

Chapter 1

Demo problem: Large-amplitude shock-wave propagation in a circular disk

Detailed documentation to be written. Here's the already fairly well documented 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 for large-displacement elasto-dynamic test problem:
// Circular disk impulsively loaded by compressive load.

#include <iostream>
#include <fstream>
#include <cmath>

//My own includes
#include "generic.h"
#include "solid.h"

//Need to instantiate templated mesh
#include "meshes/quarter_circle_sector_mesh.h"

using namespace std;

using namespace oomph;

/// //////////////////////////////////////
/// //////////////////////////////////////
/// //////////////////////////////////////

//=====
/// Global variables
//=====
namespace Global_Physical_Variables
{
    /// Pointer to constitutive law
    ConstitutiveLaw* Constitutive_law_pt;
```

```

/// Elastic modulus
double E=1.0;

/// Poisson's ratio
double Nu=0.3;

/// Uniform pressure
double P = 0.00;

/// Constant pressure load
void constant_pressure(const Vector<double> &xi,const Vector<double> &x,
                      const Vector<double> &n, Vector<double> &traction)
{
    unsigned dim = traction.size();
    for(unsigned i=0;i<dim;i++)
    {
        traction[i] = -P*n[i];
    }
}

}

/// //////////////////////////////////////
/// //////////////////////////////////////
/// //////////////////////////////////////

//=====
/// Elastic quarter circle sector mesh with functionality to
/// attach traction elements to the curved surface. We "upgrade"
/// the RefineableQuarterCircleSectorMesh to become an
/// SolidMesh and equate the Eulerian and Lagrangian coordinates,
/// thus making the domain represented by the mesh the stress-free
/// configuration.
/// \n\n
/// The member function \c make_traction_element_mesh() creates
/// a separate mesh of SolidTractionElements that are attached to the
/// mesh's curved boundary (boundary 1).
//=====
template <class ELEMENT>
class ElasticRefineableQuarterCircleSectorMesh :
public virtual RefineableQuarterCircleSectorMesh<ELEMENT>,
public virtual SolidMesh
{

public:

    /// Constructor: Build mesh and copy Eulerian coords to Lagrangian
    /// ones so that the initial configuration is the stress-free one.
    ElasticRefineableQuarterCircleSectorMesh<ELEMENT>(GeomObject* wall_pt,
                                                    const double& xi_lo,
                                                    const double& fract_mid,
                                                    const double& xi_hi,
                                                    TimeStepper* time_stepper_pt=
                                                    &Mesh::Default_TimeStepper) :
    RefineableQuarterCircleSectorMesh<ELEMENT>(wall_pt,xi_lo,fract_mid,xi_hi,
                                              time_stepper_pt)
    {
#ifdef PARANOID
        /// Check that the element type is derived from the SolidFiniteElement
        SolidFiniteElement* el_pt=dynamic_cast<SolidFiniteElement*>
        (finite_element_pt(0));
        if (el_pt==0)
        {
            throw OomphLibError(
                "Element needs to be derived from SolidFiniteElement\n",
                OOMPH_CURRENT_FUNCTION,
                OOMPH_EXCEPTION_LOCATION);
        }
#endif
        // Make the current configuration the undeformed one by
        // setting the nodal Lagrangian coordinates to their current
        // Eulerian ones
        set_lagrangian_nodal_coordinates();
    }

    /// Function to create mesh made of traction elements
    void make_traction_element_mesh(SolidMesh*& traction_mesh_pt)
    {
        // Make new mesh

```

```

traction_mesh_pt=new SolidMesh;

// Loop over all elements on boundary 1:
unsigned b=1;
unsigned n_element = this->nboundary_element(b);
for (unsigned e=0;e<n_element;e++)
{
    // The element itself:
    FiniteElement* fe_pt = this->boundary_element_pt(b,e);

    // Find the index of the face of element e along boundary b
    int face_index = this->face_index_at_boundary(b,e);

    // Create new element
    traction_mesh_pt->add_element_pt(new SolidTractionElement<ELEMENT>
                                     (fe_pt,face_index));
}
}

/// Function to wipe and re-create mesh made of traction elements
void remake_traction_element_mesh(SolidMesh*& traction_mesh_pt)
{
    // Wipe existing mesh (but don't call it's destructor as this
    // would wipe all the nodes too!)
    traction_mesh_pt->flush_element_and_node_storage();

    // Loop over all elements on boundary 1:
    unsigned b=1;
    unsigned n_element = this->nboundary_element(b);
    for (unsigned e=0;e<n_element;e++)
    {
        // The element itself:
        FiniteElement* fe_pt = this->boundary_element_pt(b,e);

        // Find the index of the face of element e along boundary b
        int face_index = this->face_index_at_boundary(b,e);

        // Create new element
        traction_mesh_pt->add_element_pt(new SolidTractionElement<ELEMENT>
                                         (fe_pt,face_index));
    }
}

};

/// //////////////////////////////////////
/// //////////////////////////////////////
/// //////////////////////////////////////

//=====
/// "Shock" wave propagates through an impulsively loaded
/// circular disk.
//=====
template<class ELEMENT, class TIMESTEPPER>
class DiskShockWaveProblem : public Problem
{
public:

    /// Constructor:
    DiskShockWaveProblem();

    /// Run the problem; specify case_number to label output
    /// directory
    void run(const unsigned& case_number);

    /// Access function for the solid mesh
    ElasticRefineableQuarterCircleSectorMesh<ELEMENT>*& solid_mesh_pt()
    {
        return Solid_mesh_pt;
    }

    /// Access function for the mesh of surface traction elements
    SolidMesh*& traction_mesh_pt()
    {
        return Traction_mesh_pt;
    }
}

```

```

/// Doc the solution
void doc_solution();

/// Update function (empty)
void actions_after_newton_solve() {}

/// Update function (empty)
void actions_before_newton_solve() {}

/// Actions after adaption: Kill and then re-build the traction
/// elements on boundary 1 and re-assign the equation numbers
void actions_after_adapt();

/// Doc displacement and velocity: label file with before and after
void doc_displ_and_veloc(const int& stage=0);

/// Dump problem-specific parameters values, then dump
/// generic problem data.
void dump_it(ofstream& dump_file);

/// Read problem-specific parameter values, then recover
/// generic problem data.
void restart(ifstream& restart_file);

private:

// Output
DocInfo Doc_info;

/// Trace file
ofstream Trace_file;

/// Vector of pointers to nodes whose position we're tracing
Vector<Node*> Trace_node_pt;

/// Pointer to solid mesh
ElasticRefineableQuarterCircleSectorMesh<ELEMENT*> Solid_mesh_pt;

/// Pointer to mesh of traction elements
SolidMesh* Traction_mesh_pt;
};

//=====
/// Constructor
//=====
template<class ELEMENT, class TIMESTEPPER>
DiskShockWaveProblem<ELEMENT, TIMESTEPPER>::DiskShockWaveProblem()
{

//Allocate the timestepper
add_time_stepper_pt(new TIMESTEPPER);
// Set coordinates and radius for the circle that defines
// the outer curvilinear boundary of the domain
double x_c=0.0;
double y_c=0.0;
double r=1.0;
// Build geometric object that specifies the fish back in the
// undeformed configuration (basically a deep copy of the previous one)
GeomObject* curved_boundary_pt=new Circle(x_c,y_c,r,time_stepper_pt());

// The curved boundary of the mesh is defined by the geometric object
// What follows are the start and end coordinates on the geometric object:
double xi_lo=0.0;
double xi_hi=2.0*atan(1.0);

// Fraction along geometric object at which the radial dividing line
// is placed
double fract_mid=0.5;

//Now create the mesh
solid_mesh_pt() = new ElasticRefineableQuarterCircleSectorMesh<ELEMENT*>(
    curved_boundary_pt,xi_lo,fract_mid,xi_hi,time_stepper_pt());

// Set up trace nodes as the nodes on boundary 1 (=curved boundary) in
// the original mesh (they exist under any refinement!)
unsigned nnod0=solid_mesh_pt()->nboundary_node(0);
unsigned nnod1=solid_mesh_pt()->nboundary_node(1);
Trace_node_pt.resize(nnod0+nnod1);
for (unsigned j=0; j<nnod0; j++)
{
    Trace_node_pt[j]=solid_mesh_pt()->boundary_node_pt(0,j);
}
}

```

```

    }
    for (unsigned j=0; j<nnod1; j++)
    {
        Trace_node_pt[j+nnod0]=solid_mesh_pt()->boundary_node_pt(1,j);
    }

    // Build traction element mesh
    solid_mesh_pt()->make_traction_element_mesh(traction_mesh_pt());
    // Solid mesh is first sub-mesh
    add_sub_mesh(solid_mesh_pt());

    // Traction mesh is first sub-mesh
    add_sub_mesh(traction_mesh_pt());

    // Build combined "global" mesh
    build_global_mesh();

    // Create/set error estimator
    solid_mesh_pt()->spatial_error_estimator_pt()=new Z2ErrorEstimator;

    // Fiddle with adaptivity targets and doc
    solid_mesh_pt()->max_permitted_error()=0.006; //0.03;
    solid_mesh_pt()->min_permitted_error()=0.0006; // 0.0006; //0.003;
    solid_mesh_pt()->doc_adaptivity_targets(cout);

    // Pin the bottom in the vertical direction
    unsigned n_bottom = solid_mesh_pt()->nboundary_node(0);

    //Loop over the node
    for(unsigned i=0; i<n_bottom; i++)
    {
        solid_mesh_pt()->boundary_node_pt(0,i)->pin_position(1);
    }

    // Pin the left edge in the horizontal direction
    unsigned n_side = solid_mesh_pt()->nboundary_node(2);
    //Loop over the node
    for(unsigned i=0; i<n_side; i++)
    {
        solid_mesh_pt()->boundary_node_pt(2,i)->pin_position(0);
    }

    //Find number of elements in solid mesh
    unsigned n_element =solid_mesh_pt()->nelement();

    //Set parameters and function pointers for solid elements
    for(unsigned i=0; i<n_element; i++)
    {
        //Cast to a solid element
        ELEMENT *el_pt = dynamic_cast<ELEMENT*>(mesh_pt()->element_pt(i));

        //Set the constitutive law
        el_pt->constitutive_law_pt() =
            Global_Physical_Variables::Constitutive_law_pt;

        // Switch on inertia
        el_pt->enable_inertia();
    }

    // Pin the redundant solid pressures
    PVDEquationsBase<2>::pin_redundant_nodal_solid_pressures(
        solid_mesh_pt()->element_pt());

    //Find number of elements in traction mesh
    n_element=traction_mesh_pt()->nelement();

    //Set function pointers for traction elements
    for(unsigned i=0; i<n_element; i++)
    {
        //Cast to a solid traction element
        SolidTractionElement<ELEMENT> *el_pt =
            dynamic_cast<SolidTractionElement<ELEMENT>*>
            (traction_mesh_pt()->element_pt(i));

        //Set the traction function
        el_pt->traction_fct_pt() = Global_Physical_Variables::constant_pressure;
    }

    //Attach the boundary conditions to the mesh
    cout << assign_eqn_numbers() << std::endl;

    // Refine uniformly
    refine_uniformly();
    refine_uniformly();
    refine_uniformly();

```

```

// Now the non-pinned positions of the SolidNodes will have been
// determined by interpolation. This is appropriate for uniform
// refinements once the code is up and running since we can't place
// new SolidNodes at the positions determined by the MacroElement.
// However, here we want to update the nodes to fit the exact
// initial configuration.

// Update all solid nodes based on the Mesh's Domain/MacroElement
// representation
bool update_all_solid_nodes=true;
solid_mesh_pt()->node_update(update_all_solid_nodes);

// Now set the Eulerian equal to the Lagrangian coordinates
solid_mesh_pt()->set_lagrangian_nodal_coordinates();
}

//=====
/// Kill and then re-build the traction elements on boundary 1,
/// pin redundant pressure dofs and re-assign the equation numbers.
//=====
template<class ELEMENT, class TIMESTEPPER>
void DiskShockWaveProblem<ELEMENT,TIMESTEPPER>::actions_after_adapt()
{
    // Wipe and re-build traction element mesh
    solid_mesh_pt()->remake_traction_element_mesh(traction_mesh_pt());
    // Re-build combined "global" mesh
    rebuild_global_mesh();

    //Find number of elements in traction mesh
    unsigned n_element=traction_mesh_pt()->nelement();

    //Loop over the elements in the traction element mesh
    for(unsigned i=0;i<n_element;i++)
    {
        //Cast to a solid traction element
        SolidTractionElement<ELEMENT> *el_pt =
            dynamic_cast<SolidTractionElement<ELEMENT>>*>
            (traction_mesh_pt()->element_pt(i));

        //Set the traction function
        el_pt->traction_fct_pt() = Global_Physical_Variables::constant_pressure;
    }

    // Pin the redundant solid pressures
    PVDEquationsBase<2>::pin_redundant_nodal_solid_pressures(
        solid_mesh_pt()->element_pt());

    //Do equation numbering
    cout << assign_eqn_numbers() << std::endl;
}

//=====
/// Doc the solution
//=====
template<class ELEMENT, class TIMESTEPPER>
void DiskShockWaveProblem<ELEMENT,TIMESTEPPER>::doc_solution()
{
    // Number of plot points
    unsigned npts;
    npts=5;

    // Output shape of deformed body
    ofstream some_file;
    char filename[100];
    sprintf(filename,"%s/soln%i.dat",Doc_info.directory().c_str(),
        Doc_info.number());
    some_file.open(filename);
    solid_mesh_pt()->output(some_file,npts);
    some_file.close();

    // Output traction
    unsigned nel=traction_mesh_pt()->nelement();
    sprintf(filename,"%s/traction%i.dat",Doc_info.directory().c_str(),
        Doc_info.number());
    some_file.open(filename);
    Vector<double> unit_normal(2);

```

```

Vector<double> traction(2);
Vector<double> x_dummy(2);
Vector<double> s_dummy(1);
for (unsigned e=0;e<nrel;e++)
{
    some_file << "ZONE " << std::endl;
    for (unsigned i=0;i<npts;i++)
    {
        s_dummy[0]=-1.0+2.0*double(i)/double(npts-1);
        SolidTractionElement<ELEMENT>* el_pt=
            dynamic_cast<SolidTractionElement<ELEMENT>*>(
                traction_mesh_pt()->finite_element_pt(e));
        el_pt->outer_unit_normal(s_dummy,unit_normal);
        el_pt->traction(s_dummy,traction);
        el_pt->interpolated_x(s_dummy,x_dummy);
        some_file << x_dummy[0] << " " << x_dummy[1] << " "
            << traction[0] << " " << traction[1] << " "
            << std::endl;
    }
}
some_file.close();

// Doc displacement and velocity
doc_displ_and_veloc();

// Get displacement as a function of the radial coordinate
// along boundary 0
{
    // Number of elements along boundary 0:
    unsigned nelem=solid_mesh_pt()->nboundary_element(0);

    // Open files
    sprintf(filename,"%s/displ%i.dat",Doc_info.directory().c_str(),
        Doc_info.number());
    some_file.open(filename);

    Vector<double> s(2);
    Vector<double> x(2);
    Vector<double> dxdt(2);
    Vector<double> xi(2);
    Vector<double> r_exact(2);
    Vector<double> v_exact(2);

    for (unsigned e=0;e<nelem;e++)
    {
        some_file << "ZONE " << std::endl;
        for (unsigned i=0;i<npts;i++)
        {
            // Move along bottom edge of element
            s[0]=-1.0+2.0*double(i)/double(npts-1);
            s[1]=-1.0;

            // Get pointer to element
            SolidFiniteElement* el_pt=dynamic_cast<SolidFiniteElement*>
                (solid_mesh_pt()->boundary_element_pt(0,e));

            // Get Lagrangian coordinate
            el_pt->interpolated_xi(s,xi);

            // Get Eulerian coordinate
            el_pt->interpolated_x(s,x);

            // Get velocity
            el_pt->interpolated_dxdt(s,1,dxdt);

            // Plot radial distance and displacement
            some_file << xi[0] << " " << x[0]-xi[0] << " "
                << dxdt[0] << std::endl;
        }
    }
    some_file.close();
}

// Write trace file
Trace_file << time_pt()->time() << " ";
unsigned ntrace_node=Trace_node_pt.size();
for (unsigned j=0;j<ntrace_node;j++)
{
    Trace_file << sqrt(pow(Trace_node_pt[j]->x(0),2)+
        pow(Trace_node_pt[j]->x(1),2)) << " ";
}
Trace_file << std::endl;

// removed until Jacobi eigensolver is re-instated

```

```

// // Output principal stress vectors at the centre of all elements
// SolidHelpers::doc_2D_principal_stress<ELEMENT>(Doc_info,solid_mesh_pt());

// // Write restart file
// sprintf(filename,"%s/restart%i.dat",Doc_info.directory().c_str(),
//         Doc_info.number());
// some_file.open(filename);
// dump_it(some_file);
// some_file.close();

cout << "Doced solution for step "
      << Doc_info.number()
      << std::endl << std::endl << std::endl;
}

//=====
/// Doc displacement and veloc in displ_and_veloc*.dat.
/// The int stage defaults to 0, in which case the '*' in the
/// filename is simply the step number specified by the Problem's
/// DocInfo object. If it's +/-1, the word "before" and "after"
/// get inserted. This allows checking of the veloc/displacement
/// interpolation during adaptive mesh refinement.
//=====
template<class ELEMENT, class TIMESTEPPER>
void DiskShockWaveProblem<ELEMENT,TIMESTEPPER>::doc_displ_and_veloc(
    const int& stage)
{
    ofstream some_file;
    char filename[100];

    // Number of plot points
    unsigned npts;
    npts=5;

    // Open file
    if (stage== -1)
    {
        sprintf(filename,"%s/displ_and_veloc_before%i.dat",
            Doc_info.directory().c_str(),Doc_info.number());
    }
    else if (stage==1)
    {
        sprintf(filename,"%s/displ_and_veloc_after%i.dat",
            Doc_info.directory().c_str(),Doc_info.number());
    }
    else
    {
        sprintf(filename,"%s/displ_and_veloc%i.dat",
            Doc_info.directory().c_str(),Doc_info.number());
    }
    some_file.open(filename);

    Vector<double> s(2),x(2),dxdt(2),xi(2),displ(2);

    //Loop over solid elements
    unsigned nel=solid_mesh_pt()->nelement();
    for (unsigned e=0;e<nel;e++)
    {
        some_file << "ZONE I=" << npts << ", J=" << npts << std::endl;
        for (unsigned i=0;i<npts;i++)
        {
            s[0]=-1.0+2.0*double(i)/double(npts-1);
            for (unsigned j=0;j<npts;j++)
            {
                s[1]=-1.0+2.0*double(j)/double(npts-1);

                // Cast to full element type
                ELEMENT* el_pt=dynamic_cast<ELEMENT*>(solid_mesh_pt()->
                    finite_element_pt(e));

                // Eulerian coordinate
                el_pt->interpolated_x(s,x);

                // Lagrangian coordinate
                el_pt->interpolated_xi(s,xi);

                // Displacement
                displ[0]=x[0]-xi[0];
                displ[1]=x[1]-xi[1];

                // Velocity (1st deriv)

```



```

        el_pt->interpolated_dxdt(s,1,dxdt);

        some_file << x[0] << " " << x[1] << " "
                    << displ[0] << " " << displ[1] << " "
                    << dxdt[0] << " " << dxdt[1] << " "
                    << std::endl;
    }
}
some_file.close();
}

//=====
/// Dump the solution
//=====
template<class ELEMENT, class TIMESTEPPER>
void DiskShockWaveProblem<ELEMENT,TIMESTEPPER>::dump_it(ofstream& dump_file)
{
    // Call generic dump()
    Problem::dump(dump_file);
}

//=====
/// Read solution from disk
//=====
template<class ELEMENT, class TIMESTEPPER>
void DiskShockWaveProblem<ELEMENT,TIMESTEPPER>::restart(istream& restart_file)
{
    // Read generic problem data
    Problem::read(restart_file);
}

//=====
/// Run the problem; specify case_number to label output directory
//=====
template<class ELEMENT, class TIMESTEPPER>
void DiskShockWaveProblem<ELEMENT,TIMESTEPPER>::run(
    const unsigned& case_number)
{
    // If there's a command line argument, run the validation (i.e. do only
    // 3 timesteps; otherwise do a few cycles
    unsigned nstep=400;
    if (CommandLineArgs::Argc!=1)
    {
        nstep=3;
    }

    // Define output directory
    char dirname[100];
    sprintf(dirname,"RESLT%i",case_number);
    Doc_info.set_directory(dirname);

    // Step number
    Doc_info.number()=0;

    // Open trace file
    char filename[100];
    sprintf(filename,"%s/trace.dat",Doc_info.directory().c_str());
    Trace_file.open(filename);

    // Set up trace nodes as the nodes on boundary 1 (=curved boundary) in
    // the original mesh (they exist under any refinement!)
    unsigned nnod0=solid_mesh_pt()->nboundary_node(0);
    unsigned nnod1=solid_mesh_pt()->nboundary_node(1);
    Trace_file << "VARIABLES=\"time\"";
    for (unsigned j=0;j<nnod0;j++)
    {
        Trace_file << ", \"radial node \" << j << "\" ";
    }
    for (unsigned j=0;j<nnod1;j++)
    {
        Trace_file << ", \"azimuthal node \" << j << "\" ";
    }
    Trace_file << std::endl;

    // // Restart?

```

```

// //-----

// // Pointer to restart file
// ifstream* restart_file_pt=0;

// // No restart
// //-----
// if (CommandLineArgs::Argc==1)
// {
//     cout << "No restart" << std::endl;
// }
// // Restart
// //-----
// else if (CommandLineArgs::Argc==2)
// {
//     // Open restart file
//     restart_file_pt=new ifstream(CommandLineArgs::Argv[1],ios_base::in);
//     if (restart_file_pt!=0)
//     {
//         cout << "Have opened " << CommandLineArgs::Argv[1] <<
//             " for restart." << std::endl;
//     }
//     else
//     {
//         cout << "ERROR while trying to open " << CommandLineArgs::Argv[1] <<
//             " for restart." << std::endl;
//     }
//     // Do the actual restart
//     pause("need to do the actual restart");
//     //problem.restart(*restart_file_pt);
// }
// // More than one restart file specified?
// else
// {
//     cout << "Can only specify one input file " << std::endl;
//     cout << "You specified the following command line arguments: " << std::endl;
//     CommandLineArgs::output();
//     //assert(false);
// }

// Initial parameter values
Global_Physical_Variables::P = 0.1;

// Initialise time
double time0=0.0;
time_pt()->time()=time0;

// Set initial timestep
double dt=0.01;

// Impulsive start
assign_initial_values_impulsive(dt);
// Doc initial state
doc_solution();
Doc_info.number()++;

// First step without adaptivity
unsteady_newton_solve(dt);
doc_solution();
Doc_info.number()++;

//Timestepping loop for subsequent steps with adaptivity
unsigned max_adapt=1;
for(unsigned i=1;i<nstep;i++)
{
    unsteady_newton_solve(dt,max_adapt,false);
    doc_solution();
    Doc_info.number()++;
}

}

//=====
/// Driver for simple elastic problem
//=====
int main(int argc, char* argv[])
{
    // Store command line arguments
    CommandLineArgs::setup(argc,argv);

    //Initialise physical parameters

```

```

Global_Physical_Variables::E = 1.0; // ADJUST
Global_Physical_Variables::Nu = 0.3; // ADJUST

// "Big G" Linear constitutive equations:
Global_Physical_Variables::Constitutive_law_pt =
    new GeneralisedHookean(&Global_Physical_Variables::Nu,
                          &Global_Physical_Variables::E);

//Set up the problem:
unsigned case_number=0;

// Pure displacement formulation
{
    cout << "Running case " << case_number
          << ": Pure displacement formulation" << std::endl;
    DiskShockWaveProblem<RefineableQPVDElement<2,3>, Newmark<1> > problem;
    problem.run(case_number);
    case_number++;
}

// Pressure-displacement with Crouzeix Raviart-type pressure
{
    cout << "Running case " << case_number
          << ": Pressure/displacement with Crouzeix-Raviart pressure" << std::endl;
    DiskShockWaveProblem<RefineableQPVDElementWithPressure<2>, Newmark<1> >
        problem;
    problem.run(case_number);
    case_number++;
}

// Pressure-displacement with Taylor-Hood-type pressure
{
    cout << "Running case " << case_number
          << ": Pressure/displacement with Taylor-Hood pressure" << std::endl;
    DiskShockWaveProblem<RefineableQPVDElementWithContinuousPressure<2>,
        Newmark<1> > problem;
    problem.run(case_number);
    case_number++;
}

// Clean up
delete Global_Physical_Variables::Constitutive_law_pt;
Global_Physical_Variables::Constitutive_law_pt=0;
}

```

1.1 PDF file

A [pdf version](#) of this document is available.