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Citation for published version (APA):

Document status and date:
Published: 15/08/2020

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Material Tests And Execution Methods Of Linear Composite Pykrete Structural Elements

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Abstract

Pykrete, a material composed of water and one or more additives (Pronk, 2019 a), is applied mostly in shell-like structures. The performances of linear elements made of this material are being researched for structural applications. Mechanical properties of linear structural pykrete composite elements are examined through experimental testing and the data is evaluated to determine the effect of the geometries of the samples in terms of strength reductions. Generally, tests on linear samples give lower strength values than earlier tests on smaller, non-slender samples. The geometry thus impacts the effective strength properties of the structural elements, with scale and slenderness being detrimental to the failure stresses. Between tests, the reduction varies from less than half to almost the same as the reference value. The apparent reduction in strength can be used as a design principle for structural applications. Since the research explores new types of samples and samples of a larger scale than in previous tests, unexpected factors affect the results. These can be taken into account in future research. Regarding the test procedures, a multitude of improvements is presented for obtaining more reliable and accurate test results. Numerical simulations are made for comparison and the implications of simplified modeling are explained. The linear composite structural elements are applied in a tower that is constructed during a competition, the execution of which poses additional topics for further research.

Introduction

Pykrete is an ice-based building material. It consists of a mixture of water with several additives, for example wood chips, dissolved sheets of cellulose, sand, gums and combinations of any of those (Pronk, 2019 a). In the current research, a mixture with dissolved cellulose sheets and gums will be used. Domes and shells are conventional ways of applying this material structurally, the feasibility of which is proven by previous projects such as an ice dome (Pronk, 2015). An alternative application is constructing linear elements, using ropes and hoses that remain part of the final structure. Such linear structural parts are the topic of this paper. The research into linear structural pykrete composite elements follows from a preliminary design for the Harbin Institute of Technology construction competition of December 2019. The design in question is shown in Figure 1.

Figure 1: The design of the pykrete tower structure

Since earlier research is done on a very small scale and only with different composite sections (Pronk, 2019 b), more knowledge is acquired on structural performances of pykrete on a realistic scale with more representative composite sections. Material tests are done on samples of both types of application that occur in this structure. The general research topic is then expressed by the following question: ‘how does pykrete perform in a structure with linear members?’.

Effective mechanical properties are determined by means of experimental research. The data obtained is compared against data from earlier, smaller tests on purely pykrete to determine how the geometry and composite makeup of the samples affects the representative values. This is described by the more specific question: ‘how do the mechanical performances of pykrete applied in linear composite members differ from small scale tests on the base material?’ Numerical simulations are used for comparisons. Since this research explores relatively new ways of using pykrete, uncertainties and unexpected flaws in the test methods are present. This is addressed in recommendations for future research.

Additionally, the execution methods of the tower are evaluated. During construction, challenges and solutions are found regarding the feasibility of the construction procedure. Differences between samples and real
structural members become apparent and deviations from the initial design are unavoidable. This is reflected upon and recommendations for future designs, experimental tests and construction procedures are presented.

**Experimental testing**

The goal is to test realistic and representative elements that occur in the structure under representative conditions. These are internal forces, (tension, compression and bending) but also subzero temperatures of -18 degrees Celsius. Important is to consider all possible sections that will occur in the structure, this will be elaborated on later.

**Types of Elements**

Two general types of samples were tested, based upon the provisional structural design. The first is a large section, dimensioned according to the vertical elements which are composed of mainly fire hoses. The hose is a tube with a diameter of 64 mm. These will be filled with pykrete. Around the fire hose, an additional layer of pykrete is applied (44 mm thick). The total diameter of the section is then 154 mm, see Figure 2. The compressive resistance of elements of this type of section is not expected to be affected by the effects of slenderness due to the relatively large diameter of the section. Rather, volume and uneven properties will be of impact. Secondly, the rope elements, which are thinner and more simple, have a rope with a diameter of 12 mm and a layer of 15 mm of pykrete. Combined, the diameter of the rope section will be 42 mm, as displayed in Figure 3. Elements with this section are most likely to buckle under compression.

![Figure 2: Section of the hoses with inner and outer pykrete](image)

**Types of Tests**

Three different kinds of tests are performed: tension, compression and bending. Bending tests are conducted as 4-point bending tests, which creates a zone of pure bending in between the two points of force introduction. Due to the irregularities of cellulose fibers in Pykrete, a 3-point bending test might not be representative due to the maximum bending moment occurring on a single point within the span of the sample. In a 4-point bending test, the irregularities will be taken into account, and results will therefore be more representative when testing for maximum bending stresses. See Figure 4 for a sample in the setup.

![Figure 3: The section of the ropes with pykrete around them](image)

![Figure 4: A sample in the test setup (lid removed)](image)

Important for the compression tests on rope elements is to make sure that the element has sufficient slenderness. Most ideally, the ends should be hinged to get the highest Euler buckling length. The ends of the samples must be cut perpendicular to the longitudinal axis, as precisely as possible, to prevent sliding of the sample once it is placed in the test setup and for even force introduction. An overview of the proposed tests is shown below:

**Bending (4-point):**

1. Fire hose filled and covered with Pykrete (BH)
2. Rope covered with Pykrete (BR)

**Compression:**

1. Fire hose filled and covered with Pykrete (CH)
2. Rope covered with Pykrete (CR)
Tension:
1. Rope covered with Pykrete (TR)
2. Pure Pykrete, with frayed rope in both ends to introduce forces into the Pykrete (TP)
3. Dog bone of the hose material (TD)

Sample construction
To be able to produce a repeatable experiment, a standardized method needs to be developed. Therefore, a mold is made, which is roughly the size and shape the parts of the designed tower also have. The goal was to have round elements, thus a round formwork is used made of PVC tubes. The smooth surface makes sure the Pykrete would not stick to the PVC, and by providing the tubes with longitudinal hinges, it could be reopened and nearly identical elements could be produced. To make the elements with rope covered with Pykrete, the rope is firstly attached in the middle at one end of the PVC tube and slightly tensioned. Thereafter, the Pykrete is poured in the tube, and finally, the other end is closed and the rope is tensioned and knotted. The tensioning makes sure the rope will roughly be centered in the element, the location it is designed, and makes reproducing it equally possible. Samples with discontinuous rope are made similarly, with frayed rope placed in the PVC tube from two ends. See Figure 5. To create the firehose elements, firstly a firehose is filled with Pykrete. This then has to freeze solid. Thereafter, this frozen element is centered in the PVC tube, after which the PVC tube is filled with Pykrete. See Figure 6 for one end of a BH sample within its formwork after the end cap was removed.

Test results
From the tests, a force-displacement graph follows for every single sample. Comparisons with earlier tests are based on the strength values for the most similar pykrete mixture, which concerns those of 25 g/l and 100 g/l cellulose content. The actual mixtures are 20 g/l and 80 g/l respectively. If applicable, corrected dimensions are used for calculations. Both general uncertainties and test-specific issues occurred, as is further elaborated on in the discussion. Corresponding conclusions and recommendations regarding the test methodology are formulated in the appropriate chapters.

Bending – Fire hose filled and covered with pykrete
The test speed is 0,014 mm/s for both bending tests. The results are characterized by a single point where the sample initially failed. Graphs of each sample (BH1 through BH3) are displayed in Figure 7.

Early behavior is largely explained by the initial settling near the supports. The data then shows a consistent stiffness of the samples in its linear trajectory. A small sudden drop that occurs most likely indicates a local failure or sudden settlement. The stiffness of the sample then decreases until the force plateaus. The onset of stiffness reduction corresponds to the first global failure and thus defines the representative strength. Since the material is not consistent in its constitution, this value will be decided by the weakest point. This is representative of structural applications. The post-failure behavior in each sample shows that residual strength exists after a member of this type has failed, which is advantageous for structural application. A sample post-failure is displayed in Figure 8.
The obtained data is used to calculate both the average material stiffnesses from the linear path, as well as the average stresses at failure. For the calculation of the representative ultimate flexural stress, the formula for the first elastic moment of area of a circle is used. See Equation I.

\[ \sigma = \frac{(FL/6)}{(\pi d^3/32)} \]  

*(Equation I)*

The average ultimate flexural stress is 1.83 MPa, with a standard deviation of 0.18 MPa (10%). The failure stress from earlier experiments is 3.9 MPa (Pronk, 2019a). A reduction by an average factor of 0.47 is thus found. The average stiffness within linear behavior is 273 MPa, with a standard deviation of 100 MPa (37%).

**Bending – Rope covered with pykrete**

The behavior of the samples varies significantly. See Figure 9 for the graphs of each of the samples. In these graphs, moving averages are displayed for readability.

![Figure 9: Force-displacement diagrams of samples BR1-6](image)

The stiffness decrease is gradual in most samples, resulting from the successive occurrence of a multitude of cracks. The notable drop in force in samples BR2 and BR5 may be a result of a single crack developing a large crack width. Sample BR1, BR2 and BR3 show unpredictable behavior as a result of flaws in the test setup.

Again, from the representative samples, the average ultimate flexural stress and stiffness are calculated. Sample BR3 is omitted. Said stresses are 4.46 MPa, with a standard deviation of 1.56 (34%), and the young’s modulus is 2579 MPa, with a standard deviation of 551 MPa or 21%. The ultimate flexural stress is 0.97 times the known value of 4.6 MPa (Pronk, 2019a), thus showing no significant reduction due to the geometry. This differs from the notable effect in the previous test, possibly because of the lower cellulose content and the larger total volume in that test.

**Compression – Fire hose with inner and outer pykrete**

The general speed of the compressive tests is 0.009 mm/s initially and later at an increased speed. The graphs of these tests are displayed in Figure 10.

![Figure 10: Force-displacement diagrams of samples CH1-3](image)

A linear trajectory is followed by a decrease in stiffness and then a plateau in force. Sample CH1 has several fluctuations early on, possibly caused by sudden settling of the supports. Failure seems to be a result of compressive failure. The samples have vertical cracks over their surface, which gradually opened up during further deformation. The plateaus can be explained because of the stocky geometry of the specimen, allowing redistribution of stresses. The samples then all reached a point where they started to deform laterally.

The average ultimate compressive stress achieved, calculated from the sectional area and the force, is 2.87 MPa with a standard deviation of 0.27 MPa (9%). This is 0.65 times the theoretical value of 4.4 MPa (Pronk, 2019a). The significantly weaker value is possibly the result of the low cellulose content in the large volume, geometric imperfections or large residual stresses that occurred due to expansion during freezing. Additionally, the average young’s modulus is calculated from the linear elastic parts of the test results, which is 281.5 MPa with a standard deviation of 17.2 MPa (6%).

Compressive failure seems to be the cause of the plat- eauing. Still, when for each sample theoretical values for the critical buckling force are determined, the expected buckling load lies between 125 kN and 502 kN. With the average failure load at 57.7 kN, the samples thus failed at 0.12 to 0.47 times the expected buckling load, making buckling as an initial failure mechanism unlikely.

**Compression – Rope covered with pykrete**

The graphs corresponding to the tests are shown in Figure 11.
The samples typically show a consistent, rapid increase in force near the beginning of the curves. For some samples, most notably CR3, settling of the support causes a disruption in this section of the curve. After reaching a maximum value, an immediate or postponed decline in force can be seen, as is expected for buckling of ductile materials. The slow load rate, limited ductility of pykrete and presence of the rope allowed the samples to buckle gradually. A sample is displayed in Figure 12.

Though the failure mechanism is clearly buckling, the highest stress that occurs can be determined. It is equal to 3.93 MPa with a standard deviation of 0.48 MPa or 12%. Compared to 5.3 MPa (Pronk, 2019 a), this is 0.74 times the theoretical ultimate value. The young’s modulus for each individual sample is also calculated again, of which the average value is 740 MPa with a standard deviation of 236 MPa or 32%.

Again, the Euler buckling load is used for calculations. Buckling lengths 0.71 L and 1.0 L are assumed to be realistic as the samples mostly failed with one end rotated and one end without rotation, sometimes having rotations on both ends. Values for E are determined for each individual sample per the same procedure as used earlier. Sample 2 is a notable outlier and has been omitted from further calculations. Average theoretical buckling loads are then 6.17 kN and 12.59 kN. The real value is 6.10 kN with a standard deviation of 0.732 kN (12%). This is 0.49 and 1.00 times the theoretical loads respectively, which indicates that a significant reduction in buckling resistance has occurred. Structural calculations may therefore have to take a similar reduction into account for the buckling resistance of similar elements.

A relatively constant stiffness exists for the samples. The somewhat sudden changes in angle can be a result of the uneven geometries of the samples and the rough fixation of the composite section where the rope enters the pykrete. The sudden drop after the highest load indicates the point of brittle failure mode when loaded in pure tension. Failure occurred at a tensile stress of 1.45 MPa, with a standard deviation of 0.14 MPa (10%). This is significantly lower than the ultimate flexural stress (4.46 MPa). Local weaknesses, for example from uneven material distribution, are likely to be more critical in tensile tests. This is representative of how such weaknesses would impact real structures.

A test rate of 0.167 mm/s applies. The force-displacement curves are displayed in Figure 14. Here, gradual changes in direction can be noted starting around a force of 2300 N. This is the load where the first failure within the samples often occurs, and additional points of failure occur soon after.

A sample is shown in Figure 15. A discernible crack distance is visible, which means that a certain length is required to transfer enough stresses to the pykrete for it to crack. After failure of the pykrete, the rope will still
take the load. When unloaded, small cracks can close again due to the elastic behavior of the rope and the remaining connection between the rope and the pykrete. The sample is expected to retain a significant portion of its post-failure structural capacity. This, however, has not been tested and can be a topic for future research.

Figure 15: Cracks in a sample with continuous rope

Ultimate tensile stresses obtained have an average of 1.50 MPa with a standard deviation of 0.21 MPa (14%). This is higher than in sections without continuous rope, but not significantly so. The post-failure behavior, however, implies a significant level of structural safety.

**Tension – Dog bone of the hose material**

The dog bone samples have resulted in the force-displacement graphs shown in Figure 16. Test speed is 0.33 mm/s for all but the first sample, which has a varying and consistently much lower test speed.

Figure 16: Force-displacement diagrams of dog bone tests

A prolonged, uneven decrease in force can be seen. This follows from a sequence of local failures, which occur at only the threads with the highest force within them, continuing until the sample has failed completely. The critical distributed force is found by dividing the force by the width of the sample. The samples’ width is 55 mm at the slimmest part. The ultimate tensile strength of the dog bones is then 65.2 N/mm with a standard deviation of 9.1 N/mm (14%). A stiffness of 494 N/mm is found with a standard deviation of 59.5 N/mm (12%).

Altogether, the representative values obtained in each test can be taken into consideration when designing a structure with these types of elements. The specific values found do have to be examined further through additional testing to adjust them according to more reliable sample sizes and testing methodologies. This is elaborated on in the recommendations.

**Numerical simulations**

Numerical experiments are carried out to evaluate and compare with the test results from experimental research. Modeling the complex composite cross sections is done in ABAQUS. Numerical modeling of compressive and tensile material tests is done. Finding stress distributions, rather than absolute values, is the main purpose of the modeling.

The composite specimen are modeled to match both of the specific cross sections. The procedure is as follows. One part resembles the pykrete and one part resembles the hose around it or the rope within. These parts are then assembled in order to form the complete specimen. Next, materials present in the specimen are defined with their density, Young’s modulus and the Poisson’s ratio. The interaction used between the parts is a tie connection as to prevent displacements between them. The load is defined as a pressure load to resemble a distributed load over the cross section, with a value corresponding to the experiments. A single load is defined for each model. Lastly, the boundary conditions are set to restrain movement in three directions at the point of connection but allow rotations.

**Compression – Fire hose with inner and outer pykrete**

The model assembly consists of pykrete inside, hose, and pykrete outside. The length is 450 mm, the total diameter is 160 mm, the inner pykrete is 64 mm in diameter and the hose has a thickness of 2 mm. The pykrete has a density of 980 kg/m³, Poisson’s ratio 0.15 and Young’s modulus 550 N/mm². The hose has Young’s modulus 150 N/mm² and Poisson’s ratio 0.3. See Figure 17 for the simulation results.

Figure 17: Stress distributions (side, top, bottom)
The stress distribution displayed is that of the axial stress present in the specimen when subjected to the compressive load. The hose acts as a clear boundary where peak stresses occur. This most likely occurs due to the Poisson effect because the pykrete inside the hose wants to expand, but cannot freely do so due to the hose. This is also expected to have occurred in the samples.

**Compression – Rope covered with pykrete**

The model assembly consists of two parts: rope and pykrete. In this model, the pykrete part is the part that covers the rope. The rope has a Young’s modulus of 118 N/mm² and a Poisson’s ratio of 0.3. The inner diameter is 12 mm and the total is 42 mm. See Figure 18.

The stress gradually increases towards the bottom where it is “pressed” onto its support. Stress gradually increases towards the edges. This most likely follows from the specific boundary conditions set. In reality, if the sample is frozen stuck to the points of load introduction, a similarly uneven stress distribution near the supports may also occur when the sample deforms.

**Tension – Rope covered with pykrete**

The only difference between this tensile test compared and the compression test is the loading of the specimen, which is inverted. See Figure 19a and b for the results.

Notable is the difference in elongation of the rope compared to the pykrete, which can be explained by the difference in Young’s modulus among the two materials. The absence of crack behavior explains the discrepancy between this and the real behavior. Otherwise, the stresses are similar to the previous model, with compressive and tensile stresses swapped.

**Tension – Purely pykrete**

The model is the same as the solid pykrete part of the previous model, loaded with a lower pressure. See Figure 20 for the simulation results.

Stresses increase gradually towards the edges of the section and towards the bottom of the specimen. This is because of the boundary conditions, which are located at the bottom. This behavior is the same as the pykrete part of the previous simulation.

Altogether, both resemblances with reality and inaccuracies are discernible in the results. Simplifications in the modeling and imposed conditions induce deviations from real behavior. This mostly concerns the uneven material properties, rough surfaces of the composite parts, crack behavior and very local boundary conditions, as is further emphasized in the discussion.

**Construction procedure**

Assuming the conditions are right (subzero temperatures), the first step of the construction is preparing a circular formwork for the base plate that serves as the foundation of the tower. Inside this plate, twenty ground connections are placed. See Figure 21.
These connections are ropes tied in a loop to be connected later with fire hoses and covered with pykrete. At a different location, ten hoses are filled up and cut to length with some extra length at the bottom of the hoses to compensate for irregularities. This can be cut later if it’s no longer needed. Ropes are measured and cut to length with an extra meter on both sides that will be used for tying up the rope between two hoses. Every alternating hose, one goes outwards, while the other goes inwards with respect to the center of the tower. This means that the pattern of ropes between two hoses mirrors every time. Once everything is tied up, the top is tied together and hoisted with a crane. The bottom sides of the hoses are tied to the loops that are placed in the foundation, with thicker pykrete used to fix the ground connections. Meanwhile, the ropes are corrected if necessary to obtain the symmetrical shape of the tower and the required straightness of the ropes. See Figure 22.

Once the desired shape is reached, pykrete can be sprayed on the structure until the desired member thickness is reached. See Figure 23. Not all pykrete will attach to the structure, accumulating at the foundation, so applying it at the top will distribute the pykrete relatively evenly. Once sufficient pykrete is sprayed on the surface, the top part (still hoisted by the crane) will be sawn off. The tower now stands on its own.

A practical problem during construction is connecting ropes with hoses. The exact length is known but is difficult to put in practice. Once the tower is hoisted in place, lots of nodes need to be re-tied because ropes are tied too long or too short. Sufficient spare length of the ropes often is an issue, compromising the quality of the knots. A possible factor was snowfall that hindered the process, but also lack of a consistent method of marking and tying of the ropes correctly. More strict checks and feedback during this phase, as well as limiting the frequency of work shift changes, could reduce mistakes. It is important to keep spraying the structure consistently to prevent the spraying hose and nozzle do not freeze and clog up. Also, the nozzle pressure and angle must be adjusted in such a way that pykrete is sprayed gently on the structure without damaging it. Cellulose can clog up at the nozzle if the opening is too tight.

In practice, the sections of the actual members in the tower are different compared to the model. The most dominant difference is how gravity puts more pykrete on one side of the rope rather than spread around it evenly. It might be valuable to investigate in controlled conditions how this affects structural behavior. The formation of icicles also was not accounted for, could potentially be hazardous if it breaks and falls down and adds weight with no additional structural value.

**Conclusion**

The test results show that the mechanical performance of pykrete in linear structural composite members is limited to a degree. From comparisons with values from earlier material research, the ultimate stresses that such elements can take appear to be smaller due to the effects of the larger volume, slenderness and the presence of geometric and local material defects. This is much more evident in the larger samples with a lower cellulose content. Explanations are uneven material distribution and larger residual stresses from freezing, both of which result from an increase in volume. Effective average ultimate stresses are determined but a large spread and many uncertain factors exist in the results. Buckling, too, occurs at a lower load than the theoretical value. Reduction factors can be determined but many untested variables have a role in the magnitude of the reduction of both this and stress capacities. Additionally, post-failure behavior is determined as favorable in most cases as any type of composite section has residual load-bearing capacity after the initial point of failure.

When pykrete is applied in structural design with linear composite elements, it is recommended that reductions
be applied to the design values of the material’s strength properties. Reduced effective strength and buckling properties must be used for reliable optimized structural designs. Test methods need to be refined to obtain reliable design values, as is elaborated on in the discussion.

Numerical simulations are in an early stage and many simplifications bring inaccuracies with them. Several aspects do correspond to reality and give insight into certain occurrences in composite sections, most notably the higher stresses in the enclosed inner pykrete in the hose based structural parts.

In practice, it is difficult to build the tower exactly like the one according to the model. This is mostly due to circumstances like altering weather conditions, design decisions, preparation issues and human errors.

Discussion
Experimental results are likely affected by several aspects in both sample preparation as well as the test setup and handling of the samples. The samples themselves have inconsistencies and uncertainties in the settling of additives during freezing, initial stresses, initial cracks, storage conditions in terms of temperature and time frames, slight thawing of the surface and refreezing, eccentricities in the rope and hose material, unregulated prestress in that material and geometric defects such as bulging out of the formwork. Besides that, some samples have prolonged exposure to room temperature before testing. Additionally, the test setup has flaws in its supports, which introduce peak stresses in bending tests, lack proper hinge and roller mechanisms and do not always have guaranteed stiffness or the right degrees of freedom. Besides that, the methods by which samples are produced are not the same as in the real structure: asymmetric sections, layered spraying rather than pouring, different types of rope and uneven sections with icicles present in the actual structure. This may impact the real performances of the structural parts.

Numerical modeling at this stage brings many inaccuracies with it. Inhomogeneous material properties are not taken into account, as are geometric flaws that occur in reality. Additionally, failure behavior such as cracking and plastic deformations are important aspects of structural behavior that are not defined in the models.

Finally, the execution methods of a full structure bring uncertainties with them. Since prestresses are unknown, sections are inaccurate, not all geometries are achievable and the precision of the geometry is rather low, the structure has notable differences from the design.

Recommendations
Testing methods should be refined and larger amounts of samples are needed for more reliable results. Only then, reliable values and safety factors can be determined for calculations with these types of members. The types of samples can also be reconsidered: current samples are fully symmetrical but real sections will have their rope and hose mostly at the bottom portion of the section. Many variables are not yet tested in isolation. The following can be considered the most notable variables that need dedicated testing: different slenderness ratios, test speeds, ratios of cellulose content, the structural effect of the gums, prestress in rope and hose parts, temperature with regards to failure and post-failure behavior, geometric ratios between hose or rope and pykrete layers and different types of rope. The production of the samples can more specifically approach real structures by using layered production rather than pouring. The test setup needs improvements in the degrees of freedom, continuous temperature control, precision in force introduction and consistent test speeds.

For numerical modeling, developing more advanced geometrical properties, inclusion of local material distribution, initial stresses and defined failure mechanisms can help achieve more accurate simulations.

Improvements in the construction procedure are possible. More strictly defined procedures and precise preparations can give improvements. Additionally, the design should also be based on limitations imposed by the construction methods.

Keywords: Pykrete, structural ice, experimental research, numerical modeling, slenderness, composite structures

References