Note: for this web pdf version, text has been added to some slides for clarity, graphs have been modified, and blank slides used during the conference have been omitted. SM.

Canadian Conservation Institute

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Correction to the proofed fluctuation concept by stress relaxation and fatigue

Allowable microclimatic variations for polychrome wood
18-19 February 2010
Norwegian Institute for Cultural Heritage Research – NIKU, Oslo,
International Focussed Meeting of COST Action IE0601

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Canadian Conservation Institute

Canadian Heritage Patrimoine canadien

Canada

The proofed fluctuation

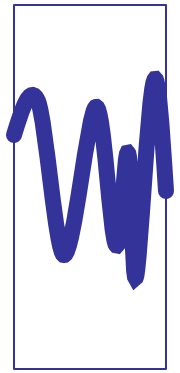
establishes a region of safety

Stress relaxation

increases the region?

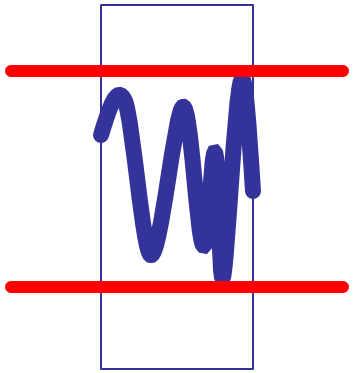
Fatigue

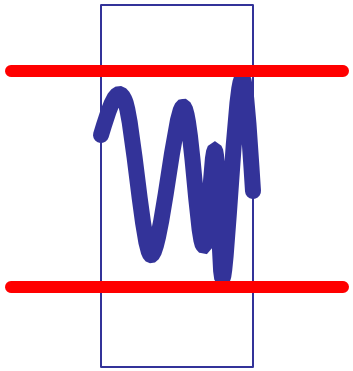
decreases the region ?



The “proofed fluctuation” is...

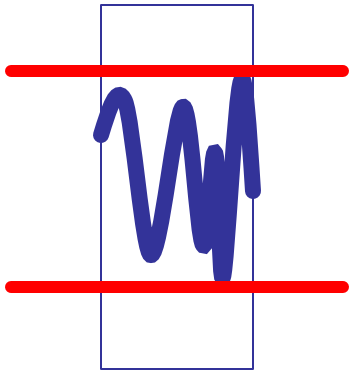
The largest fluctuation experienced by the object in the past.





The proofed fluctuation concept

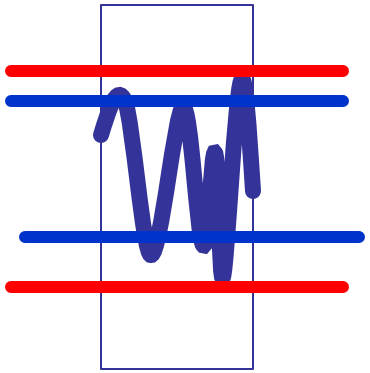
The proofed fluctuation will have caused all the mechanical damage possible by that size of fluctuation, therefore:



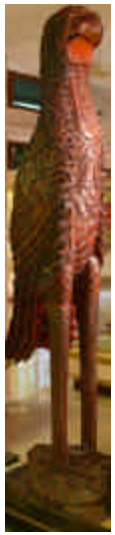
The proofed fluctuation concept

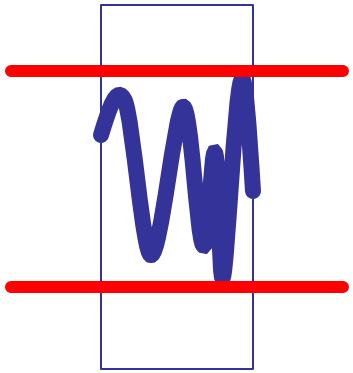
Future fluctuations equal to, or smaller than, the proofed fluctuation will not cause further mechanical damage.

(Assuming the objects have not significantly aged chemically, or been damaged, or consolidated.)



Michalski, S. 1993. Relative Humidity: A Discussion Of Correct/incorrect Values. *Tenth Triennial Meeting, ICOM-CC*, ICOM-CC. pp 624-629.

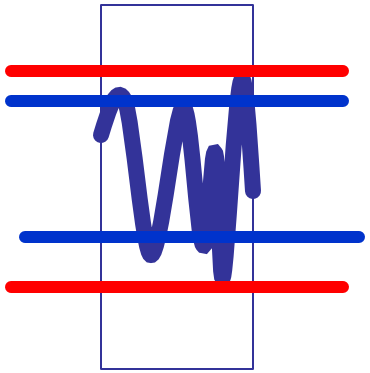




Why is it important?

It cuts through the fog of complexity

It uses historical data, not scientific analysis

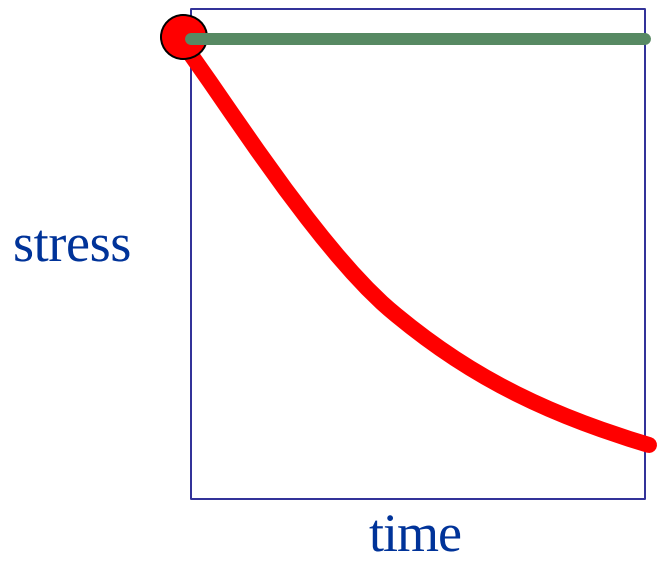


Stress relaxation

If a stress is applied to a polymer (by RH change or applied force) and this RH or force is maintained...

then the stress in the material might drop, i.e., “relax” ----

(or it might not) ----

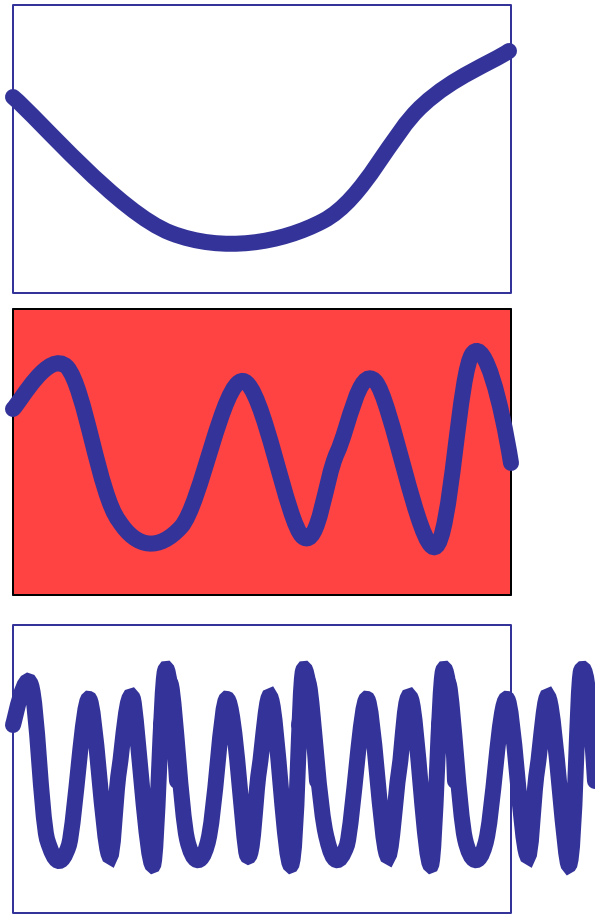


Stress relaxation implies that

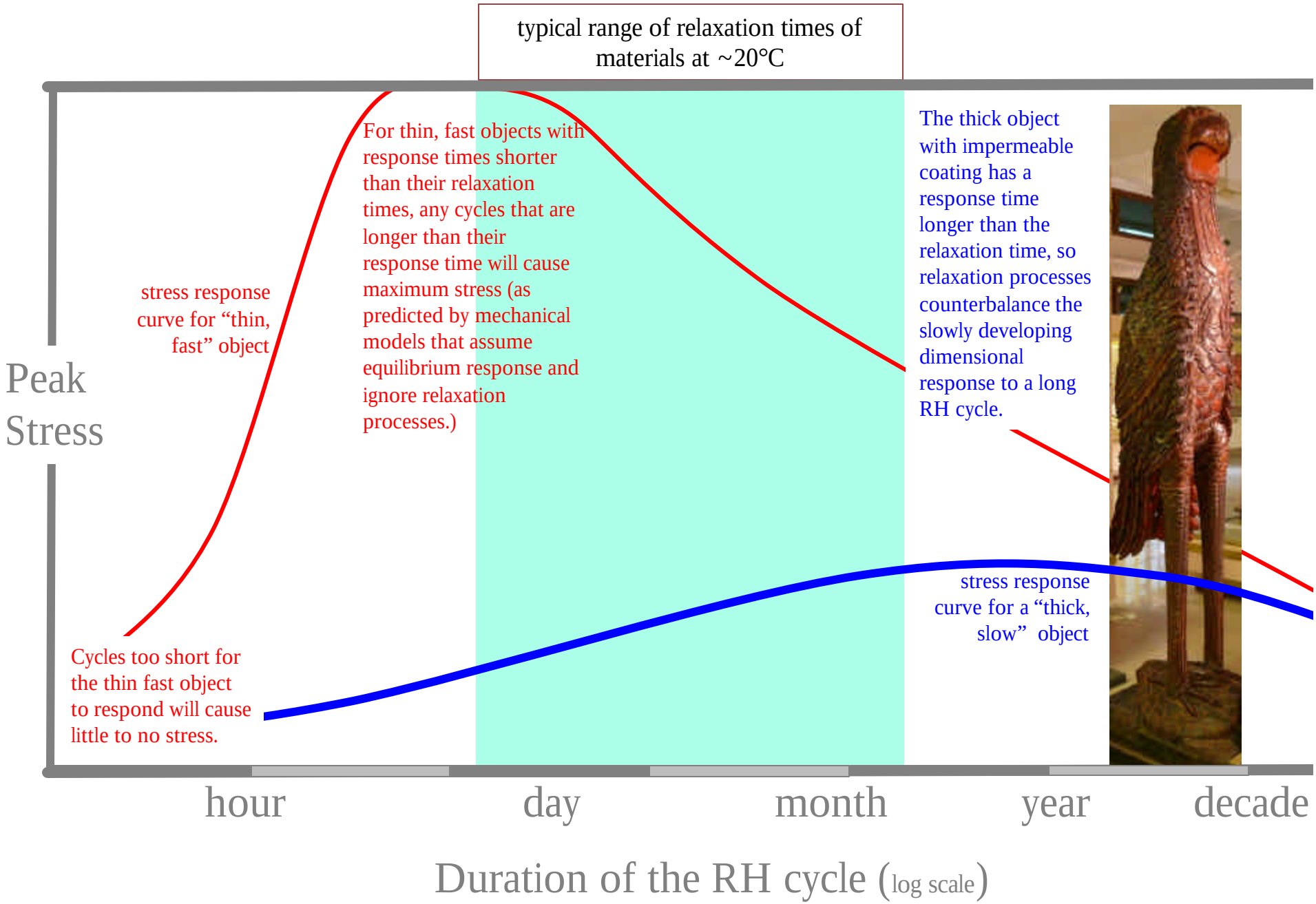
long cycles of RH will cause less stress

short cycles will cause more stress

but very short cycles will be too short for the object to respond



What are “long” and “short” times ??


typical range of relaxation times of materials at ~20°C
For thin, fast objects with response times shorter than their relaxation times, any cycles that are longer than their response time will cause maximum stress (as predicted by mechanical models that assume equilibrium response and ignore relaxation processes.)
The thick object with impermeable coating has a response time longer than the relaxation time, so relaxation processes counterbalance the slowly developing dimensional response to a long RH cycle.
stress response curve for "thin, fast" object
Peak Stress
stress response curve for a "thick, slow" object
Cycles too short for the thin fast object to respond will cause little to no stress.
hour
day
month
year
decade
Duration of the RH cycle (log scale)

A note on the previous slide...

Most polychrome objects are “medium” size, that is, their behaviour falls between the two extremes of the previous slide.

Implications for proofed fluctuation

A historic fluctuation, e.g., 3 days of very low RH, establishes a proofed fluctuation only for fluctuations that are the same or shorter than the historic one, e.g., 3 days.

The “best” proofed fluctuation is one that is known to have been sustained long enough for all objects to respond.

One can refine the proofed fluctuation principle to this: The historic pattern of RH fluctuations provides a proofed pattern of fluctuations.

Fatigue

Small cycles of stress can each “accumulate” a microscopic amount of damage that leads eventually to a visible crack

Fatigue implies that...

1000000000000000 ??? or so small cycles...

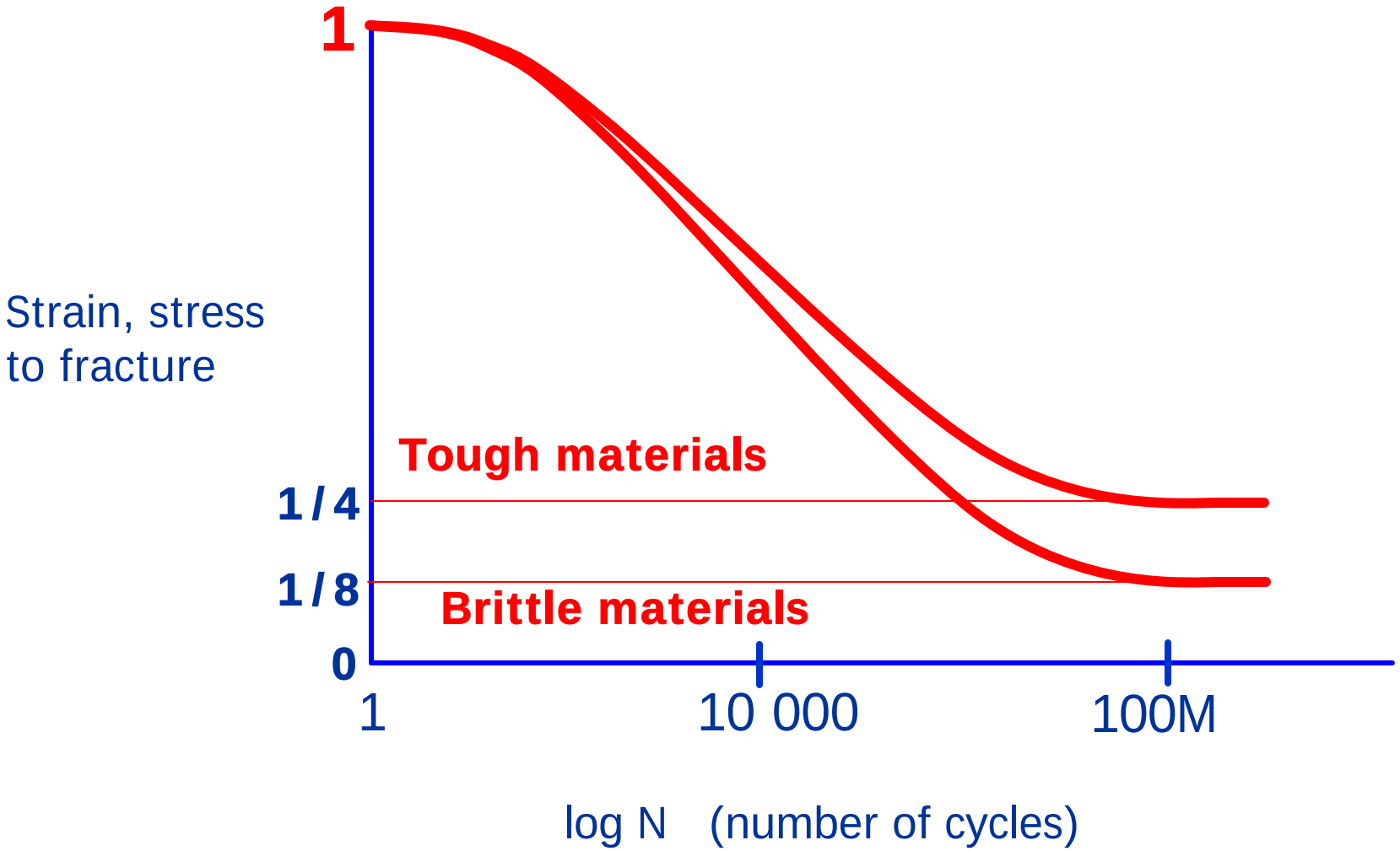
can cause a crack that would otherwise need one large cycle.

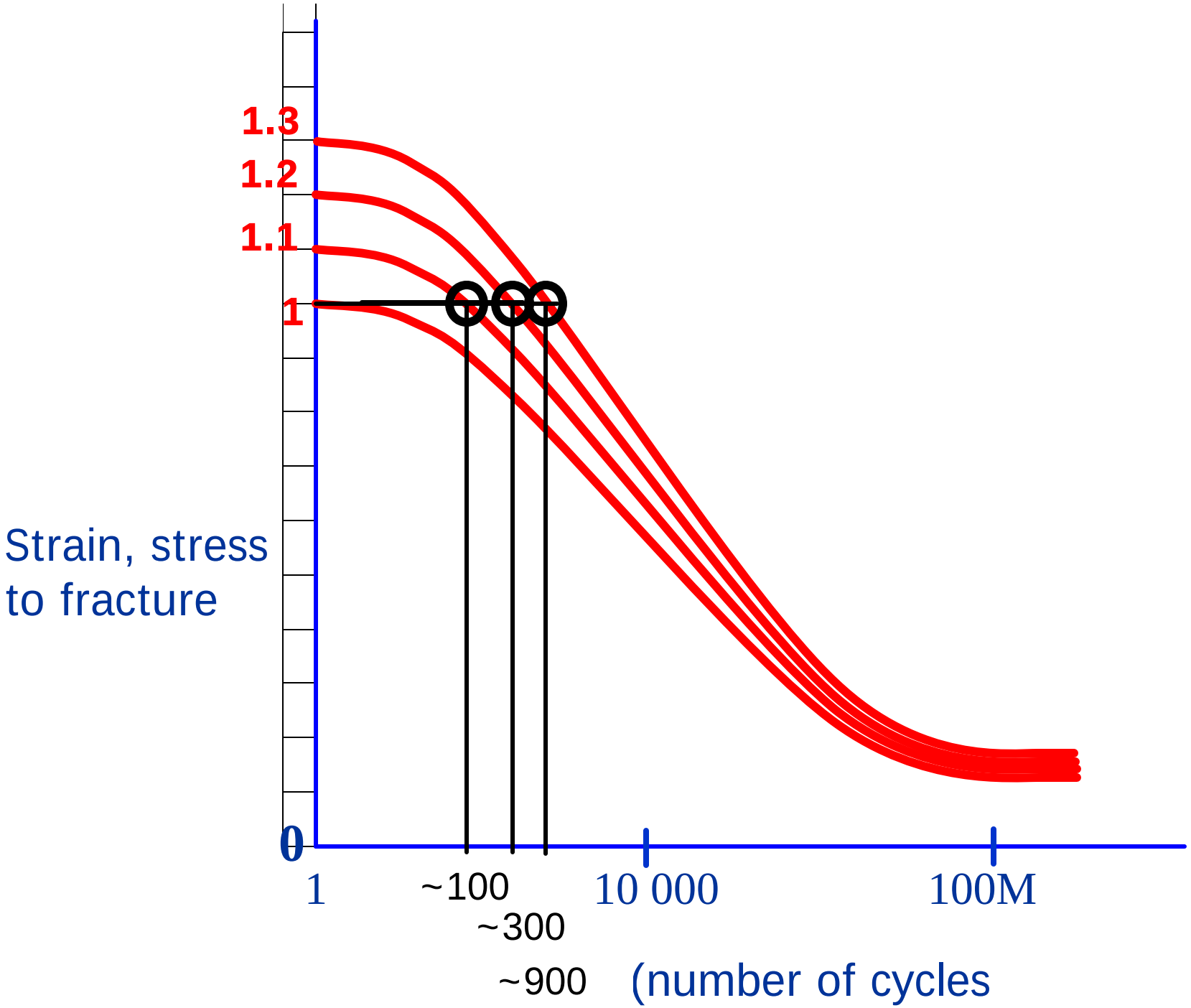
Now, more detailed explanations...

Fatigue

Stress relaxation

Fatigue


1
Strain, stress
to fracture
Tough materials
1 / 4
1 / 8
Brittle materials
0
1
10 000
100M
log N (number of cycles)


1.3
1.2
1.1
1
0
Strain, stress
to fracture
1
~100
~300
~900
10 000
100M
(number of cycles

If the single proofed fluctuation is ±PF
e.g. PF= a drop of 30%RH from a stress free RH then…

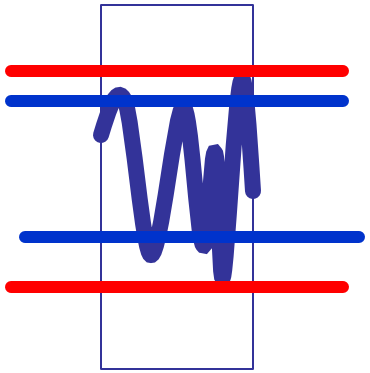
~100 more cycles at PF can cause a crack that would require a fluctuation of 1.1PF
e.g. a drop of 33%RH from the stress free RH

conversely,
a single cycle PF establishes that a group of 100 cycles must be ~0.9 PF in order to develop new damage
e.g. a drop of 27%RH from the stress free RH

each additional increase of 0.2 adds approximately one order of magnitude (x10) in necessary cycles

A simple rule for fatigue and stress relaxation corrections???

The pattern of historic fluctuations establishes a proofed fluctuation pattern (PFP)



Whatever one can establish as the worst annual PFP recorded, then keeping within 0.9 PFP would mean that ~100 more such years could be tolerated.

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and now a model...in formation

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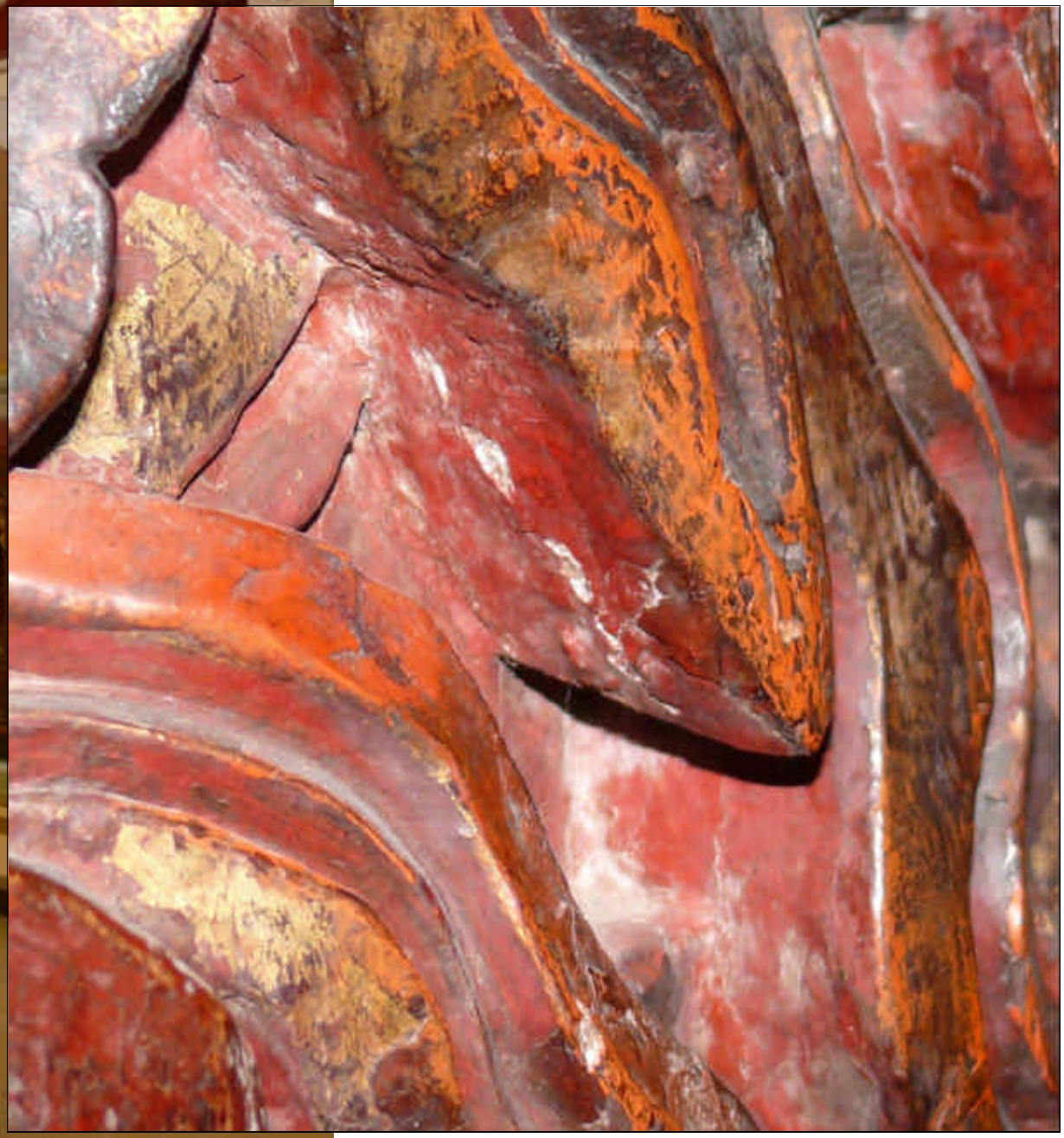
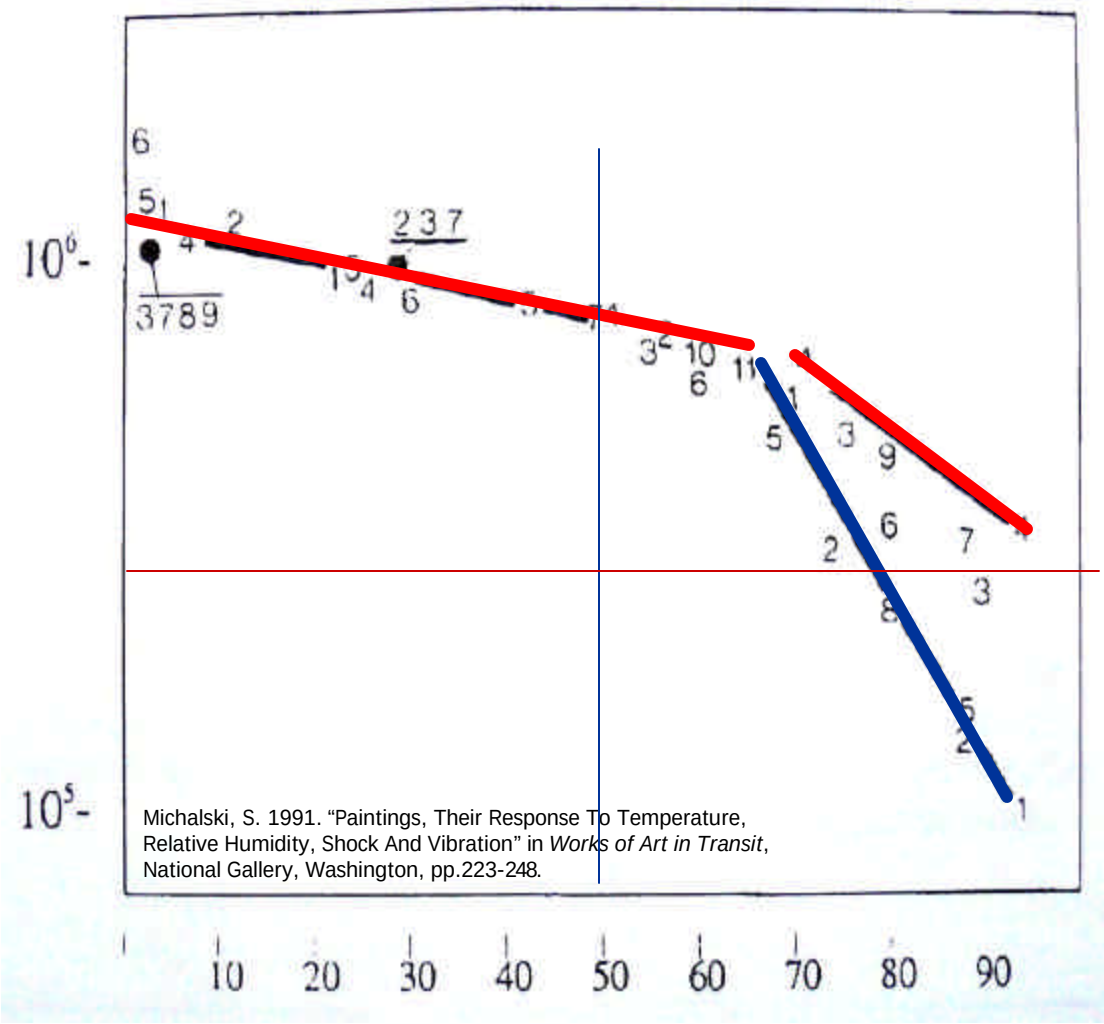


Elasticity changes with RH

log E



Michalski, S. 1991. "Paintings, Their Response To Temperature, Relative Humidity, Shock And Vibration" in *Works of Art in Transit*, National Gallery, Washington, pp.223-248.

Label No.	Description	Scale Source (Figure No. 1)
1	Artists' Prussian blue, safflower	(x 1100)
2	Artists' azo red, safflower	(x 580)
3	Artists' burnt umber, safflower	(x 370)
4	Artists' titanium white, linseed	(x 340)
5	Artists' lead white, linseed	(x 210)
6	Zinc white, linseed, 14% PVC	(x 180)
7	Artists' burnt umber, linseed	(x 58)
8	Lithopone, linseed, 20% PVC	(x 22)
9	Lead white, linseed, 21% PVC	(x 16)
10	Clear linseed	(x 1)
11	Clear stand oil	(x 1)
11E	Clear stand oil, minus leachables	(x 10)
A	Same paint as #3; TMA data	
B	Same as #6; creep data	
C	Leaded zinc, linseed; creep data	
D	Artists' burnt sienna; DMTA data	
E	Same as D, but acetone leached	
F	Same as #10; creep data	

1-5, 7: Mecklenburg 1982.

6, 8-10: Nelson and Rundle 1923a.

11, 11E: Talen; 1962.

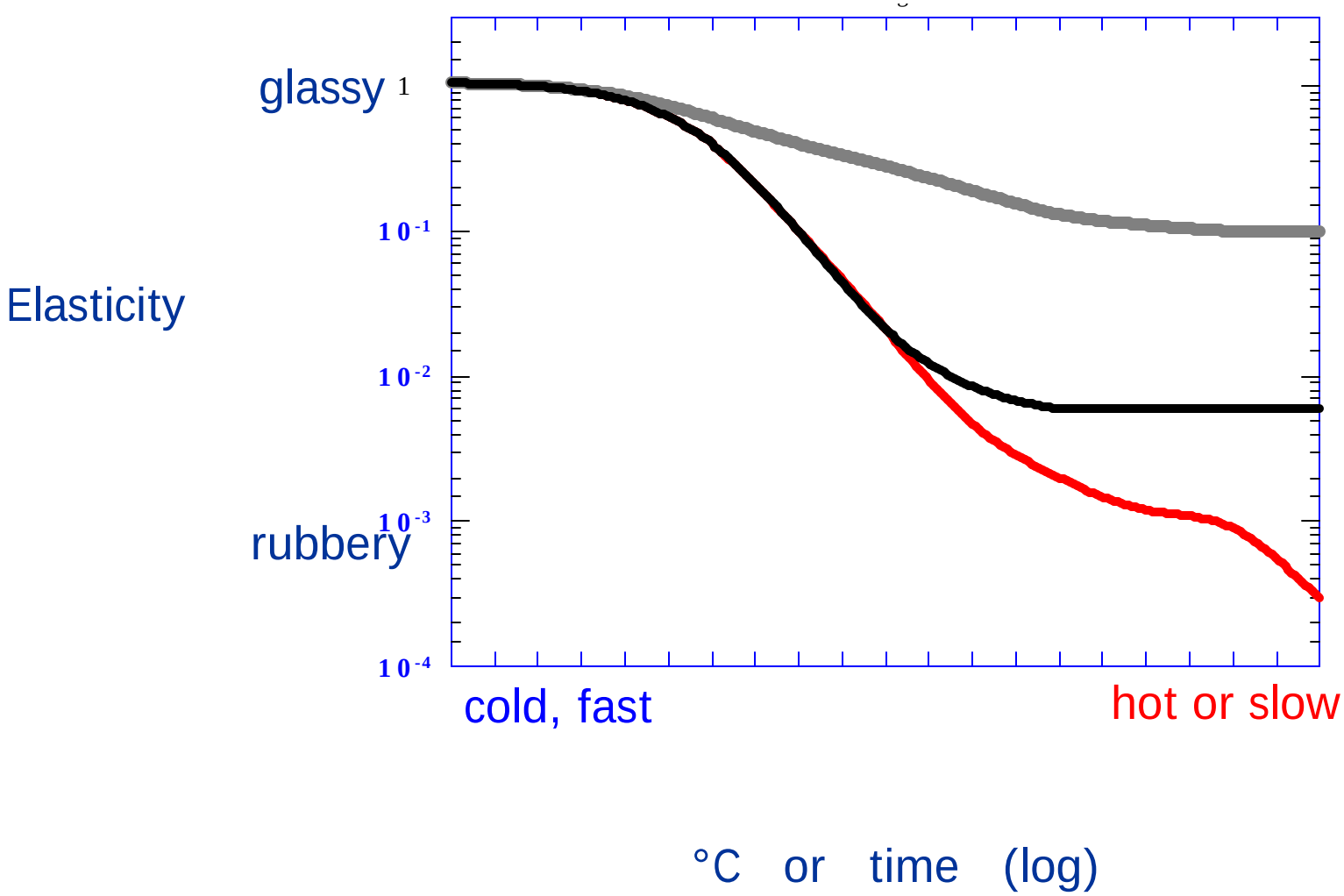
A: Michalski 1989, unpublished.

C: Gutfreund 1965.

D: Hedley et al. 1990.

% RH

Time and temperature are “equivalent”



Acrylic paints

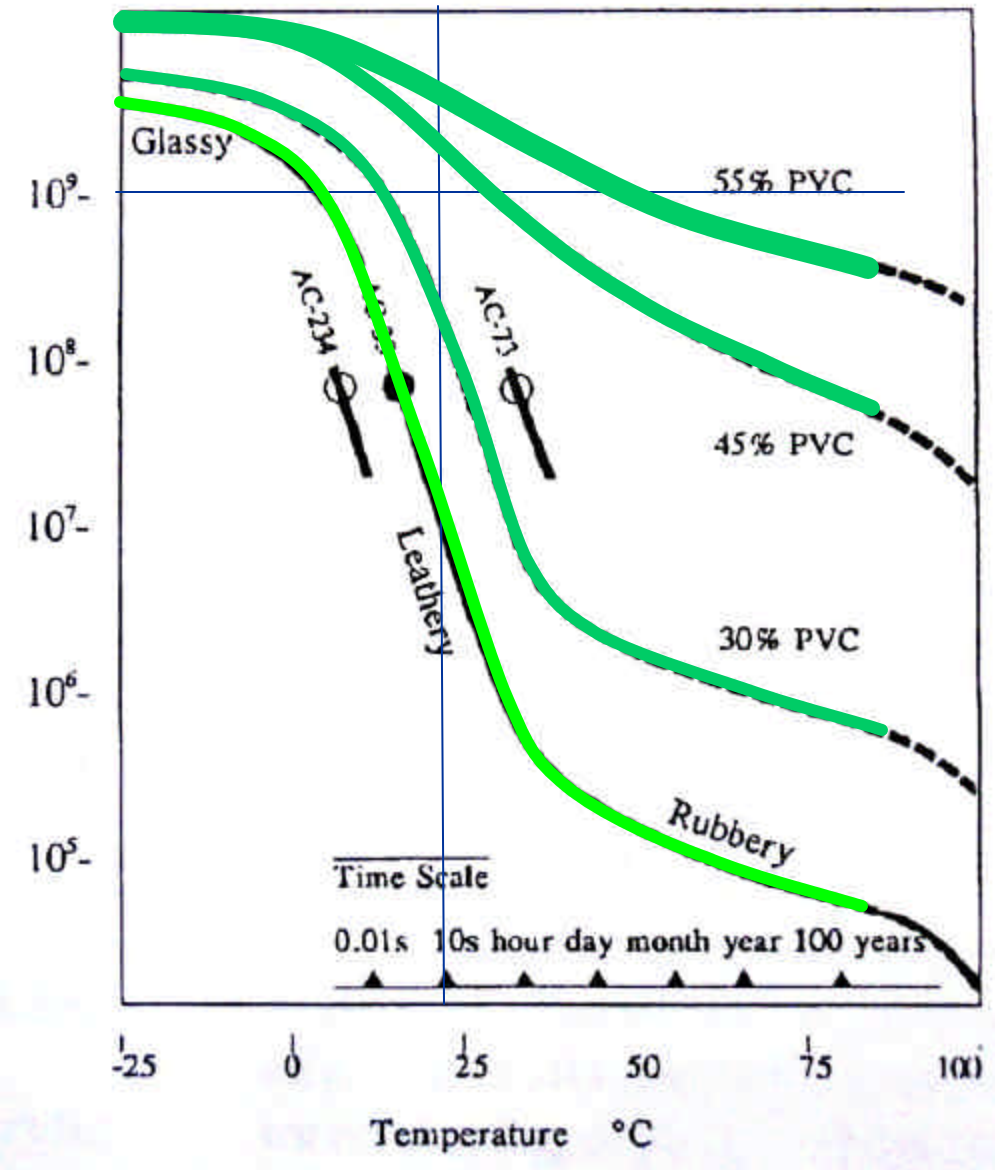
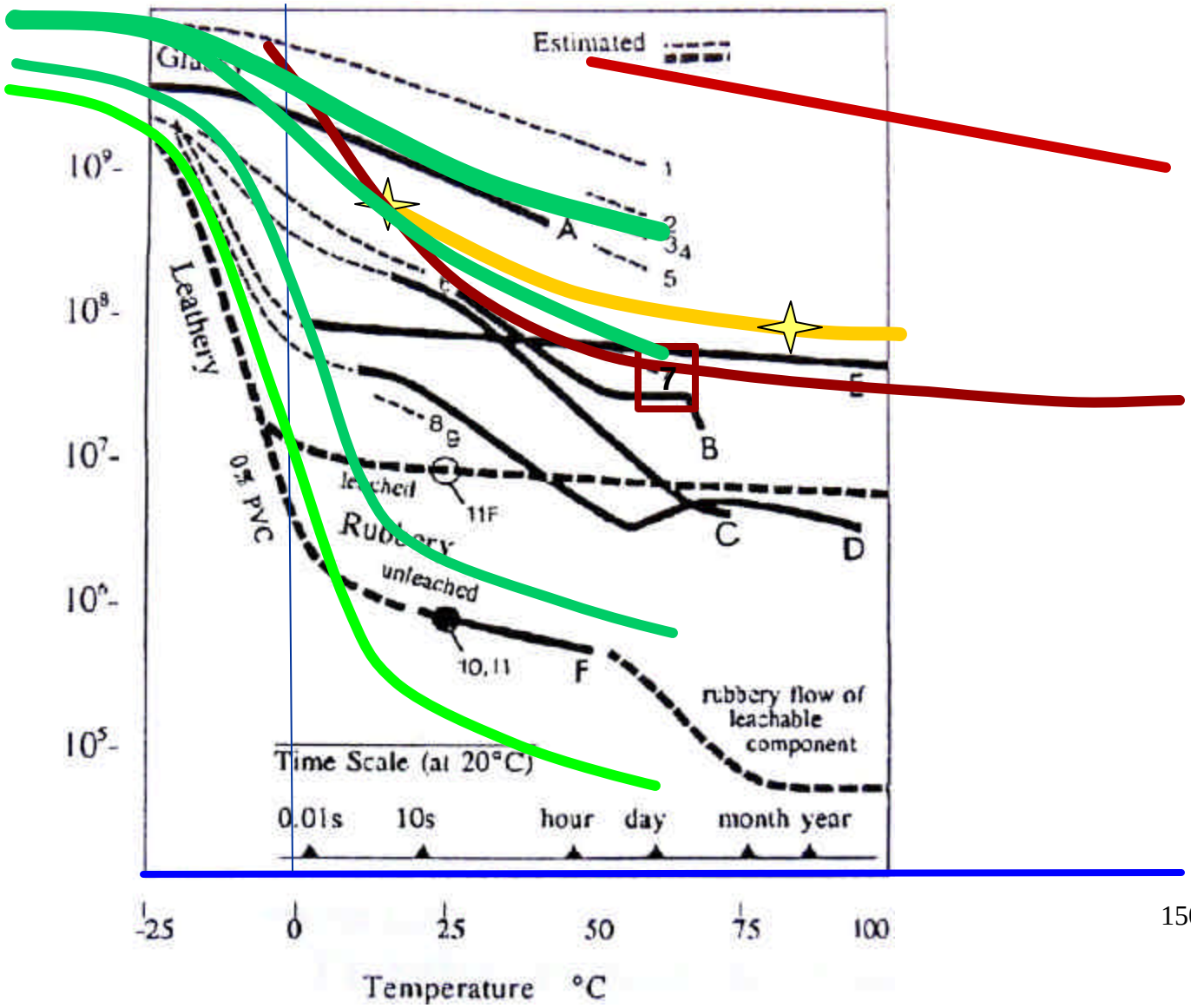


Figure and time scale from Michalski, S. 1991. "Paintings, Their Response To Temperature, Relative Humidity, Shock And Vibration" in *Works of Art in Transit*, National Gallery, Washington, pp.223-248. Original data on T scale all from Zosel, 1980.

Oil paints



Black lines: Michalski, S. 1991. "Paintings, Their Response To Temperature, Relative Humidity, Shock And Vibration" in Works of Art in Transit, National Gallery, Washington, pp.223-248.
See log E/RH slide for number legend and sources of data

(except where noted, all data are from tensile tests at ~20C, plotted on the time scale based on duration of the test. Creep data on time scale. TMA and DMTA data on T scale)

More recent data in colour:

yellow points: Naples yellow, Mecklenburg, 2006

brown lines: Burnt umber, Michalski unpublished TMA data

green lines: transposed lines for AC33 (previous slide), for PVC of 0%, 30%, 45% and 55%, shifted by -25°C, so that pure media plots of acrylic and oil overlap.

So…what do we know already about the mechanics of paint and wood?

There are ample data and models for the expansion and contraction of wood and paint with RH.

We have a well characterised pattern for the role of pigment volume concentration (PVC), time, and temperature on the modulus of acrylic paints, and enough individual oil paint data, to model a universal pattern for paint modulus.

We have a known pattern for RH effect on oil paint modulus.

We have partial data on tensile strength of paints at various times and PVC, and we can estimate some patterns for its change over time of the event.

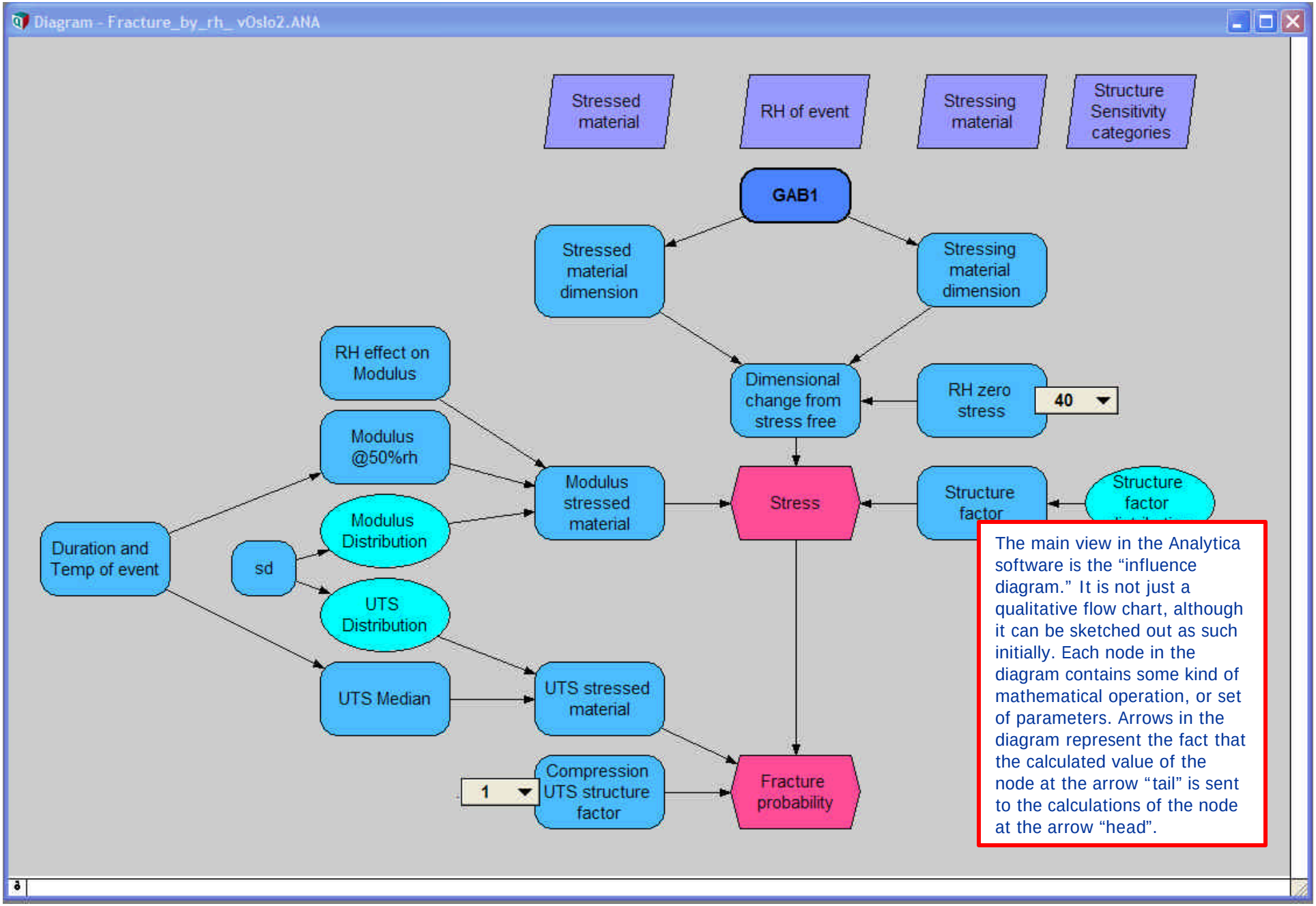
We have some similar data for glue and gesso.

But...

We know that the practical question is no longer about a single object, but collections of objects, with uncertain and variable characteristics

At CCI, for the last four years, we have been developing familiarity in a modelling tool used in risk analysis, designed to handle uncertainty and distributions in variables (and designed for scientists who have forgotten their math!) called *Analytica*. We have started modelling various risks to collections.

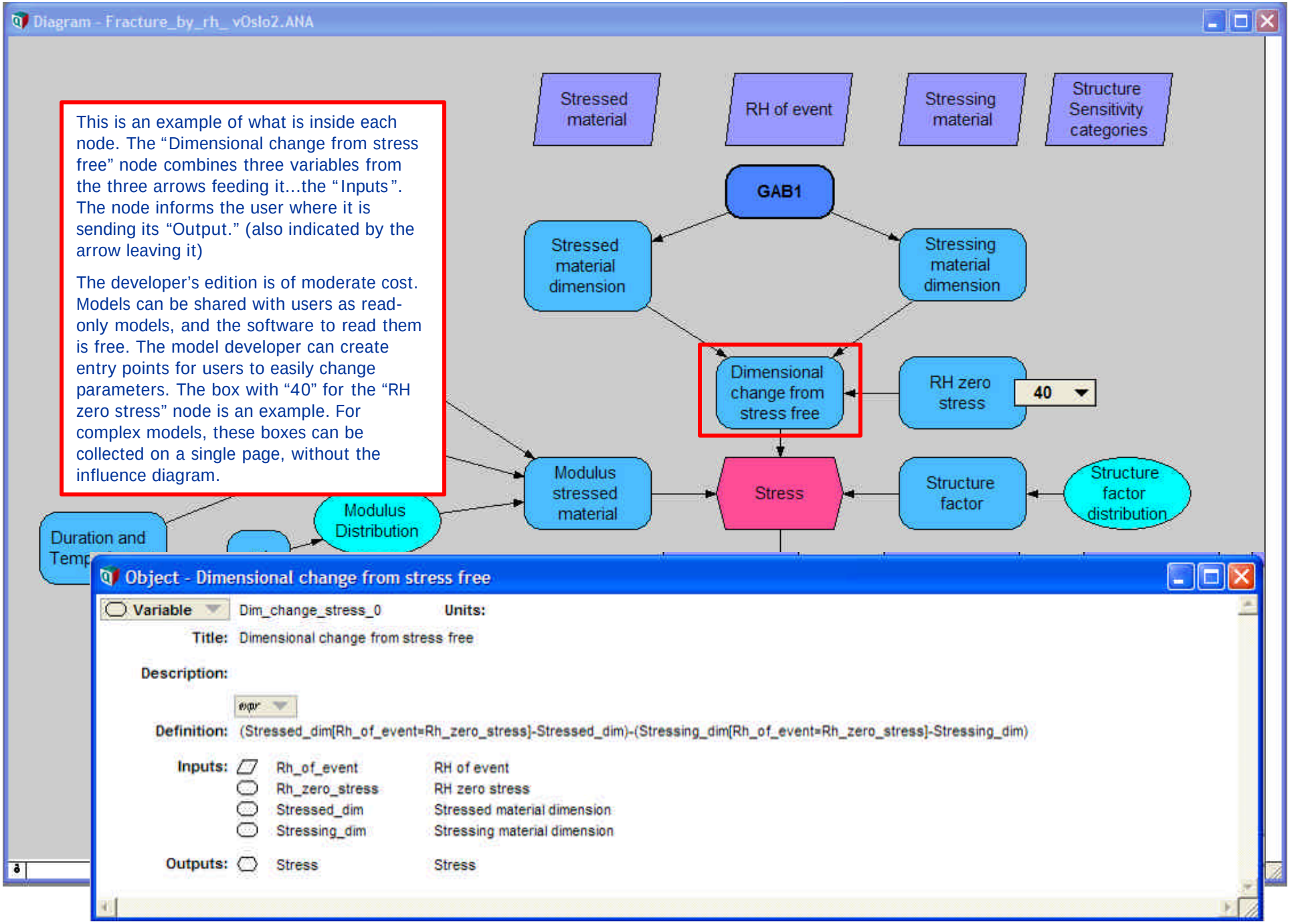
One model is for objects where fracture is dependent on differential expansion of attached elements. The role of the object structure is collapsed into a single "structure factor." (1 for layers of uniform thickness and uniform constraints that result in uniform stress distribution.)

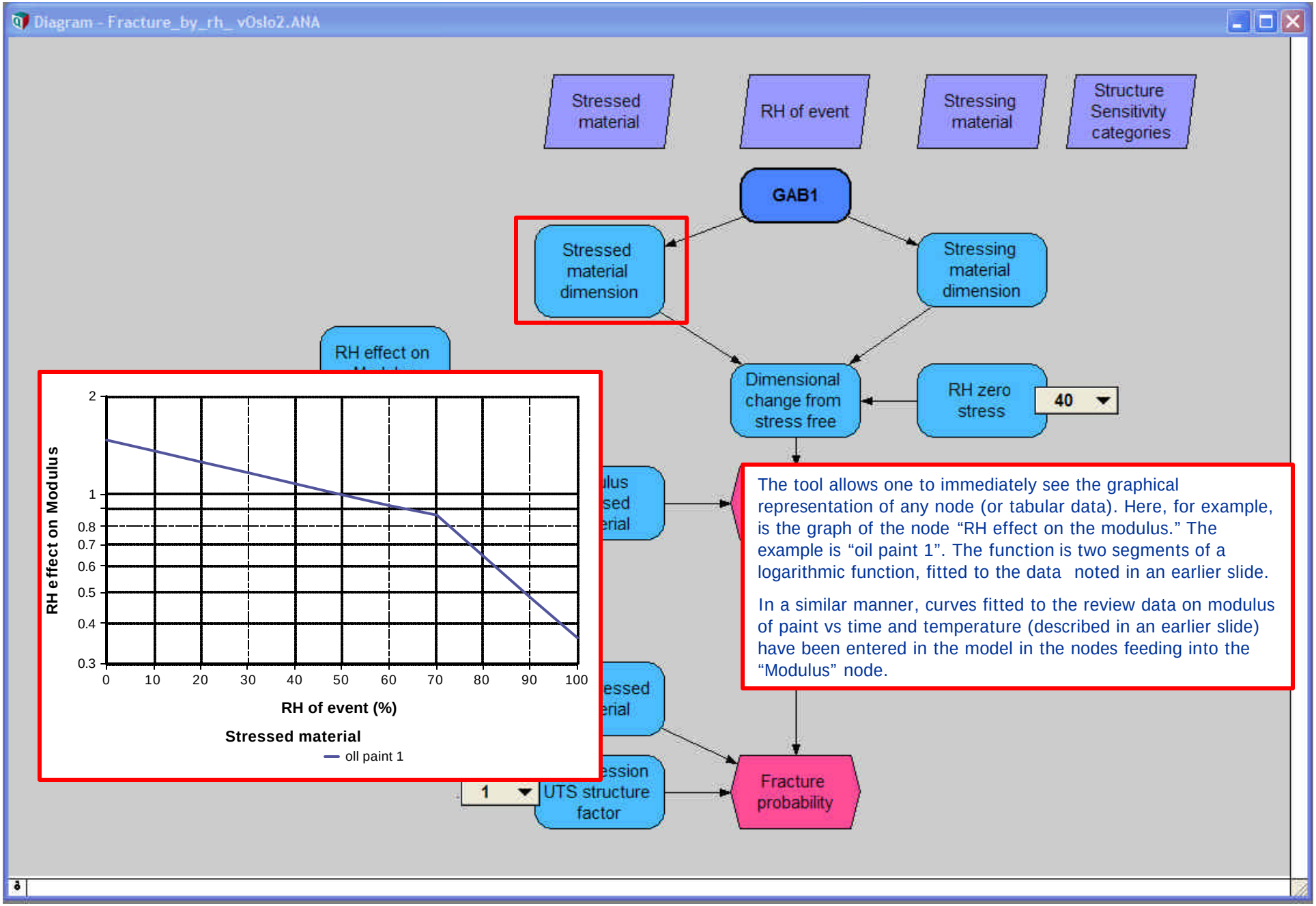


The main view in the Analytica software is the "influence diagram." It is not just a qualitative flow chart, although it can be sketched out as such initially. Each node in the diagram contains some kind of mathematical operation, or set of parameters. Arrows in the diagram represent the fact that the calculated value of the node at the arrow "tail" is sent to the calculations of the node at the arrow "head".

This is an example of what is inside each node. The "Dimensional change from stress free" node combines three variables from the three arrows feeding it…the "Inputs". The node informs the user where it is sending its "Output." (also indicated by the arrow leaving it)

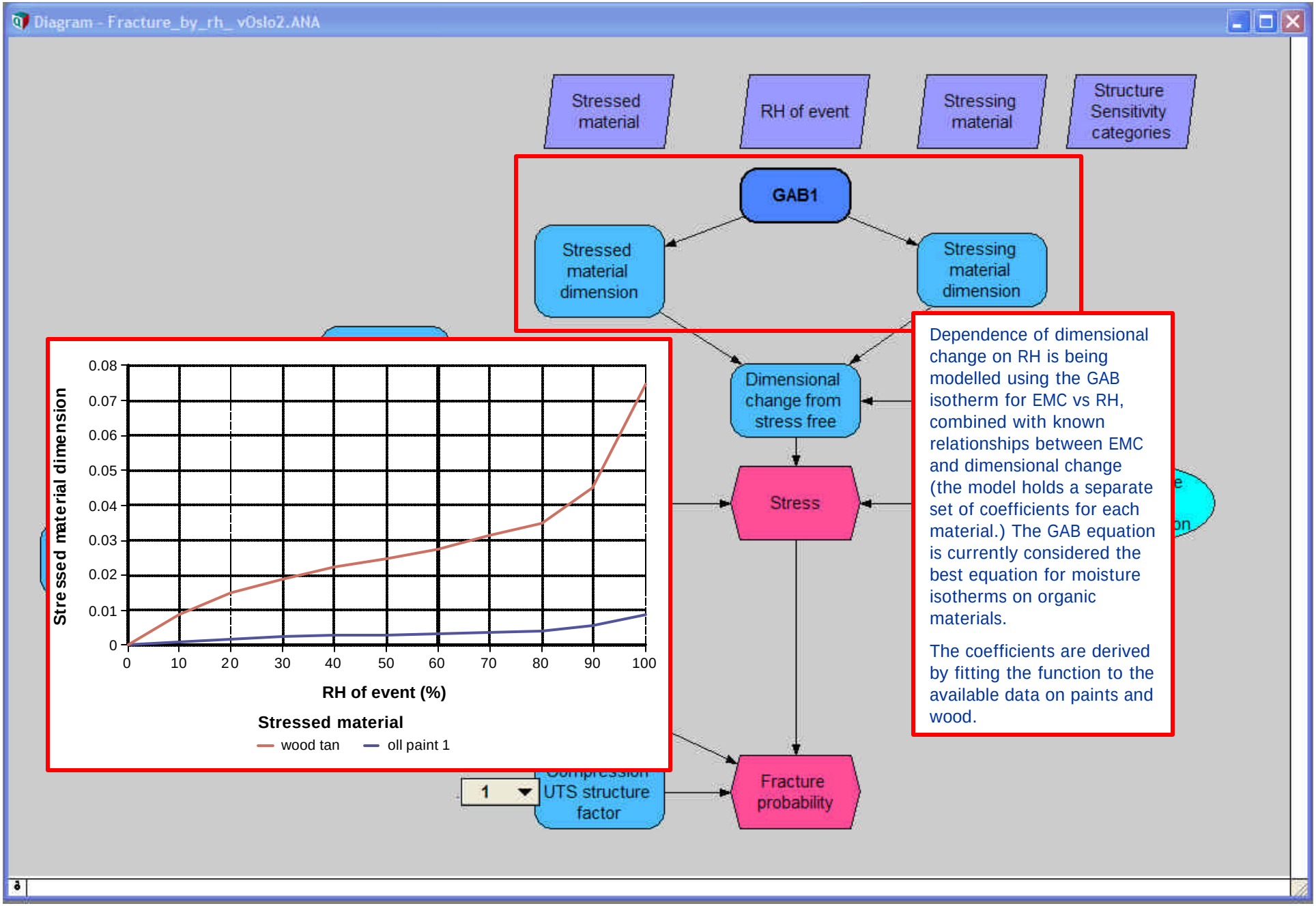
The developer's edition is of moderate cost. Models can be shared with users as read-only models, and the software to read them is free. The model developer can create entry points for users to easily change parameters. The box with "40" for the "RH zero stress" node is an example. For complex models, these boxes can be collected on a single page, without the influence diagram.





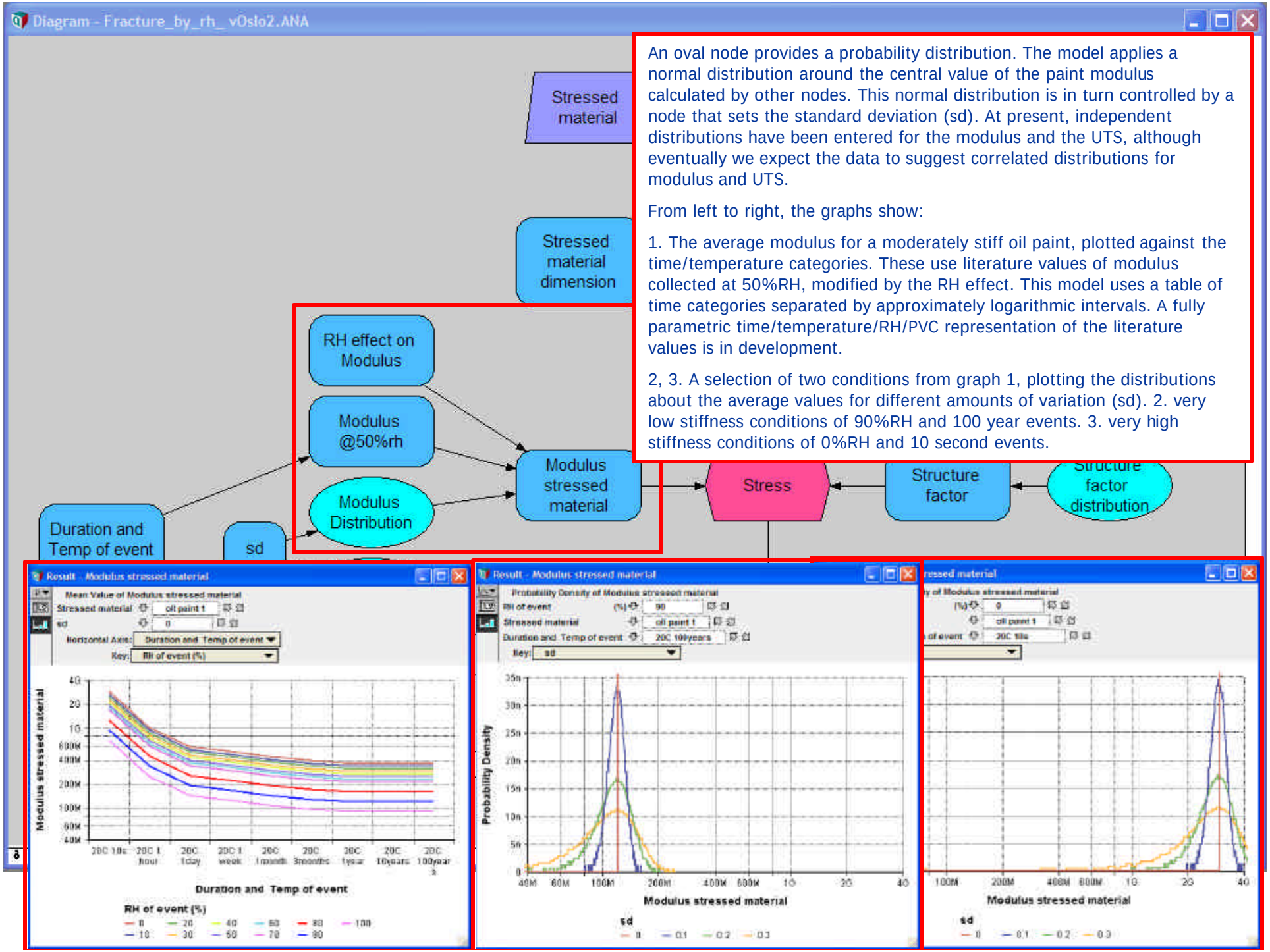
The tool allows one to immediately see the graphical representation of any node (or tabular data). Here, for example, is the graph of the node "RH effect on the modulus." The example is "oil paint 1". The function is two segments of a logarithmic function, fitted to the data noted in an earlier slide.

In a similar manner, curves fitted to the review data on modulus of paint vs time and temperature (described in an earlier slide) have been entered in the model in the nodes feeding into the "Modulus" node.



Dependence of dimensional change on RH is being modelled using the GAB isotherm for EMC vs RH, combined with known relationships between EMC and dimensional change (the model holds a separate set of coefficients for each material.) The GAB equation is currently considered the best equation for moisture isotherms on organic materials.

The coefficients are derived by fitting the function to the available data on paints and wood.

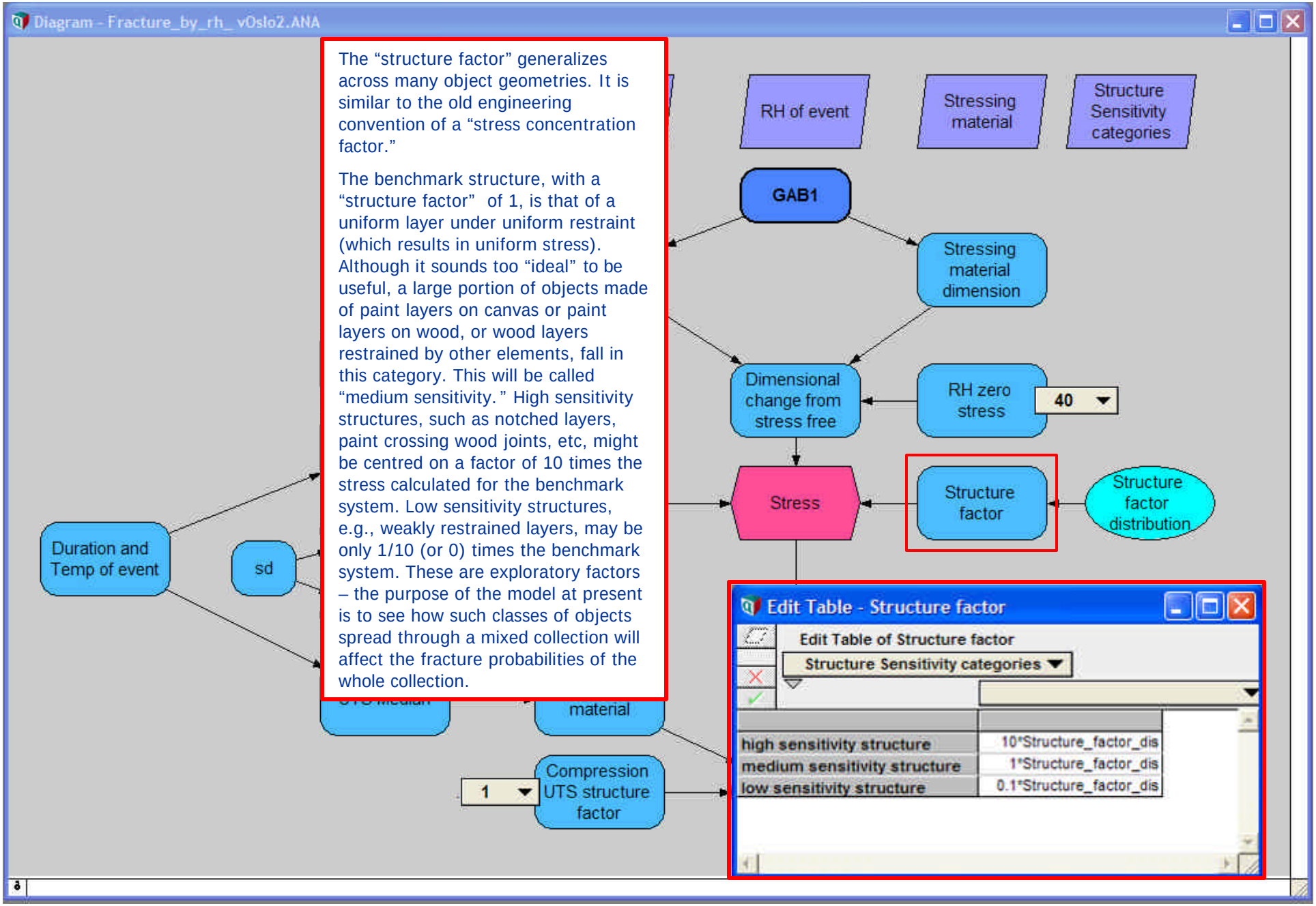


An oval node provides a probability distribution. The model applies a normal distribution around the central value of the paint modulus calculated by other nodes. This normal distribution is in turn controlled by a node that sets the standard deviation (sd). At present, independent distributions have been entered for the modulus and the UTS, although eventually we expect the data to suggest correlated distributions for modulus and UTS.

From left to right, the graphs show:

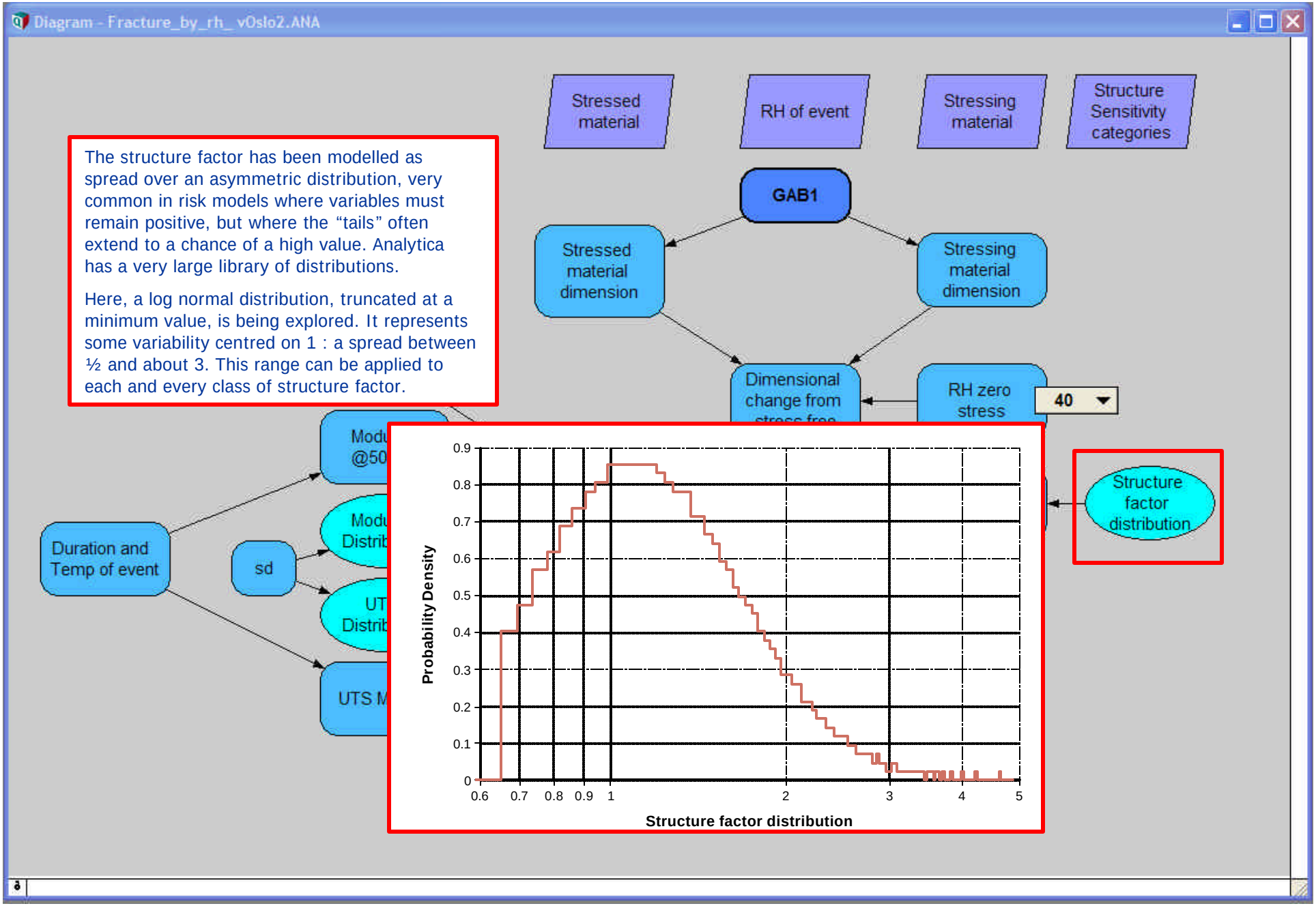
1. The average modulus for a moderately stiff oil paint, plotted against the time/temperature categories. These use literature values of modulus collected at 50%RH, modified by the RH effect. This model uses a table of time categories separated by approximately logarithmic intervals. A fully parametric time/temperature/RH/PVC representation of the literature values is in development.

2, 3. A selection of two conditions from graph 1, plotting the distributions about the average values for different amounts of variation (sd). 2. very low stiffness conditions of 90%RH and 100 year events. 3. very high stiffness conditions of 0%RH and 10 second events.



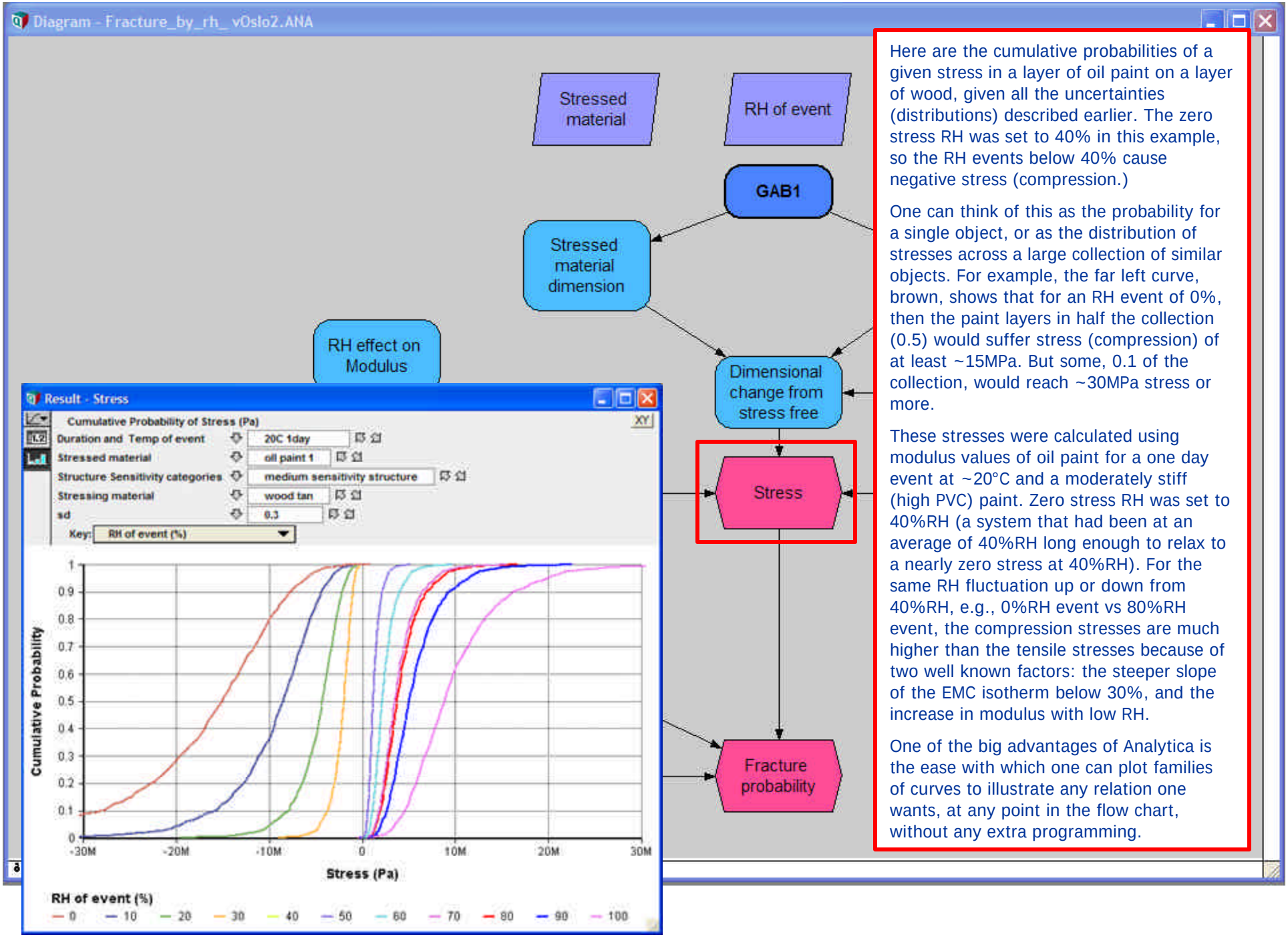
The "structure factor" generalizes across many object geometries. It is similar to the old engineering convention of a "stress concentration factor."

The benchmark structure, with a "structure factor" of 1, is that of a uniform layer under uniform restraint (which results in uniform stress). Although it sounds too "ideal" to be useful, a large portion of objects made of paint layers on canvas or paint layers on wood, or wood layers restrained by other elements, fall in this category. This will be called "medium sensitivity." High sensitivity structures, such as notched layers, paint crossing wood joints, etc, might be centred on a factor of 10 times the stress calculated for the benchmark system. Low sensitivity structures, e.g., weakly restrained layers, may be only 1/10 (or 0) times the benchmark system. These are exploratory factors – the purpose of the model at present is to see how such classes of objects spread through a mixed collection will affect the fracture probabilities of the whole collection.



The structure factor has been modelled as spread over an asymmetric distribution, very common in risk models where variables must remain positive, but where the "tails" often extend to a chance of a high value. Analytica has a very large library of distributions.

Here, a log normal distribution, truncated at a minimum value, is being explored. It represents some variability centred on 1 : a spread between ½ and about 3. This range can be applied to each and every class of structure factor.

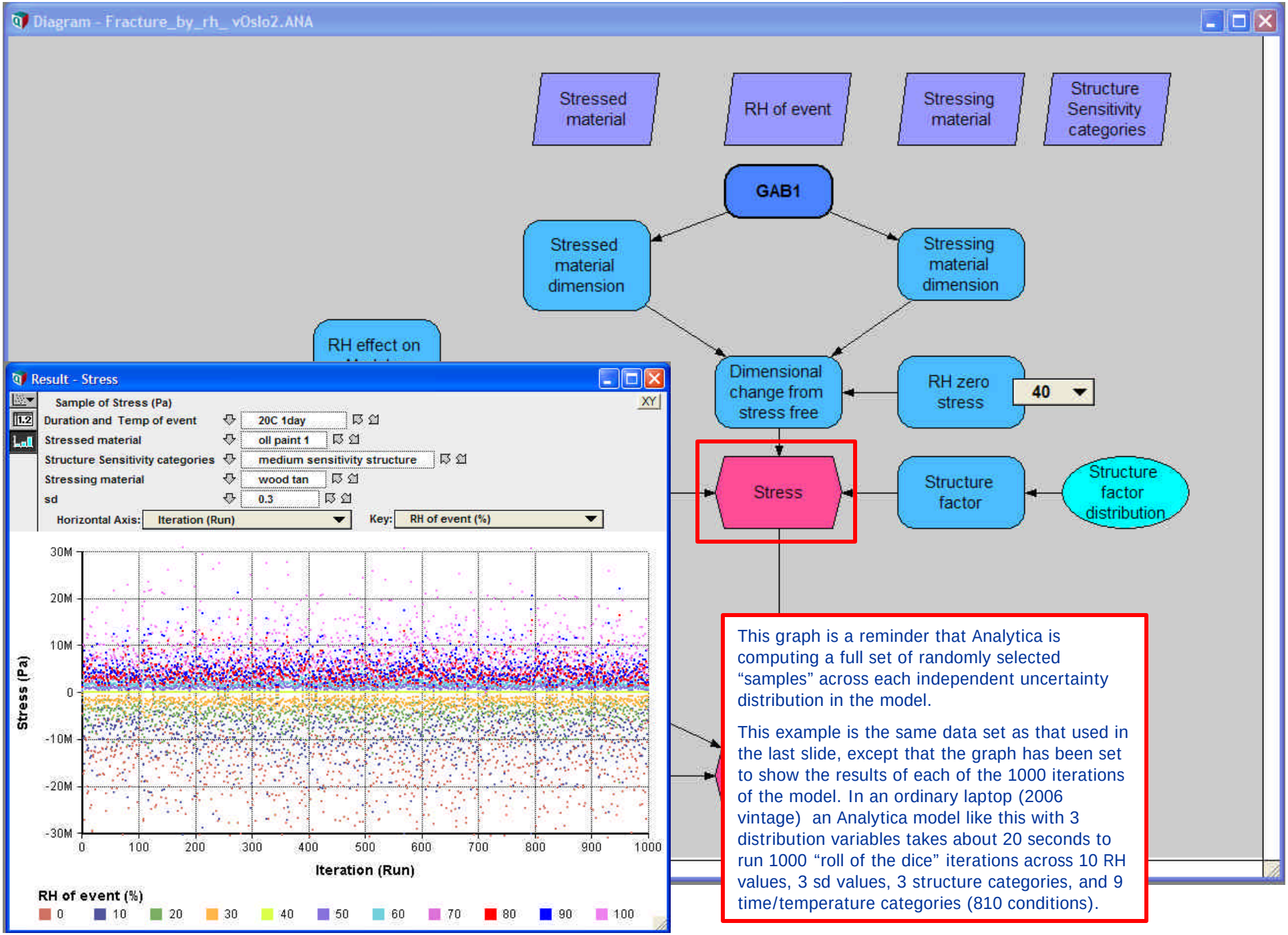


Here are the cumulative probabilities of a given stress in a layer of oil paint on a layer of wood, given all the uncertainties (distributions) described earlier. The zero stress RH was set to 40% in this example, so the RH events below 40% cause negative stress (compression.)

One can think of this as the probability for a single object, or as the distribution of stresses across a large collection of similar objects. For example, the far left curve, brown, shows that for an RH event of 0%, then the paint layers in half the collection (0.5) would suffer stress (compression) of at least ~15MPa. But some, 0.1 of the collection, would reach ~30MPa stress or more.

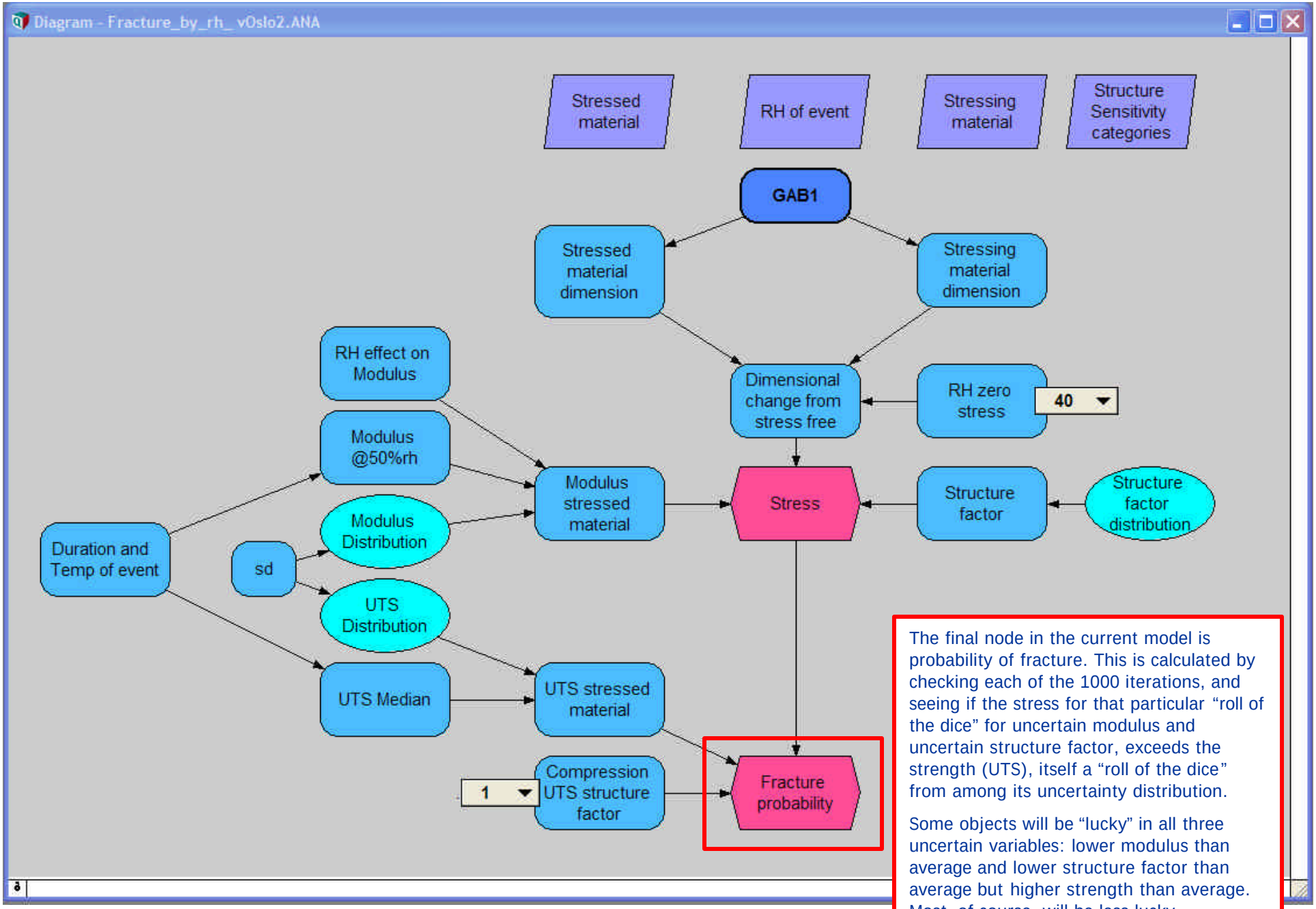
These stresses were calculated using modulus values of oil paint for a one day event at ~20°C and a moderately stiff (high PVC) paint. Zero stress RH was set to 40%RH (a system that had been at an average of 40%RH long enough to relax to a nearly zero stress at 40%RH). For the same RH fluctuation up or down from 40%RH, e.g., 0%RH event vs 80%RH event, the compression stresses are much higher than the tensile stresses because of two well known factors: the steeper slope of the EMC isotherm below 30%, and the increase in modulus with low RH.

One of the big advantages of Analytica is the ease with which one can plot families of curves to illustrate any relation one wants, at any point in the flow chart, without any extra programming.



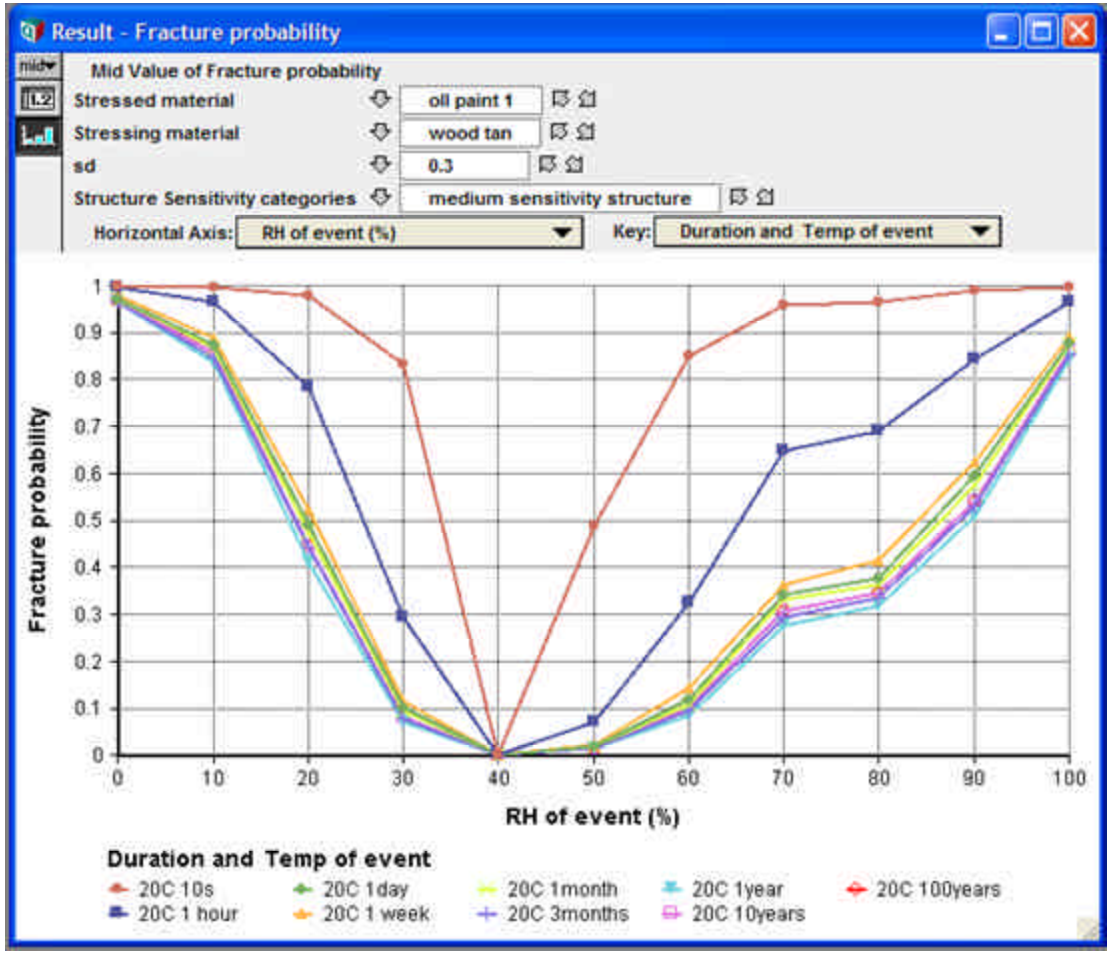
This graph is a reminder that Analytica is computing a full set of randomly selected "samples" across each independent uncertainty distribution in the model.

This example is the same data set as that used in the last slide, except that the graph has been set to show the results of each of the 1000 iterations of the model. In an ordinary laptop (2006 vintage) an Analytica model like this with 3 distribution variables takes about 20 seconds to run 1000 "roll of the dice" iterations across 10 RH values, 3 sd values, 3 structure categories, and 9 time/temperature categories (810 conditions).



The final node in the current model is probability of fracture. This is calculated by checking each of the 1000 iterations, and seeing if the stress for that particular "roll of the dice" for uncertain modulus and uncertain structure factor, exceeds the strength (UTS), itself a "roll of the dice" from among its uncertainty distribution.

Some objects will be "lucky" in all three uncertain variables: lower modulus than average and lower structure factor than average but higher strength than average. Most, of course, will be less lucky.



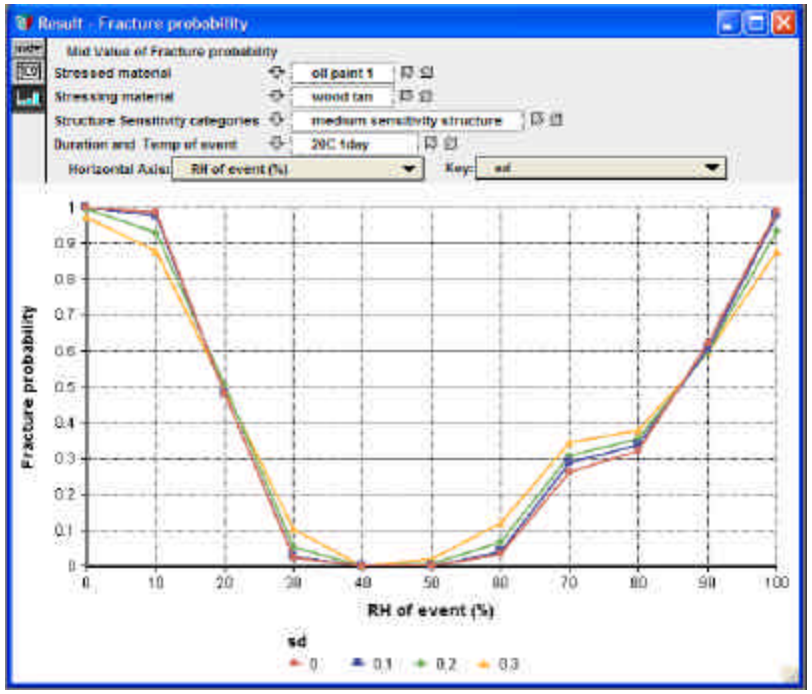
This graph shows the effect of event duration (stress relaxation) for events above the selected zero stress RH of 40%RH.

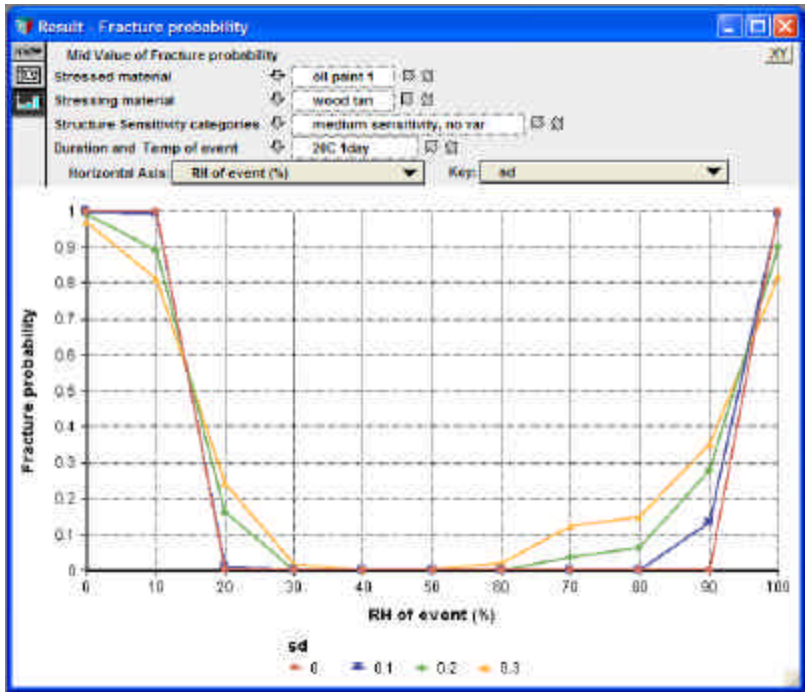
Consider the tension cracking side, the right hand group of curves, for 40%RH and higher. There is a huge gap between the curve for a 10 second event (brown line), which suggests half the collection forms cracks at 50%RH, and the one hour event (blue line) which suggests an event of 65%RH is necessary. Then there is another big jump to the closely grouped curves for all remaining time categories, 1 day to 100 years. (the strange crossovers of sequence within this group reflect the inadequate smoothing of the approximations made to the available data on strength versus time.)

Fortunately, a 10 second RH event is impossible for polychromes. A 10 second event at 20°C, however, has the same modulus in oil paint as a 1 day event at -20°C (see the previous slide on Oil paint, find the interval between 10s and 1 day on the X axis time scale, and then find the same interval below 20°C on the temperature scale.) But perhaps this is also an impossible event in polychrome because moisture diffusion slows by ½ for every drop of ~10°C, so RH response time will be about 16 times slower at -20°C than at 20°C. The question becomes: is the effect of temperature on modulus proportionally greater than the effect on response time? It might be in the leathery region of time/temperature for paints with moderate to low pigmentation. On the other hand, if the event stays within the quasi-equilibrium plateaus of either glassy of rubbery behaviour, for cross-linked media such as oil paint, there is no change in modulus with time or temperature. And what about very thin supports? We know that paintings on sized canvas with exposed backs can easily respond in a few minutes to RH change.

The value of a software model is that it allows us to enter all these interacting facts once, precisely, so that we can then watch the endless possibilities unfold as we play “what-if?”

(The curious plateau from 70% to 80% RH shows that in this range, the effect of RH on modulus is dominating the effect of RH on expansion coefficients, and that the two segment approximation to the RH effect on modulus needs smoothing at the 70%RH transition.)





These graphs show the effect of varying the variability in the paint characteristics and in the structure factor.

The top graph shows fracture probability with structure factor set to “medium sensitivity”, plus variability in this factor as shown in an earlier slide. Briefly, one can say that the curves are close together, i.e., the effect of a shift in standard deviation (sd) of the paint characteristics from none ±0.0 to ±0.3 (±30%) is noticeable but not something significant enough to change collection risk estimates.

The bottom graph shows what happens when the variability in the structure factor is switched off, i.e., fixed at 1. Two effects emerge: the variability in structure factor (as selected) diminishes chances of cracking, at the same time as making changes in the variability of the paint characteristics more noticeable. (The latter is a predictable effect statistically: large uncertainty in another variable smears the distinctions between degrees of uncertainty in other variables).

In graphs not shown here, one finds, as expected, that the difference between categories of structure factor (high, medium, low) plays a much bigger role than the more modest variation within each category. A computer model is not needed to know that!

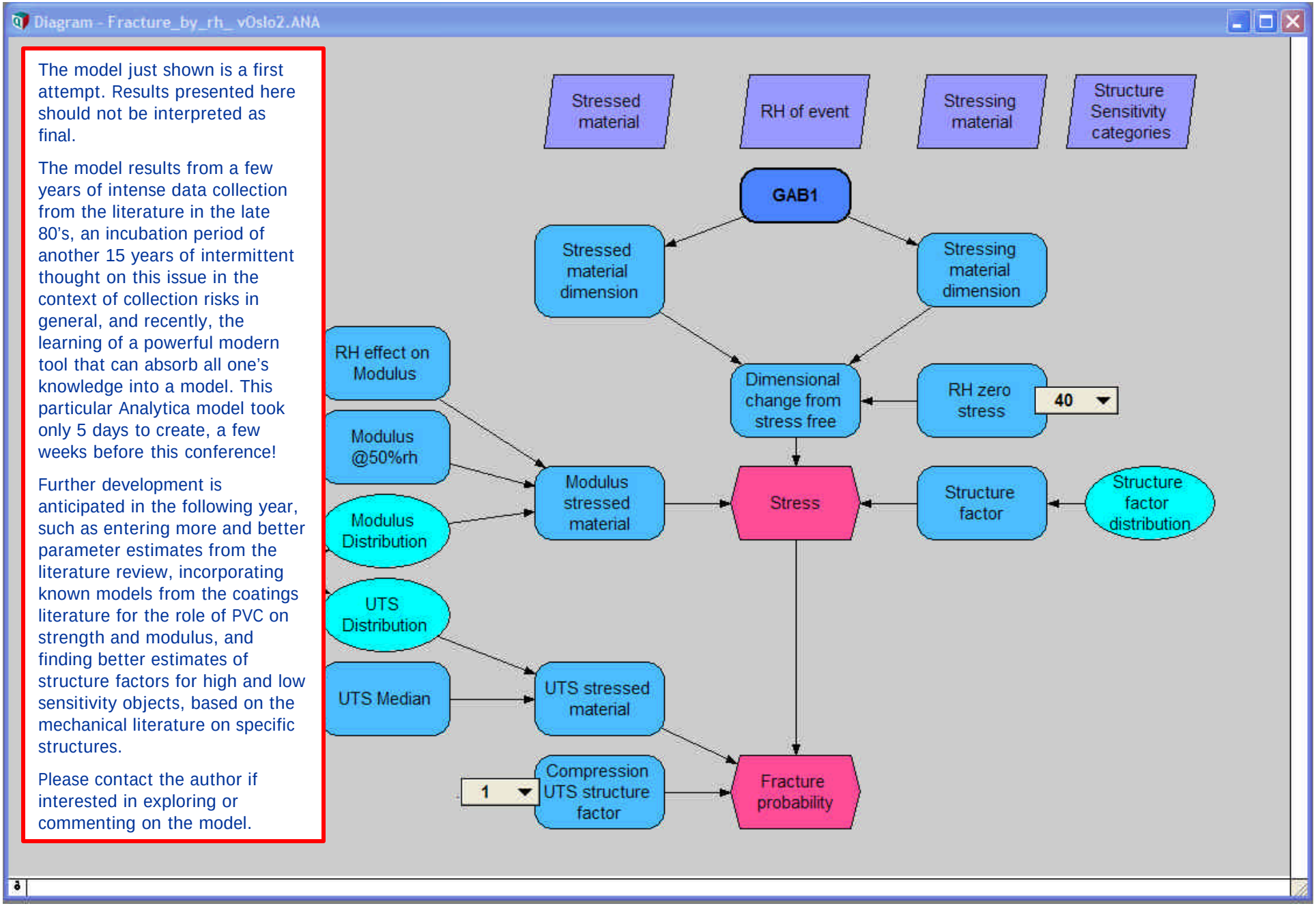
Smoother graphs can be created by setting smaller RH intervals in the model, but computation times increase proportionally. This would be done for final results.

The model just shown is a first attempt. Results presented here should not be interpreted as final.

The model results from a few years of intense data collection from the literature in the late 80's, an incubation period of another 15 years of intermittent thought on this issue in the context of collection risks in general, and recently, the learning of a powerful modern tool that can absorb all one's knowledge into a model. This particular Analytica model took only 5 days to create, a few weeks before this conference!

Further development is anticipated in the following year, such as entering more and better parameter estimates from the literature review, incorporating known models from the coatings literature for the role of PVC on strength and modulus, and finding better estimates of structure factors for high and low sensitivity objects, based on the mechanical literature on specific structures.

Please contact the author if interested in exploring or commenting on the model.



Thank you for your attention

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