of all the students in the class. It is the starting point in creating an enduring collaborative learning environment, already at the beginning of the semester.

In another case, I sketched a reinforced concrete wall. Someone kicked a football against the wall, and the ball bounced back. This time, the same person kicked the ball with equal force into a soccer/football goal. The ball hit the net and slid down to the ground.

Another real-life situation is a violently vibrating pedestrian bridge responding to the wind load, which shows that the wind load acting on the bridge changed with time, location, and direction, as seen by the wildly moving bridge. The video clearly convinced students that a quasi-static load, defined by any standard, does not reflect reality.

All three cases show that the dynamic load cannot be predefined because it depends on the structure's response.

Load (time, locations, directions) ←→ structural responses

In structural engineering, engineers assume that the structure is fixed at its base, although structures are almost always supported by the ground, which allows some movement. In the case of floating structures, they are supported by the water. When earthquakes occur while responding to travelling seismic waves, the structural vibration causes interaction between structural footing and soil. This interaction causes waves in the soil. These waves propagate and transmit part of the vibration energy of the structure (see the discussion of Figure 1(b)). Consequently, the structure experiences an energy loss that cannot be considered if a fixed support is assumed. In addition, the spreading waves in soil alter the successive seismic waves. The seismic load thus changes. An assumption of a quasi-static load according to NZS1170.5 or free surface ground motion recorded from past earthquakes clearly does not reflect the dynamic load the object structure actually experiences. In the case of wind or earthquakes, even without the involvement of the

structural response, how the wind will blow or how the ground will move is unpredictable. It is like the natural movement of a cat. Predicting how a cat will move next time it wakes up is impossible. It is known that if the load is inadequately specified, the design will only be as good as the load assumption, regardless of the engineer's expertise or use of sophisticated approaches.
Discussing real-life situations in an open, interactive way did not scare the students, even though they realised that the subject "structural dynamics" was much more difficult than they imagined. In contrast, students become more eager to know how to tackle complex real-life situations. Even though they know that what they were learning could not incorporate all the factors of influence that occur in real life. The structures considered in this undergraduate course are assumed to be fixed at their base, and the dynamic loads are predefined.

P(t) → structures with an assumed fixed base → structural response (t)

In this course, we emphasise the physical meaning of the structural behaviour under dynamic loadings. The mathematical formulations are tools to help us to describe the behaviour. In traditional course delivery, the dynamic load activates the restoring, inertial and damping forces. At any instant, all forces must be in equilibrium. The equation of equilibrium describes the relationship between the dynamic load and the structural response and is called the equation of motion. Depending on the load characteristics, the equation is mathematically solved with corresponding assumptions. Instead of following the traditional delivery, in this course, students conduct discussions to understand the core of each approach for solving the equation of motion.

In the following load cases:

1) Harmonic load: It is assumed that the load last forever. This enables a solution to be derived. Since, in real life, the load has a finite duration, depending on the load duration relative to the capability of the structure to vibrate freely, characterised by T_n, the load will have the effect of an impact load, even if it has a harmonic development.
2) Periodic load: The load is represented by a series of harmonic loads. Each of these loads is assumed to last forever.
3) Short duration/impact load: The dynamic load is represented by a series of short-duration impulses, and the structural response to each impulse is described by free vibration due to an initial velocity at the time of the impulse. The structural response is then the summation of all activated free vibrations.
4) Arbitrary dynamic load: The structural response is determined at small time increments. Each response is calculated based on the immediate predecessor response. Since the future response is unknown, the response development within a time increment is assumed.
5) When the response at multiple locations describes the structural response, it is assumed that the response is a combination of all excited-free vibrations of the structure.

In discussions, students learn to

1) take a distance. If we hold a text physically very close, we cannot identify the words; too far is also not helpful. A proper distance is required to "see" clearly, i.e., the proper physical distance. There are many other distances. If the time is wrong, the person we would like to be involved will not listen because, for example, the person has other thoughts in his/her mind. Apart from this time distance, there are cultural, emotional and a combination of all these distances.
2) listen actively. To avoid misunderstanding, we may need to reconfirm what we heard. We should question ourselves if what we understand is what the initiator wants to convey. If necessary, we should question the speaker before making up our minds.
3) consider other perspectives. We usually detect the difference between objects. If we find their similarities, the same objects will provide a totally different answer.
4) selecting the most precise words to express our thoughts. Students can be asked to remember that the words they use will affect not only people who listen to what they say or read what they write, but the words they use will affect them instantly. A careful selection of words enables a clear mind, so choosing precise words will affect their learning in all facets.

In the design, a structure is assumed to be standalone and fixed at its base regardless of its proximity to its neighbours and the soil conditions. The reality is that while responding to the incoming seismic waves, adjacent structures influence each other via their common ground due to their joint interaction with the surrounding soil. These waves not only affect structural responses but also alter the arriving seismic waves. Consequently, the ground excitation is no longer the arriving seismic waves but becomes an altered ground motion. This is another illustration that the dynamic load depends on the response of the structures. Although students learn the basic structural dynamics, they learn in the context of the latest research insights. If, in strong earthquakes, the soil liquefies, even if the buildings are intact, they can become unusable. The video of the 2018 Palu Earthquake shows that large-scale liquefaction turned the ground into a massive flow of soil that swallowed many houses in several regions of the city. Students are taught to be aware that to have resilient structures, the behaviour of the surroundings is also relevant. A standalone structure with an assumed fixed base is currently common practice. However, students are suggested to consider that, of the many assumptions made in design, none are an absolute reality. Even though what they learnt in this course has many limitations, their understanding of the basic knowledge is relevant, especially if they decide to continue in Advanced Structural Dynamics.

In class and laboratory experiments

In-class experiments are performed spontaneously whenever needed to clarify some aspects of the course contents. The models used consist of commonly available materials so that students can easily reproduce the experiments at home.

One relevant aspect is the relationship between the dynamic properties of structures and load. Figure 4 shows a model of a multi-storey building under earthquake excitation. The building is simplified by a tennis ball and a string. The excited mass during the fundamental vibrations should be the model mass, and the string's stiffness represents the bending stiffness of the building. For simplicity, the earthquake is represented by a harmonic motion with the period (the time of one vibration cycle) of the dominant ground motions. When attempting to support the underside of the ball by the string vertically, the string is too flexible in the direction of its length, i.e., it cannot hold the weight of the ball. Consequently, to do the experiment, the ball is held upside down, i.e., from above. The natural frequency of the ball-string structure can be estimated by counting the number of cyclic vibrations within a second after the ball was released from a height. The hand movement simulates the excitation.

Several cases can be observed:

1) If the hand moves with a very low frequency, the ball moves with the hand.
2) If the hand moves with a very high frequency, the ball remains almost at the same spot.
3) Theoretically, if the frequency of the hand movement and that of the structure is the same, a resonant-like response will occur. This is difficult to simulate because the string may not be strong enough to hold the ball.
4) If the excitation frequency is between a very low frequency and the structural frequency, the ball response is larger than the hand movement.
5) If the excitation frequency is between the natural frequency of the structure and a very high frequency, the ball moves in the opposite direction of the hand movement.

Students discussed among themselves and concluded the reasons for their observations. The experiments give the impression that the structural response is determined by the excitation frequency relative to the natural frequency of the structure. In real life, other factors are involved.

Let us take the case of marching soldiers with the same step across a pedestrian bridge: If the step frequency is equal to the natural frequency of the bridge, will the bridge be caused to resonate? Will the bridge with the same natural frequency but with a shorter span have the same response? Will the bridge with the same natural frequency and the same span length have the same response as above if, instead of soldiers, only small kids march with the same frequency? The analogy shows students that structural response is not only determined by the coincidence of the natural frequency of the structure and the frequency of the dynamic load. The response is also determined by the magnitude and the duration of the load.

Figure 4(b) shows the response spectrum due to a recorded ground motion. The spectrum covers a range of the natural frequencies of considered structures with a damping ratio of 5%. Students should determine the maximum value of the ground motion without doing any calculations or additional information and using only the insight obtained from the experiment described above. It has taken a while before students provided the correct answer that it must be 3 m/s^2 (as shown by the blue dashed line) because structures with very high natural frequencies must move like the ground, no matter whether the ground moves harmonically or randomly. I informed students that I would not provide the answer because I should not take away their opportunity to find the answer. They should "experience" their learning, and learning can only be represented by finding the answer.

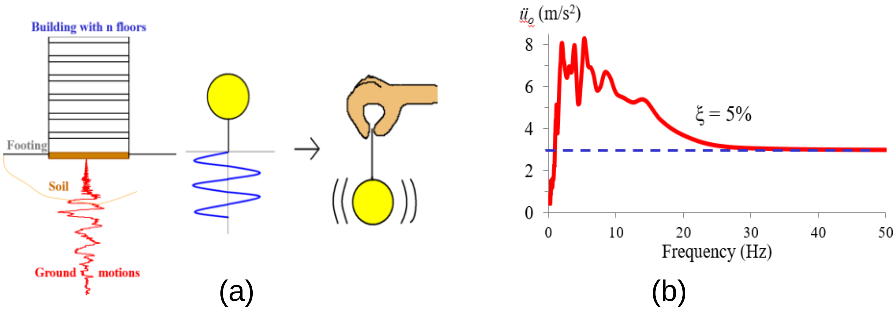

Figure 4. Simulation of structural response due to ground motions. (a) Structural model and simulation using a tennis ball with a string and (b) determination of the maximum ground motion using a given response spectrum

In this course, two laboratory activities were conducted. Students worked in groups of five. They have to design, construct their structural model, install it on a shake table, conduct the experiment, and analyse and interpret the experimental results. The ground motions considered are pulse motion, harmonic motions of different frequencies, ground motions with gradually changing frequencies and recorded earthquake motions. Students need to compare and explain the discrepancy between the theoretical and experimental results. This task was the most challenging part of the laboratory activities because the real-life experimental results differed from what they calculated. They could not ask other group members for help because all groups did not experience the same situation.
Since each group investigated a structure with a different natural frequency, each group must work with other groups to reveal the consequences of the relationship between the frequency content of the ground motion and the natural frequency of their structure.

Student feedback

Some students perceived the course as challenging. The lively and frequent discussions in class and tutorials involving many real-life examples were well received. Although they have seen the need to embrace real-life conditions, a few students still have difficulty abandoning the desire to collect formulae and solution templates as they are so used to doing.

Close to the end of the semester, a voluntary and anonymous student survey was conducted online via CANVAS. The proportion of survey participants in the total 48 students is 37.5%. Figure 5 shows the overall score for the course compared to the average overall score within the Department, Faculty and University. Five is the highest score. Overall, 94.4% of students participating in the 2024 survey agreed or strongly agreed with the quality of the course. Incorporating real-life situations and analogies in the 2024 teaching further improves the course performance. The course performs better than the department, faculty and university average scores, as indicated by the horizontal dashed line.

The following most common feedback shows that some students considered the course content not easy. The intensive interaction in the class seems to be helpful.

> *"Course content is quite difficult, but that's a me problem."*
>
> *"The content of this course was quite challenging."*
>
> *"The interactive style of teaching was very good as it helped me to stay engaged and think about the content that we were learning."*
>
> *"Class discussions and life lessons from the lecturer"*
>
> *"I loved the life lessons and in-person demonstrations; keeps up active and thinking."*
>
> *"The way Nawawi focused on explaining the theoretical concepts was very impactful as it was done in an easy-to-understand way."*
>
> *"The labs were very helpful for seeing the concepts put into practice."*
>
> *"Being in class, listening to discussion and attending tutorials really helped me understand the overall material."*
>
> *"In-class demonstrations"*

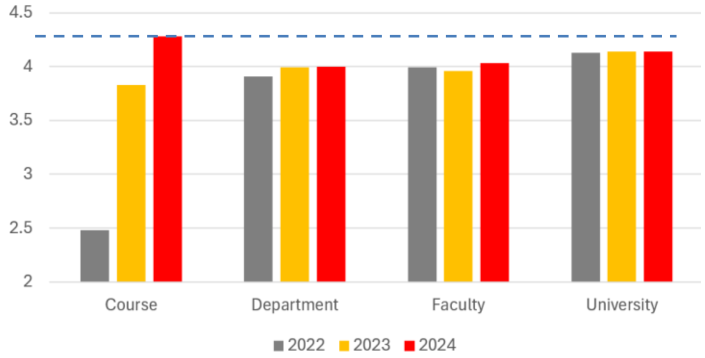

Figure 5. Student satisfaction with the quality of the course

Summary

At first glance, the involvement in the class of real-life situations seems to have nothing to do with the course content. The reality is that it influences the entire learning process. The more unusual the real-life situations and analogies, the better. Students are more likely to remember the context of the discussions. Involvement in class helps remove the fear or concern of the course. It makes students aware that they have to embrace reality. It enables students to learn course materials with the awareness of real structural and load characteristics. In addition, students are aware of the limitations of what they learn. When interpreting the results, they must always incorporate the assumptions made. The realistic depiction arouses the students' desire to learn more, as shown by their questions, for example, about an advanced course in the fourth year or how to incorporate soil behaviour in their structural design.

The generated collaborative learning environment is helpful. Over the weeks, students changed their passive attitude and became more and more active. The frequent discussions, spontaneous in-class experiments and the joint attempt to answer questions from the teaching materials help students experience their learning. They develop their critical thinking by questioning what they observe, what they are about to say in the discussions and what they think. Students should be aware of the words they use in discussions because selecting precise words will help their awareness of learning.

Initially, students were passive and busy copying what I wrote on the screen, even after the announcement that everything would be uploaded to the course website after each contact hour. Students are encouraged to listen and make notes of what they think is relevant because only if we understand can it be written down using our own words. In the last 2.5 weeks of the semester, the discussions in class became very lively without my intervention. Some students even came to the whiteboard during recess to clarify their different opinions.

Students should understand and experience what they learnt in a wider context of real-life situations, not collect information and solution templates. In dynamics, there are many possible solutions. The question is how to find elegant solutions. This is only possible if we understand the relationship between dynamic load and structural behaviour well. Their experience in the semester can be used in their later life-long learning.

Although students know that in real life, there are many possible ways to solve a dynamic problem depending on how we describe the structural behaviour under the considered load, some students could not abandon their desire to collect solution templates. How they used to do in the past impedes them from relying on their ability to find their own solutions and thus hinders them from having self-confidence. Like the word "self-confidence" says, only we can give ourselves the confidence. Others cannot do this giving.

To further encourage students to rely on their own abilities, I intend to invite guest lecturers from the industry to address the class with projects containing an interesting application of the course content. It is the most challenging task for a lecturer to encourage students to develop and rely on their own skills. It is challenging because just knowing their abilities give them the freedom to solve problems is not enough; they need the willingness. Being willing is also not enough; they need to do it. To do it is also not enough; they need to do it properly.

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