# ICE RESPONSE TO CYCLIC LOADING FOR LOW STRESSES AND FREQUENCIES - APPLICATION TO ICY SATELLITES.

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**Introduction:** Tidal heating is considered to be an important energy source controlling the interior dynamics, thermal evolution, and orbital characteristics of icy satellites like Europa, Enceladus or Titan. However the attenuation properties of ices at stresses and frequencies relevant to these icy bodies are still missing. In an effort to determine these characteristics, we have set up an experimental laboratory where ice samples are synthetized, deformed and analyzed. Here we report on the first cycling loading experiments that have been performed on single crystals in order to compare our results to previous results [e. g. 1]. We have started performing a series of tests for temperatures between 150 K and 270 K on single ice crystals and are planning similar tests on polycrystalline water ice samples. We present the experimental setup, sample preparation, preliminary results, and future projects.

**Experiments:** *Setup:* Measurements were obtained at ambient pressure with an *Instron* compression system equipped with an environmental chamber that can achieve temperatures from 80 K to ambient temperature with a thermal control of 0.2 ºC. The temperature is also controlled just outside the top and bottom of the chamber. We are working on improving the thermal insulation of the whole system in order to limit the impact of diurnal variations within the laboratory. This is especially important when we perform cyclic loading measurements at frequencies lower than $5\times10^{-4}$ Hz over several days.

*Samples:* We present results obtained for single-crystal water ice. These crystals were grown and characterized in the Mars Simulation and Ice Laboratory at Caltech. Using a single crystal seed, the water was frozen from the bottom to the top of a cylindrical mold in a cold room at -15 ºC at a rate slower than $10^{-6}$ m/s with air constantly flowing at a slow rate in the remaining water. This method guarantees freezing excluding bubbles and cracks that leads to the production of perfect single ice crystals. Thermal stressing of the samples was avoided during transportation to the measurement system using common water ice at a temperature of -15 ºC.

*Measurements:* Samples were inserted into the environmental chamber at a temperature of -15 ºC. After thermal equilibrium was achieved, a load was applied to the sample corresponding to a mean stress of 1 MPa. The system was automated and controlled with *LabVIEW*. The measurements proceed as follows: the sample creep under constant load was measured for several hours, followed by a cyclic loading sequence that ranged over ten frequencies from 0.1 Hz down to $10^{-4}$ Hz for stress amplitudes between 0.1 and 0.25 MPa. This range is comparable to the amplitude of tidal stress acting on outer planet satellites. It is important to note the capability of the system to perform accurate position measurements (accuracy better than 2 microns), at strain rates as low as $1\times10^{-8}$ $s^{-1}$, and relatively low stress.

For each temperature we perform an independent measurement of the *Instron* system compliance needed for correcting the measurements obtained on icy samples.

**Data Processing**: An example of a 69 hr. cyclic loading test is presented in Fig. 1 for a single ice crystal sample tested at -30 ºC, for a mean stress of 1 MPa and stress amplitude of 0.25 MPa. Using the compliance test we can correct the total response from the response of the system. The sharp strain evolution happening during the first three hours is mostly driven by the response of the Instron system to the cooling of the environmental chamber.

At this stage we are still working on characterizing the creep behavior of the sample, whose amplitude is affected by the diurnal variations in temperature. We expect this problem to have a negligible effect on the phase lag, since the maximum thermal variations undergone by the system for the test in Fig. 1 was 5 ºC over 24 hrs (while the longest cycles applied during the test are 3 hrs long). The attenuation of the sample can be inferred from measuring the phase lag between stress and strain, similarly to [1]. The phase lag $\delta$ is directly related to the attenuation coefficient (or dissipation factor) $Q$ by $Q^{-1} = \tan \delta$. The phase lag is inferred from signal processing methods (Fourier transform), and by direct visualization of the waves (Figure 3). For the measurements at a frequency of $10^{-4}$ Hz presented in Figs. 2, we can clearly see the time lag between stress and strain, which is about 420 s in the example displayed in Figure 3, after correction from the attenuation of the system at that frequency inferred from the compliance test. From these initial measurements we estimate a dissipation factor $Q \sim 3\text{-}4$ for a cyclic loading frequency of $10^{-4}$ Hz.

Analysis of the sample properties for frequencies from 0.1 to $10^{-4}$ Hz shows a decrease of the attenuation factor from about 60 to about 3. After performing cyclic loading a first time over the range 0.1 to $10^{-4}$ Hz, we performed another cyclic loading test on the same sample. The results show a difference in the phase lag measured at $10^{-4}$ Hz, by about 10%, which illustrates the effect of ice history on its attenuation behavior.

**Future Activities:** We have just started acquiring research-grade data with this new system. Cyclic loading measurements on single ice crystals and polycrystalline ice for various temperatures and stress amplitudes are planned in the near future.

Samples will be characterized using optical polarizing microscopy and cryo-ESEM techniques.

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**References:** [1] Tatibouet Tatibouet, J., Perez, J. and Vassoille, R., 1981, J. Physique. Coll. 42 (C5) 541. [2] McCarthy C. *et al.* (2007) AGU *Fall meet.*, #MR11A-07.

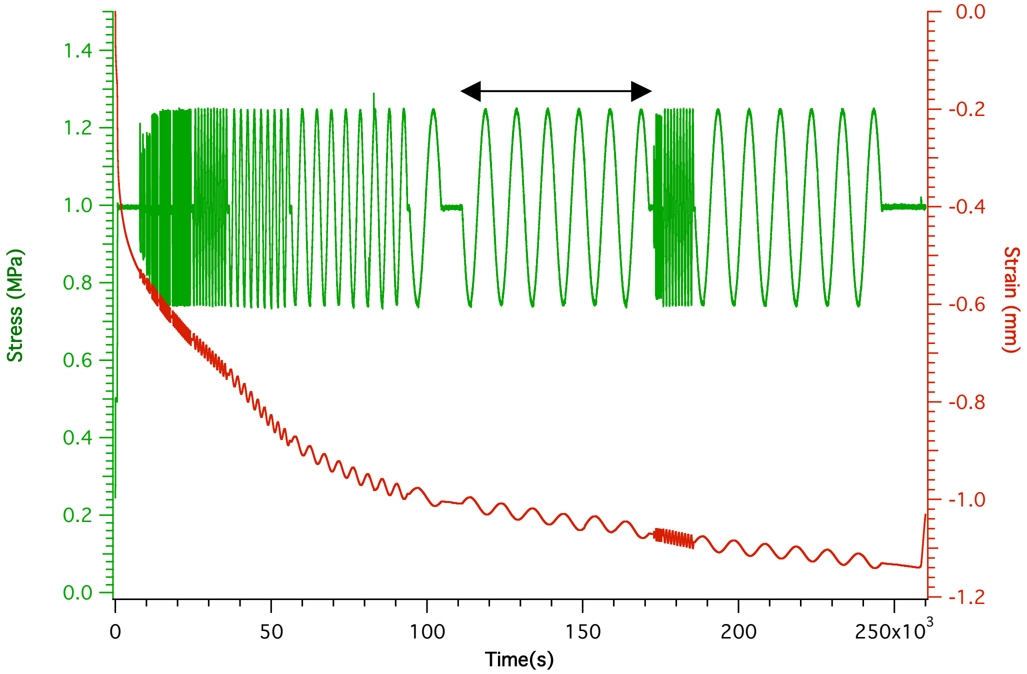

Figure 1. *Stress and strain measured over the full duration of the test on a single ice crystal at -30 $^oC$.*

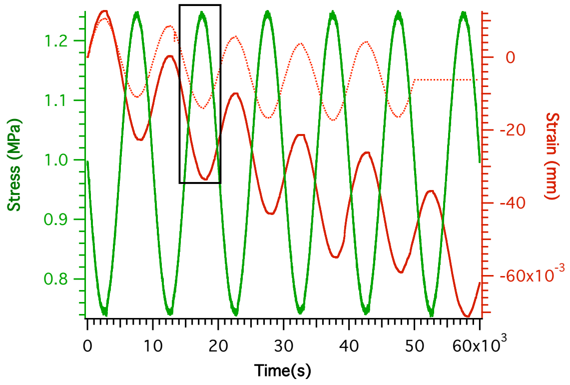

Figure 2. D*etail of the measurements obtained at a frequency of $10^{-4}$ Hz, shown in Fig. 1 by the horizontal arrows. The plain red line correspond to the measurements obtained on the sample and the dashed red line to the compliance test.*

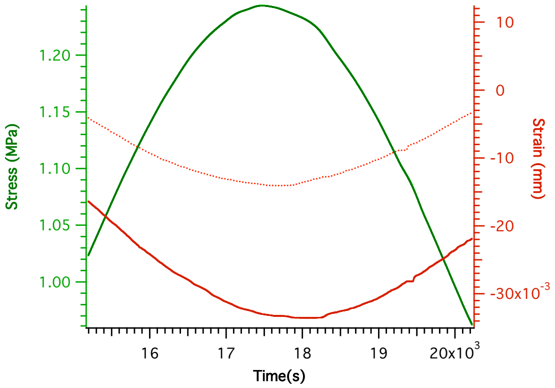

Figure 3. *Zoom of the strain of the sample and of the system obtained during the compliance test for the data highlighted in the box in Figure 2.*