VA-Squish User's Guide

Introduction

This guide provides instructions for using software developed at VA Palo Alto and Stanford University to determine the biphasic properties of cartilage based on experimental data from a creep or stress relaxation indentation test. The three biphasic material constants (aggregate modulus, Poisson's ratio, permeability) are determined via a comparison of the experimental results with a Cartilage Interpolant Response Surface (CIRS) (described below) (Keenan et al, 2009).

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The Model:

Cartilage was modeled as a homogenous, isotropic and poroelastic material. For quasi-static, small deformation analysis with constant permeability, poroelastic models have been shown to be mathematically equivalent to linear biphasic models (Levenston et al., 1998). Strain-dependent permeability was not incorporated. In the finite element model, the interface between the indenter and the cartilage surface was modeled both as frictionless and with an experimentally determined coefficient of static friction. The nonlinear, time-dependent finite element model was solved using ABAQUS/Standard (SIMULIA, Providence, RI).

Quadrilateral continuum elements with bilinear displacement and bilinear pore pressure shape functions (CAX4P) were used. The cartilage specimen diameter in the model was five times the diameter of the indenter in order to simulate an infinite plane of cartilage.

There are seven parameters that influence the results of a typical indentation test: three experimental parameters (indenter diameter, ramp time to achieve the target indenter force/displacement, magnitude of the target indenter force or indenter displacement), cartilage thickness, and the three linear biphasic constants (aggregate modulus, Poisson's ratio and permeability). The interpolant response surfaces were created to model specific experimental conditions.

To date, we have examined three basic models, including ones with: 1) a flat, porous indenter with frictionless contact; 2) a flat, porous indenter with frictional contact; 3) a hemispherical, non-porous indenter with frictionless contact. In addition, we have simulated both a creep test (in which indenter force is specified as a function of time) and a stress-relaxation test (in which indenter displacement is specified as a function of time). In the specific implementation presented here we provide the interpolant response surfaces only for a creep test using a flat, porous indenter that is modeled with frictional contact at the indenter/cartilage interface.

Flat, porous indenter with contact friction

The model and boundary conditions for a flat, porous indenter with contact friction are illustrated in Fig. 1. A small fillet radius (0.127 mm) was introduced at the outer edge of the indenter to match the experimental indenter. Based on the results of convergence studies, the double biased mesh required 20 nodes through the thickness and 60 nodes in the radial direction. The nodes were linearly biased in the radial direction, radiating from the indenter corner and through the thickness to create a finer mesh under the indenter. The coefficient of static friction (0.26) was determined through experimental testing of the flat, porous indenter on the cartilage surface in the presence of phosphate-buffered saline.

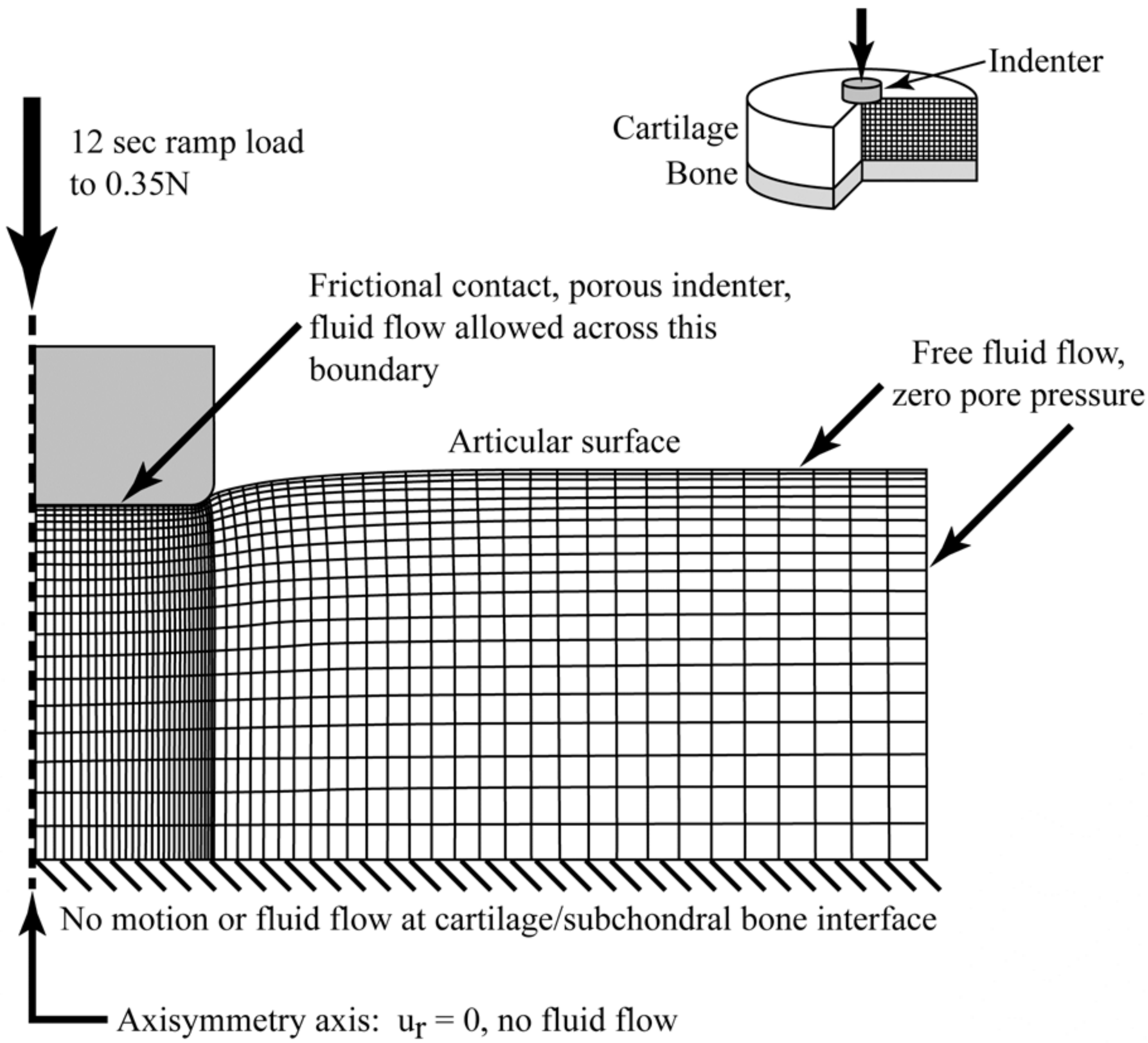

Fig. 1: Flat, porous indentation finite element model with friction at the indenter cartilage contact and a double biased mesh.

Hemispherical, non-porous indenter

The model and boundary conditions for a hemispherical, non-porous indenter are illustrated in Fig. 2. The non-porous indenter required the use of an ABAQUS user subroutine to model the correct fluid flow condition (no flow in the outward or normal direction) at the evolving interface between the rigid indenter and the cartilage surface (Warner et al, 2001 and Warner et al, 2001). There were 60 nodes through the thickness and 50 nodes in the radial direction. The nodes were linearly biased in the radial direction. Based on convergence studies, a high number of nodes at the contact surface are required for biphasic contact to converge.

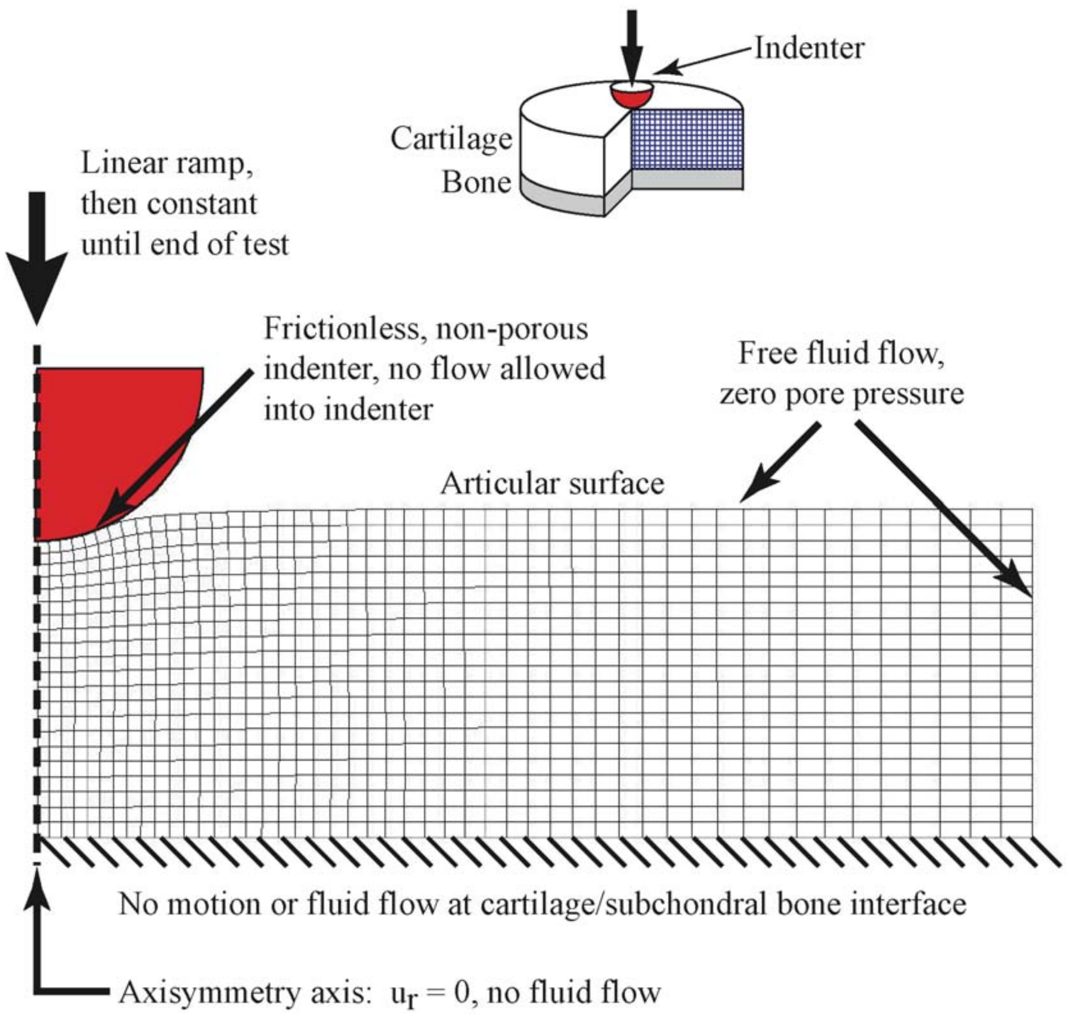

Fig. 2: Hemispherical, non-porous indentation finite element model. Simplified mesh shown; actual mesh is more refined.

Creep Test

In a creep test a specified load is applied over a linear ramp time followed by a creep phase during which the applied loading is held constant (see Fig. 3). The measured output is the displacement-time history.

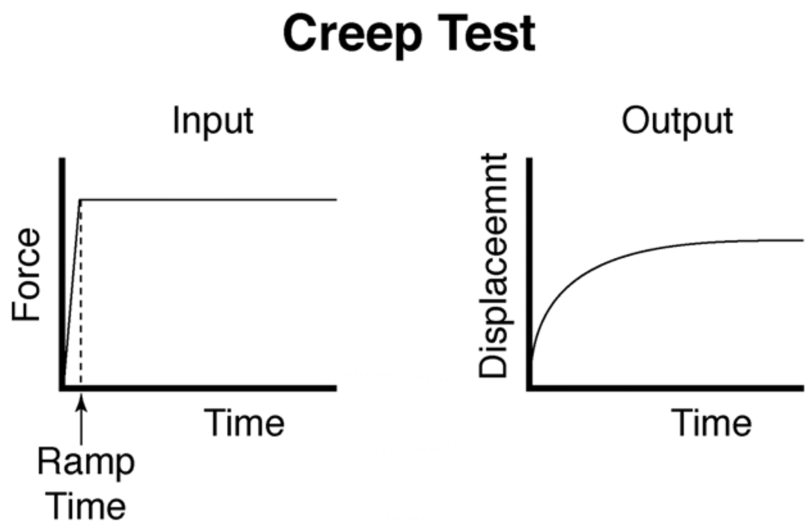

Fig. 3: Creep test illustration

Stress Relaxation Test

In a stress-relaxation test a displacement is applied over a specified ramp time, after which the displacement is held constant during the stress-relaxation phase (see Fig. 4). The measured output is the reaction force-time history.

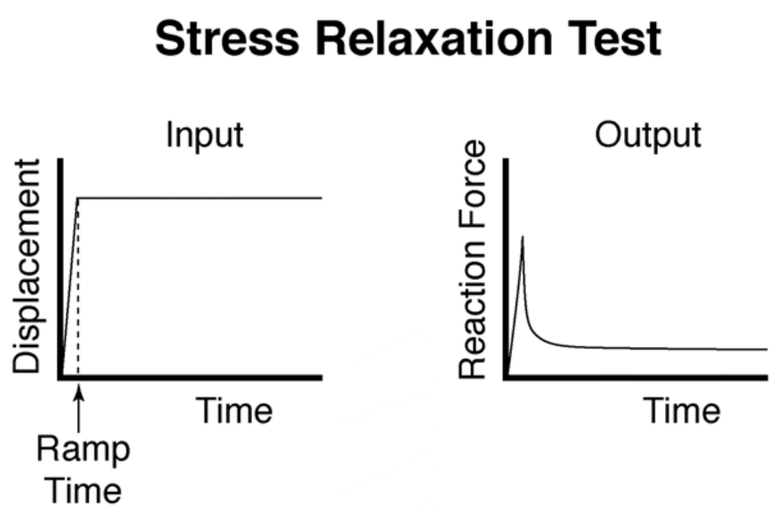

Fig. 4: Stress Relaxation test illustration

Input parameters

All CIRS files are specific to human articular cartilage. The range of input values for the finite element analyses (Table 1) was guided by the range of linear biphasic material property values reported for human tibial cartilage (Akizuki et al, 1986). The spacing of values within each range was determined based on a sensitivity analysis (not presented). The aggregate modulus (H_A) total range was broken into two sub-ranges because, all other inputs remaining constant, there was a greater linear variation in end-of-test displacement for lower aggregate modulus than for higher aggregate modulus. Specimen thickness varied from 1.0 mm to 5.0 mm.

There are different ranges of aggregate modulus for each indenter based on convergence studies. The flat indenter model with friction does not solve for an aggregate modulus less than 0.3MPa using the given mesh due to element distortion at the indenter periphery. The strains in these elements become too large for the linear theory to hold.

Input linear, biphasic constants to ABAQUS solution

(Range of values given: lower bound : interval : upper bound)

Parameter	**Range of Values**
Poisson's ratio	0.0 : 0.05 : 0.3
Aggregate modulus (MPa)	0.3 : 0.1 : 0.5 and 0.65 : 0.25 : 1.9 (flat) 0.1 : 0.25 : 1.6 (hemispherical)
Permeability ($E^{-15}m^4/Ns$)	0.1 : 2.0 : 8.1
Cartilage thickness (mm)	1.0 : 0.5 : 5.0

Table 1: The range of values is coarse; next, interpolating between these curves creates the fine CIRS.

Currently Supported Test Set-ups

Response surface files have been generated for the conditions listed in the table. It is recommended that anyone who is considering performing tests chose a test setup and testing parameters that exactly match with one row in Table 2.

Currently Supported Test Set-ups

Test Type (Creep/SR)	Indenter Force (N) or Displacement (mm)	Indenter Type	Indenter Diameter (mm)	Ramp Time (s)	Test Time (s)
***Creep**	0.35 N	Flat, porous	2.0 mm	12 s	4000 s

Table 2: Test set-ups which currently have complete response surface maps.

***** There have been three CIRS created that match this test condition. Currently we are using version 2.0.1 which has a coefficient of static friction (0.26) at the contact between the indenter tip and the cartilage surface and has a test time of 4000s. Version 2.0 has a test time of 4000s. Version 1.0 was a frictionless model.

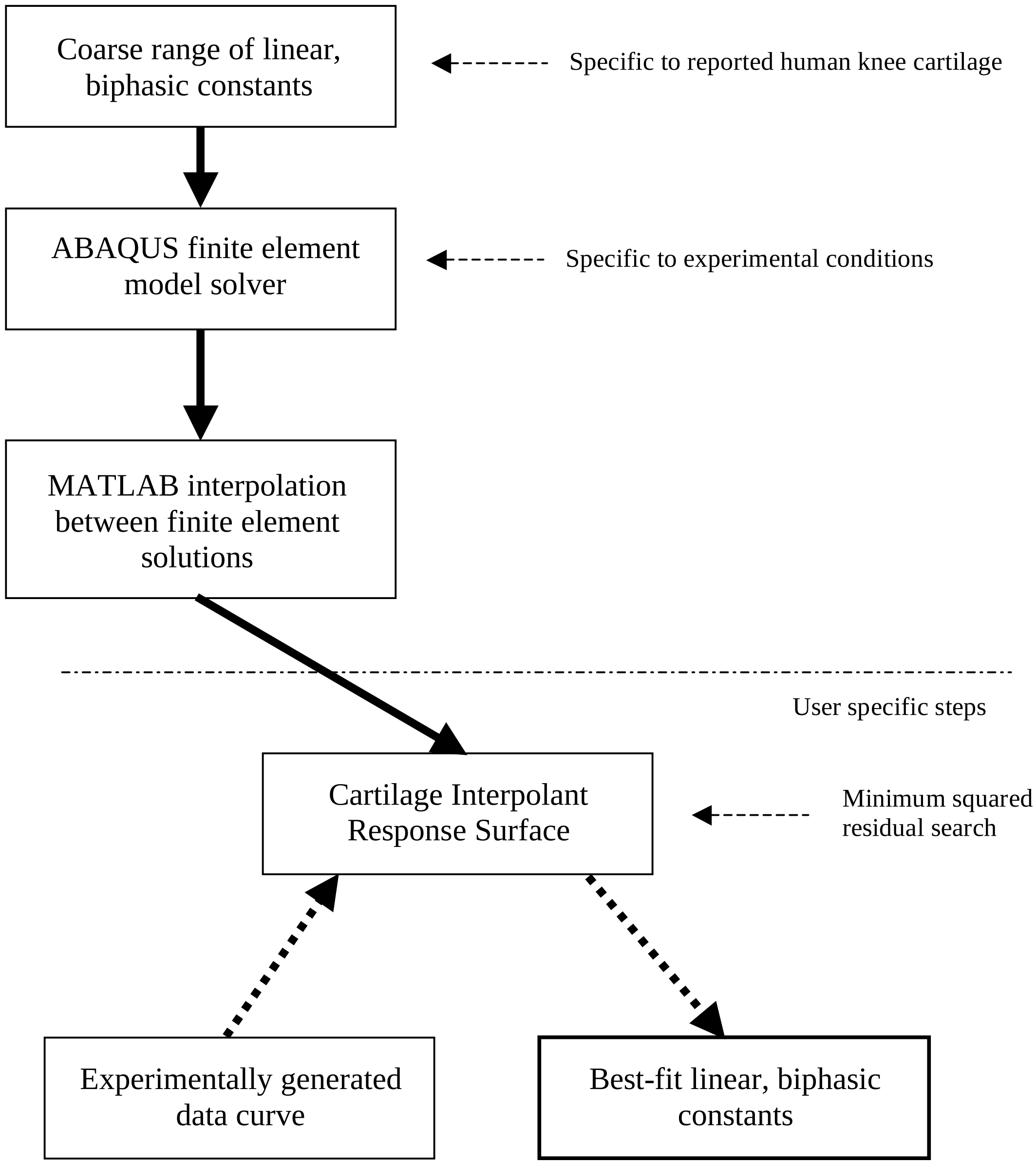

Fig. 5: Cartilage Interpolant Response Surface Process Diagram

The Cartilage Interpolant Response Surface (CIRS):

The interpolant response surface was generated from an initial coarse set of finite element solutions followed by shape-preserving, piecewise cubic Hermite polynomial interpolation (MATLAB, Mathworks, Inc., Natick, MA) between the finite element generated solutions (see Table 3). For example, in the creep test, a total of 2,835 finite element solutions were found. The subsequent interpolation resulted in 2,806,245 total solutions.

The ABAQUS generated curves are sampled, in the case of the creep test at 75 linearly spaced points over the entire time (0 to 4000s). The CIRS curves are generated using the sampled values – the interpolated CIRS curves only have given values at the sampled time points. In order to compare the experimental data to the CIRS curves, the entire experimental data is sampled at the same time points (see Fig.6).

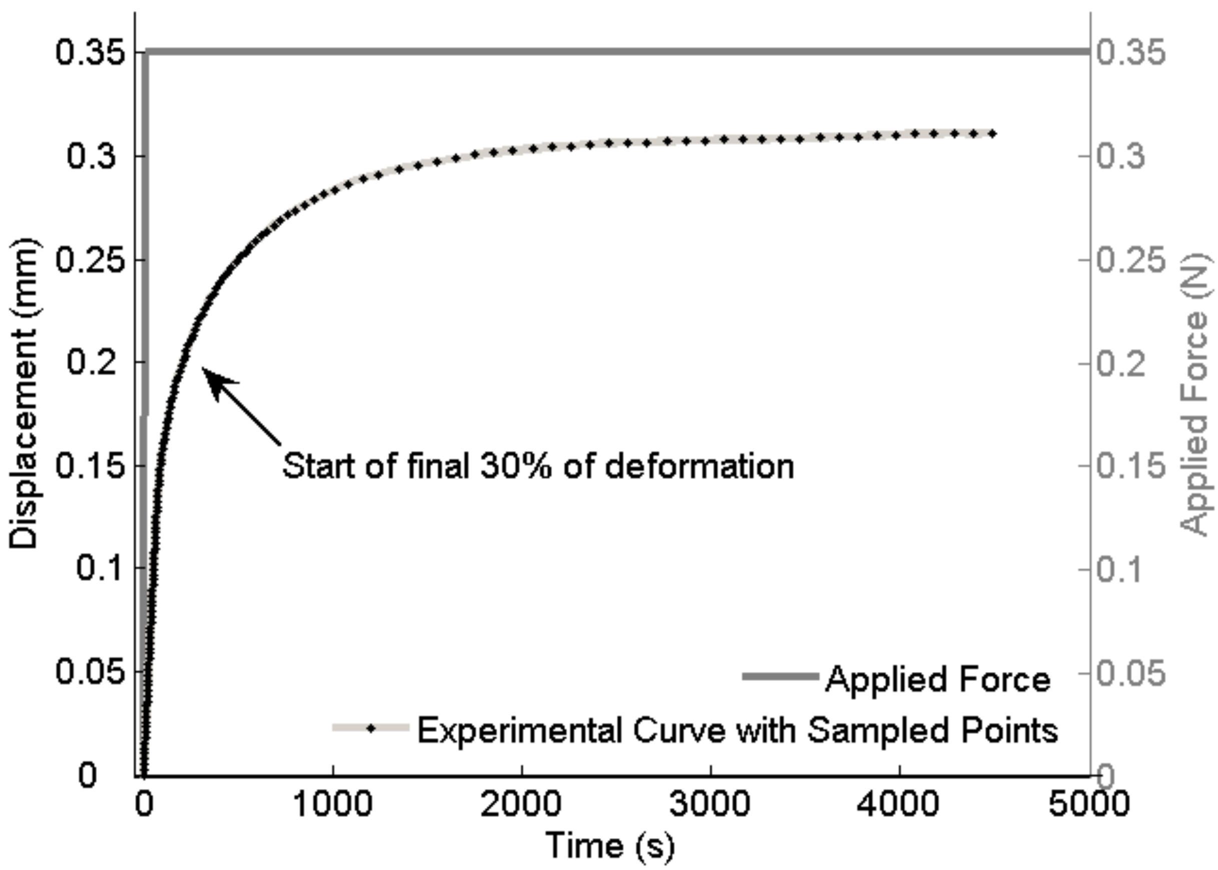

Fig. 6: Experimental data, sampled points on the experimental curve and the applied force for a creep test (note: not all 75 sample points are shown in this illustration). The start of the final 30% of the deformation is shown.

The experimental data is compared to the CIRS using a minimum squared residual search over the entire response surface. The initial conditions as modeled are difficult to achieve experimentally: perpendicular contact of the indenter and smooth cartilage surface and linear ramp loading. The data during the initial loading phase, defined to be the first 70% of the deformation, were not used to find the best-fit curve be consistent with several previous studies that used the semi-analytical/semi-numerical method (Mow et al., 1989; Roemhildt et al., 2006). Removing the initial loading phase retains the final 30% of the displacement data over 90% of the total time. Both the experimental and CIRS curves are cropped to the time point corresponding to the start of the last 30% of the deformation (see Fig. 7). Additionally, using the known thickness of the cartilage, the CIRS search is decreased to three parameters, i.e., the linear biphasic constants.

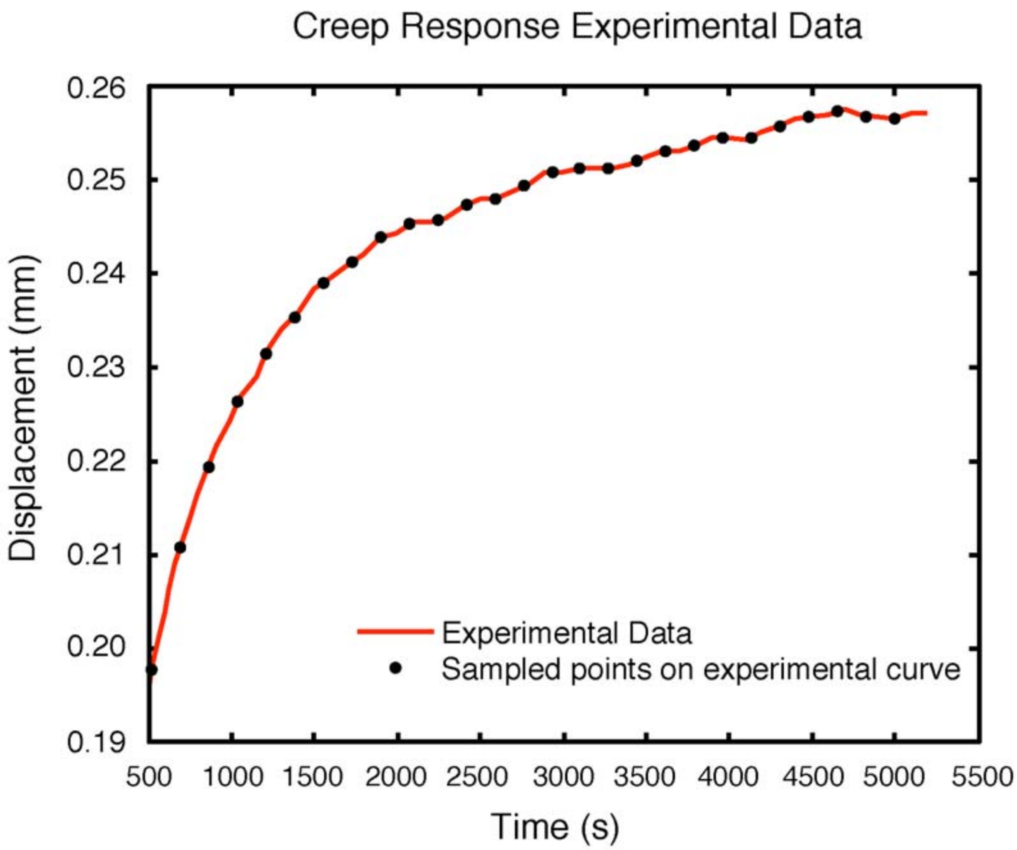

Fig. 7: Experimental data and sampled points on the experimental curve for the final 30% of the deformation of a creep test.

The experimental curve is compared to every curve in the CIRS at each sampled time point. The value of the experimental curve is subtracted from the value of the CIRS and squared to give a residual. The minimum residual corresponding to the best-fit CIRS curve is defined as:

$$residual = \sum_{n=1}^{N} \left(Model(t_n) - Experimental(t_n)\right)^2 .$$

The experimental data and best-fit curve are plotted (see Fig. 9). The three biphasic constants associated with the best-fit curve within the CIRS represent the predicted biphasic constants for the region of cartilage tested. Since every curve in the CIRS is searched, it is not possible to fall into a local minimum using this method. Therefore, the solution found represents a global minimum, given the resolution of the CIRS. Users should be aware that if the CIRS-predicted values of either the aggregate modulus or the permeability are at their lower or upper limits the solution does not necessarily represent a global minimum; Poisson's ratio solution is valid at the lower bound. If aggregate modulus or permeability is at their bounds, it is likely that the cartilage is abnormal in some way (too thin, too degenerated, etc.) and the bounds of the existing CIRS do not permit an accurate determination of the biphasic constants.

Range of values in CIRS

(Range of values given as: lower bound : interval : upper bound)

Parameter	**Range of Values**
Poisson's ratio	0.0 : 0.025 : 0.3
Aggregate modulus (MPa)	0.3 : 0.025 : 1.9 (flat indenter) 0.1 : 0.025 : 1.6 (hemispherical indenter)
Permeability ($E^{-15}m^4/Ns$)	0.1 : 0.1 : 8.1
Cartilage thickness (mm)	1.0 : 0.1 : 5.0

Table 3: The range of values is the same as Table 1 (input parameters to ABAQUS), but the interval between values is much smaller, creating the fine CIRS.

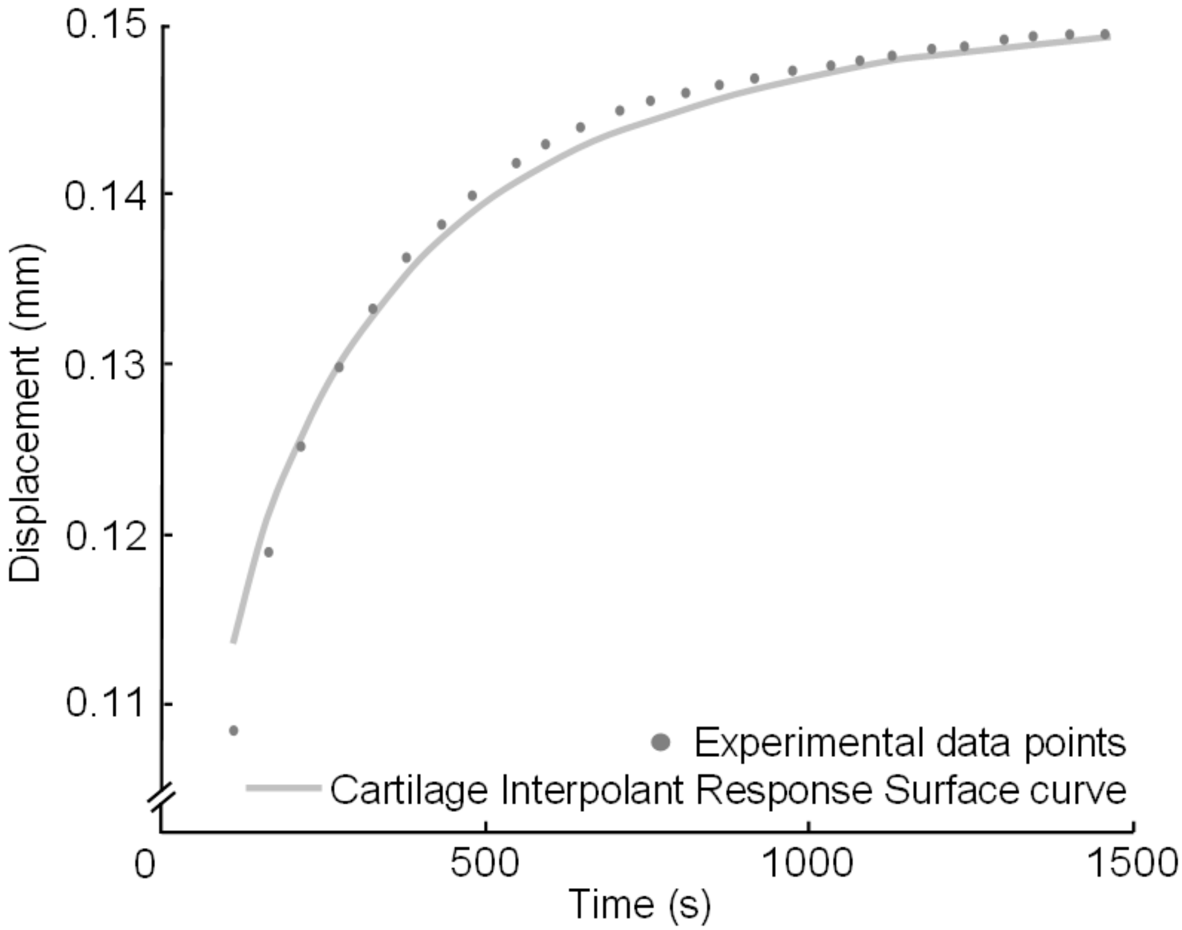

Fig. 8: Plot of Experimental and best-fit Cartilage Interpolant Response Curves for a creep test (the final 30% of the deformation).

User Instructions:

MATLAB is required to use the CIRS.

1. Create a folder (hereafter the Folder) which will contain the appropriate *.mat and *.m files.
2. On the webpage, find the experimental test set-up which was used to obtain your data. Download the corresponding *.mat file which contains the CIRS, the appropriate time vector and the given key files. Place this *.mat file in the Folder.
3. From the webpage download the compare_MSR.m (or compare_MSR_friciton.m) file. Place this file in the Folder.
4. Place the experimental data to be compared in the Folder.
    a. **The experimental data needs to be in a two column format as a *.dat file.** The first column is the time and the second column is the experimentally measured result. In the case of a creep test the experimental result is the displacement. In a stress relaxation test, the experimental result is the reaction force.
    b. **Be sure to examine your raw data graphically before using VA-Squish.** If your experimental result does not look like either a classic creep (Fig. 3) or stress relaxation (Fig. 4) result, please do not use VA-Squish.
    c. The experimental data should begin at zero time and zero experimentally measured result. **The experimental data file should end with the end of the creep phase or relaxation portion of the data** (typically defined by minimal changes in the response curve slope, see Figs. 3 and 4).
5. Follow the instructions given in the compare_MSR.m file. There are two user defined parameters in this file specific to each experimental data trial. The program will prompt the user to enter these parameters. The user does not need to enter any values directly into the compare_MSR.m file.
    a. The name of the experimental data set (expFilename). As the code runs, the program will ask the user to select the appropriate experimental data file.
    b. The specimen thickness, in millimeters, should be entered for the value of the parameter specimenThickness. This is the specimen thickness corresponding to the experimental data file selected.
6. After the experimental file is selected, the minimum squared residual search takes less than 2 seconds on a PC with 512MB of RAM. The compare_MSR.m file will create a new figure window and plot of the experimental data. In the MATLAB command window, the values of the best fit biphasic constants and the minimum of the residuals computed will be printed.

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Example 1:
        Results for filename.dat:

        Values of
          H_a (MPa) : 3.750000e-001
          nu :    0
          K (m^4/Ns) : 1.800000e-015

        Min Squared Residual (mm^2): 1.118e-004
```

In this example, the minimum squared residual is $1.118E^{-4}$ mm^2. The aggregate modulus is 0.375MPa; Poisson's ratio is 0.0; Permeability is $1.8E^{-15}$ m^4/Ns.

Compare_MSR_friction.m Details:

The code alters five additional parameters based on those defined by the user.

1. In the case of the creep test: the start of the final 30% of deformation(thirtyPercentStartRow) is determined from the final value given of the experimental result (dataEndRow). This value is obtained by multiplying the final result value by 0.7. That intermediate value is compared to the result vector to determine the index of the value closest, and not less than, the intermediate value. expR30 and expT30 are vectors which contain all the experimental result data points and time points respectively for the last 30% of the total deformation.
2. The experimental end of time (endTimeIndex). If the experimental data does not last the same length as the experiment specific timeVector (the time points used for interpolation of the CIRS and experimental datasets), then this value will be the index closest, and not greater than, the actual end of time. If the experimental data is the same length as the experiment specific timeVector, then this parameter, endTimeIndex, will equal the size of the timeVector. The timeVector is included in the *.mat file.
3. In the case of the creep test: the index of timeVector of the start of the final 30% of the deformation. Determines the time at which the last 30% of the displacement initiates. begin30 is an index of the timeVector (the time points used for interpolation of the CIRS and experimental datasets) which is closest, and not less than, the time at which the last 30% of the displacement initiates.
4. The thickness of the cartilage specimen (thicknessIndex) determined from experimental results and the user defined specimenThickness. The thicknessIndex is determined using the range of thicknesses contained in the *.mat file. The code rounds the specimen thickness to the nearest tenth of a millimeter.

References:

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3. Levenston ME, Frank EH, Grodzinsky AJ, 1998. Variationally derived 3-field finite element formulations for quasistatic poroelastic analysis of hydrated biological tissues. Computational Methods in Applied Mechanics and Engineering 156: 231-46.
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5. Roemhildt ML, Coughlin KM, Peura GD, Fleming BC, Beynnon BD, 2006. Material properties of articular cartilage in the rabbit tibial plateau. Journal of Biomechanics 39(12):2331-7.
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7. Warner MD, Taylor WR, Clift SE, 2001. Finite element biphasic indentation of cartilage: a comparison of physiological and experimental indenter geometries. Proc I Mech E Part HJ Eng Med, 215:487-96.