Chapter 1

Demo problem: Buckling of a clamped cylindrical shell under pressure loading

In this document, we discuss the solution of the buckling of a cylindrical shell using `oomph-lib's` Kirchhoff↵
LoveShell elements.

[No documentation yet: Here's the driver code.]

```
//LIC// ====================================================================
//LIC// This file forms part of oomph-lib, the object-oriented,
//LIC// multi-physics finite-element library, available
//LIC// at http://www.oomph-lib.org.
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//LIC//
//LIC//====================================================================
//Driver function for a simple test shell problem:
//Calculate the deformation of an elastic tube approximated
//using Kirchhoff--Love shell theory
//Standard system includes
#include <iostream>
#include <fstream>
#include <cmath>
#include <typeinfo>
#include <algorithm>
#include <cstdio>
//Include files from the finite-element library
#include "generic.h"
#include "shell.h"
#include "meshes/rectangular_quadmesh.h"
using namespace std;
using namespace oomph;
//========================================================================
/// Global variables that represent physical properties
//========================================================================
namespace Global_Physical_Variables
{

 /// Prescribed position of control point
 double Prescribed_y = 1.0;

 ///  Pointer to pressure load (stored in Data so it can
 /// become an unknown in the problem when displacement control is used
```

```
 Data* Pext_data_pt;

 /// Perturbation pressure
 double Pcos=1.0;

 ///  Return a reference to the external pressure
 /// load on the elastic tube.
 double external_pressure()
  {return (*Pext_data_pt->value_pt(0))*pow(0.05,3)/12.0;}

 /// Load function, normal pressure loading
 void press_load(const Vector<double> &xi,
                 const Vector<double> &x,
                 const Vector<double> &N,
                 Vector<double>& load)
 {
  //std::cout « N[0] « " " « N[1] « " " « N[2] « std::endl;
  //std::cout « xi[0] « " " « xi[1] « std::endl;
  for(unsigned i=0;i<3;i++)
   {
    load[i] = (external_pressure() -
               Pcos*pow(0.05,3)/12.0*cos(2.0*xi[1]))*N[i];
   }
 }
}
//=========================================================================
/// A 2D Mesh class. The tube wall is represented by two Lagrangian
/// coordinates that correspond to z and theta in cylindrical polars.
/// The required mesh is therefore a  2D mesh and is therefore inherited
/// from the generic RectangularQuadMesh
//========================================================================
template <class ELEMENT>
class ShellMesh : public virtual RectangularQuadMesh<ELEMENT>,
                  public virtual SolidMesh
{
public:

 ///Constructor for the mesh
 ShellMesh(const unsigned &nx, const unsigned &ny,
           const double &lx, const double &ly);

 ///  In all elastic problems, the nodes must be assigned an undeformed,
 /// or reference, position, corresponding to the stress-free state
 /// of the elastic body. This function assigns the undeformed position
 /// for the nodes on the elastic tube
 void assign_undeformed_positions(GeomObject* const &undeformed_midplane_pt);
};
//========================================================================
/// Mesh constructor
/// Argument list:
/// nx  : number of elements in the axial direction
/// ny : number of elements in the azimuthal direction
/// lx  : length in the axial direction
/// ly  : length in theta direction
//========================================================================
template <class ELEMENT>
ShellMesh<ELEMENT>::ShellMesh(const unsigned &nx,
                              const unsigned &ny,
                              const double &lx,
                              const double &ly) :
 RectangularQuadMesh<ELEMENT>(nx,ny,lx,ly)
{
 //Find out how many nodes there are
 unsigned n_node = nnode();

 //Now in this case it is the Lagrangian coordinates that we want to set,
 //so we have to loop over all nodes and set them to the Eulerian
 //coordinates that are set by the generic mesh generator
 for(unsigned i=0;i<n_node;i++)
  {
   node_pt(i)->xi(0) = node_pt(i)->x(0);
   node_pt(i)->xi(1) = node_pt(i)->x(1);
  }

 //Assign gradients, etc for the Lagrangian coordinates of
 //hermite-type elements

 //Read out number of position dofs
 unsigned n_position_type = finite_element_pt(0)->nnodal_position_type();
 //If this is greater than 1 set the slopes, which are the distances between
 //nodes. If the spacing were non-uniform, this part would be more difficult
 if(n_position_type > 1)
  {
   double xstep = (this->Xmax - this->Xmin)/((this->Np-1)*this->Nx);
   double ystep = (this->Ymax - this->Ymin)/((this->Np-1)*this->Ny);
   for(unsigned n=0;n<n_node;n++)
    {
```

```
      //The factor 0.5 is because our reference element has length 2.0
      node_pt(n)->xi_gen(1,0) = 0.5*xstep;
      node_pt(n)->xi_gen(2,1) = 0.5*ystep;
     }
   }
}
//=======================================================================
/// Set the undeformed coordinates of the nodes
//=======================================================================
template <class ELEMENT>
void ShellMesh<ELEMENT>::assign_undeformed_positions(
 GeomObject* const &undeformed_midplane_pt)
{
 //Find out how many nodes there are
 unsigned n_node = nnode();
 //Loop over all the nodes
 for(unsigned n=0;n<n_node;n++)
  {
   //Get the Lagrangian coordinates
   Vector<double> xi(2);
   xi[0] = node_pt(n)->xi(0);
   xi[1] = node_pt(n)->xi(1);

   //Assign memory for values of derivatives, etc
   Vector<double> R(3);
   DenseMatrix<double> a(2,3);
   RankThreeTensor<double>  dadxi(2,2,3);

   //Get the geometrical information from the geometric object
   undeformed_midplane_pt->d2position(xi,R,a,dadxi);

   //Loop over coordinate directions
   for(unsigned i=0;i<3;i++)
    {
     //Set the position
     node_pt(n)->x_gen(0,i) = R[i];
     //Set the derivative wrt Lagrangian coordinates
     //Note that we need to scale by the length of each element here!!
     node_pt(n)->x_gen(1,i) = 0.5*a(0,i)*((this->Xmax - this->Xmin)/this->Nx);
     node_pt(n)->x_gen(2,i) = 0.5*a(1,i)*((this->Ymax - this->Ymin)/this->Ny);
     //Set the mixed derivative
     //(symmetric so doesn't matter which one we use)
     node_pt(n)->x_gen(3,i) = 0.25*dadxi(0,1,i);
    }
  }
}
//======================================================================
//Problem class to solve the deformation of an elastic tube
//=====================================================================
template<class ELEMENT>
class ShellProblem : public Problem
{
public:

 /// Constructor
 ShellProblem(const unsigned &nx, const unsigned &ny,
              const double &lx, const double &ly);

 /// Overload Access function for the mesh
 ShellMesh<ELEMENT>* mesh_pt()
  {return dynamic_cast<ShellMesh<ELEMENT>*>(Problem::mesh_pt());}

 /// Actions after solve empty
 void actions_after_newton_solve() {}

 /// Actions before solve empty
 void actions_before_newton_solve() {}

 //A self_test function
 void solve();
private:

 /// Pointer to GeomObject that specifies the undeformed midplane
 GeomObject* Undeformed_midplane_pt;

 /// First trace node
 Node* Trace_node_pt;

 /// Second trace node
 Node* Trace_node2_pt;
};
//======================================================================
/// Constructor
//======================================================================
template<class ELEMENT>
ShellProblem<ELEMENT>::ShellProblem(const unsigned &nx, const unsigned &ny,
                                    const double &lx, const double &ly)
```

```
{
 //Create the undeformed midplane object
 Undeformed_midplane_pt = new EllipticalTube(1.0,1.0);
 //Now create the mesh
 Problem::mesh_pt() = new ShellMesh<ELEMENT>(nx,ny,lx,ly);
 //Set the undeformed positions in the mesh
 mesh_pt()->assign_undeformed_positions(Undeformed_midplane_pt);
 //Reorder the elements, since I know what's best for them....
 mesh_pt()->element_reorder();
 //Apply boundary conditions to the ends of the tube
 unsigned n_ends = mesh_pt()->nboundary_node(1);
 //Loop over the node
 for(unsigned i=0;i<n_ends;i++)
  {
   //Pin in the axial direction (prevents rigid body motions)
   mesh_pt()->boundary_node_pt(1,i)->pin_position(2);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(2);
   //Derived conditions
   mesh_pt()->boundary_node_pt(1,i)->pin_position(2,2);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(2,2);
   //------------------CLAMPING CONDITIONS----------------------
   //------Pin positions in the transverse directions-----------
   // Comment these out to get the ring case
   mesh_pt()->boundary_node_pt(1,i)->pin_position(0);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(0);
   //Derived conditions
   mesh_pt()->boundary_node_pt(1,i)->pin_position(2,0);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(2,0);
   mesh_pt()->boundary_node_pt(1,i)->pin_position(1);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(1);
   //Derived conditions
   mesh_pt()->boundary_node_pt(1,i)->pin_position(2,1);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(2,1);
   //----------------------------------------------------------
   // Set the axial gradients of the transverse coordinates to be
   // zero --- need to be enforced for ring or tube buckling
   //Pin dx/dz and dy/dz
   mesh_pt()->boundary_node_pt(1,i)->pin_position(1,0);
   mesh_pt()->boundary_node_pt(1,i)->pin_position(1,1);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(1,0);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(1,1);
   //Derived conditions
   mesh_pt()->boundary_node_pt(1,i)->pin_position(3,0);
   mesh_pt()->boundary_node_pt(1,i)->pin_position(3,1);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(3,0);
   mesh_pt()->boundary_node_pt(3,i)->pin_position(3,1);
 }
 //Now loop over the sides and apply symmetry conditions
 unsigned n_side = mesh_pt()->nboundary_node(0);
 for(unsigned i=0;i<n_side;i++)
  {
   //At the side where theta is 0, pin in the y direction
   mesh_pt()->boundary_node_pt(0,i)->pin_position(1);
   //Derived condition
   mesh_pt()->boundary_node_pt(0,i)->pin_position(1,1);
   //Pin dx/dtheta and dz/dtheta
   mesh_pt()->boundary_node_pt(0,i)->pin_position(2,0);
   mesh_pt()->boundary_node_pt(0,i)->pin_position(2,2);
   //Pin the mixed derivative
   mesh_pt()->boundary_node_pt(0,i)->pin_position(3,0);
   mesh_pt()->boundary_node_pt(0,i)->pin_position(3,2);
   //At the side when theta is 0.5pi  pin in the x direction
   mesh_pt()->boundary_node_pt(2,i)->pin_position(0);
   //Derived condition
   mesh_pt()->boundary_node_pt(2,i)->pin_position(1,0);
   //Pin dy/dtheta and dz/dtheta
   mesh_pt()->boundary_node_pt(2,i)->pin_position(2,1);
   mesh_pt()->boundary_node_pt(2,i)->pin_position(2,2);
   //Pin the mixed derivative
   mesh_pt()->boundary_node_pt(2,i)->pin_position(3,1);
   mesh_pt()->boundary_node_pt(2,i)->pin_position(3,2);
//    //Set an initial kick to make sure that we hop onto the
//    //non-axisymmetric branch
//    if((i>1) && (i<n_side-1))
//     {
//      mesh_pt()->boundary_node_pt(0,i)->x(0) += 0.05;
//      mesh_pt()->boundary_node_pt(2,i)->x(1) -= 0.1;
//     }
  }
 // Setup displacement control
 //--------------------------
//  //Setup displacement control
//  //Fix the displacement at the mid-point of the tube in the "vertical"
//  //(y) direction.
//  //Set the displacement control element (located halfway along the tube)
// Disp_ctl_element_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(3*Ny-1));
//  //The midpoint of the tube is located exactly half-way along the element
```

```
//  Vector<double> s(2);  s[0] = 1.0; s[1] = 0.0; //s[1] = 0.5
//  //Fix the displacement at this point in the y (1) direction
//  Disp_ctl_element_pt->fix_displacement_for_displacement_control(s,1);
//  //Set the pointer to the prescribed position
//  Disp_ctl_element_pt->prescribed_position_pt() = &Prescribed_y;

 // Choose element in which displacement control is applied: This
 // one is located about halfway along the tube -- remember that
 // we've renumbered the elements!
 unsigned nel_ctrl=0;
 Vector<double> s_displ_control(2);
 // Even/odd number of elements in axial direction
 if (nx%2==1)
  {
   nel_ctrl=unsigned(floor(0.5*double(nx))+1.0)*ny-1;
   s_displ_control[0]=0.0;
   s_displ_control[1]=1.0;
  }
 else
  {
   nel_ctrl=unsigned(floor(0.5*double(nx))+1.0)*ny-1;
   s_displ_control[0]=-1.0;
   s_displ_control[1]=1.0;
  }
 // Controlled element
 SolidFiniteElement* controlled_element_pt=
  dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(nel_ctrl));

 // Fix the displacement in the y (1) direction...
 unsigned controlled_direction=1;
 // Pointer to displacement control element
 DisplacementControlElement* displ_control_el_pt;

 // Build displacement control element
 displ_control_el_pt=
  new DisplacementControlElement(controlled_element_pt,
                                 s_displ_control,
                                 controlled_direction,
                                 &Global_Physical_Variables::Prescribed_y);

 // Doc control point
 Vector<double> xi(2);
 Vector<double> x(3);
 controlled_element_pt->interpolated_xi(s_displ_control,xi);
 controlled_element_pt->interpolated_x(s_displ_control,x);
 std::cout « std::endl;
 std::cout « "Controlled element: " « nel_ctrl « std::endl;
 std::cout « "Displacement control applied at xi = ("
           « xi[0] « ", " « xi[1] « ")" « std::endl;
 std::cout « "Corresponding to                x  = ("
           « x[0] « ", " « x[1] « ", " « x[2] « ")" « std::endl;
 // The constructor of the  DisplacementControlElement has created
 // a new Data object whose one-and-only value contains the
 // adjustable load: Use this Data object in the load function:
 Global_Physical_Variables::Pext_data_pt=displ_control_el_pt->
  displacement_control_load_pt();

 // Add the displacement-control element to the mesh
 mesh_pt()->add_element_pt(displ_control_el_pt);

 // Complete build of shell elements
 //---------------------------------
 //Find number of shell elements in mesh
 unsigned n_element = nx*ny;
 //Explicit pointer to first element in the mesh
 ELEMENT* first_el_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(0));

 //Loop over the elements
 for(unsigned e=0;e<n_element;e++)
  {
   //Cast to a shell element
   ELEMENT *el_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(e));
   //Set the load function
   el_pt->load_vector_fct_pt() = & Global_Physical_Variables::press_load;
   //Set the undeformed surface
   el_pt->undeformed_midplane_pt() = Undeformed_midplane_pt;
   //The external pressure is external data for all elements
   el_pt->add_external_data(Global_Physical_Variables::Pext_data_pt);

   //Pre-compute the second derivatives wrt Lagrangian coordinates
   //for the first element only
   if(e==0)
    {
     el_pt->pre_compute_d2shape_lagrangian_at_knots();
    }
   //Otherwise set the values to be the same as those in the first element
   //this is OK because the Lagrangian mesh is uniform.
```

```
   else
    {
     el_pt->set_dshape_lagrangian_stored_from_element(first_el_pt);
    }
  }
 //Set pointers to two trace nodes, used for output
 Trace_node_pt = mesh_pt()->finite_element_pt(2*ny-1)->node_pt(3);
 Trace_node2_pt = mesh_pt()->finite_element_pt(ny)->node_pt(1);
 // Do equation numbering
 cout « std::endl;
 cout « "# of dofs " « assign_eqn_numbers() « std::endl;
 cout « std::endl;
}
//=================================================================
// /Define the solve function, disp ctl and then continuation
//=================================================================
template<class ELEMENT>
void ShellProblem<ELEMENT>::solve()
{
 //Increase the maximum number of Newton iterations.
 //Finding the first buckled solution requires a large(ish) number
 //of Newton steps -- shells are just a bit twitchy
 Max_newton_iterations = 40;
 Max_residuals=1.0e6;

 //Open an output trace file
 ofstream trace("trace.dat");
 //Gradually compress the tube by decreasing the value of the prescribed
 //position
 for(unsigned i=1;i<11;i++)
  {
   Global_Physical_Variables::Prescribed_y -= 0.05;
   cout « std::endl « "Increasing displacement: Prescribed_y is "
        « Global_Physical_Variables::Prescribed_y « std::endl;
   // Solve
   newton_solve();

   //Output the pressure (on the bending scale)
   trace « Global_Physical_Variables::external_pressure()/(pow(0.05,3)/12.0)
         « " "
         //Position of first trace node
         « Trace_node_pt->x(0) « " " « Trace_node_pt->x(1) « " "
          //Position of second trace node
         « Trace_node2_pt->x(0) « " " « Trace_node2_pt->x(1) « std::endl;
   // Reset perturbation
   Global_Physical_Variables::Pcos=0.0;
  }
 //Close the trace file
 trace.close();

 //Output the tube shape in the most strongly collapsed configuration
 ofstream file("final_shape.dat");
 mesh_pt()->output(file,5);
 file.close();
}
//=====================================================================
/// Driver
//=====================================================================
int main()
{
 //Length of domain
 double L = 10.0;
 double L_phi=0.5*MathematicalConstants::Pi;
 //Set up the problem
 ShellProblem<StorableShapeSolidElement<DiagHermiteShellElement> >
  problem(5,3,L,L_phi);
 //Solve the problem
 problem.solve();
}
```

1.1 PDF file

A pdf version of this document is available.