Technical University of Catalonia

# COMPUTATIONAL SOLID MECHANICS

## ASSIGNMENT 2

## First Part

## ONE DIMENSIONAL PLASTICITY MODELS

M.Sc. Computational Mechanics – CIMNE

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## 1. *Introduction*

This is the first part of the report for Assignment_2, the course "Computational Mechanics in Solids" which deals with ***1D Plasticity models***. The goal in this project is to implement the algorithm of constitutive model at gauss integration level in order to check the performance of 1D plastic model, so there would be no discretization of continuum model nor mesh procedure for the finite element method.

In this project, data base (Input variables) would be strains; so we have a strain driven code and along this way, backward Euler time stepping algorithm for one dimensional plasticity is implement covering both rate independent and rate dependent models. However, the code is only implemented for the rate dependent case and as a consequence of choosing zero viscosity parameter it would behave rate independent.

Different models for including hardening behaviors which are exploited in the code are introduced in ***Chart1*** and for all mentioned scenarios different numerical simulation of uniaxial cyclic plastic loading/elastic unloading examples are performed using the Matlab code which is provided and discussed in the ***Annex***.

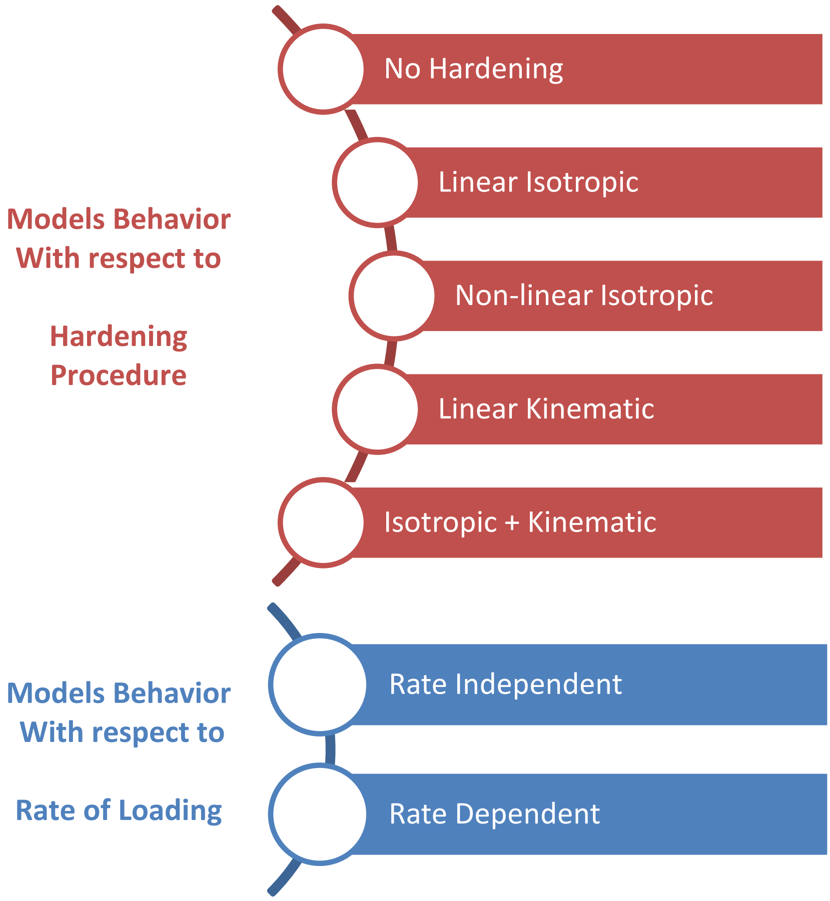


**Chart1. Plasticity Models.**

For all cases the Young modulus is taken [***E = 200,000 MPa***] and the yield stress as [***σy = 200 MPa***]. These material property values are almost in the range of *steel*.

For the cyclic loading path, two scenarios are considered in ***Table1***. One is the regular three paths loading which is the main loading scenario for ***Chapter2*** to ***Chapter6*** and captures the **Tension-Compression-Tension** behavior of material. The other one is a full 9 path cyclic loading and captures final asymptotical values for some special cases which is detailed in ***Chapter7***.

| Strain point | Loading scenario 1 | Loading scenario 1 |
|---|---|---|
| **1$^{st}$ point** | **0** | 0 |
| **2$^{nd}$ point** | **0.0025** | 0.0025 |
| **3$^{rd}$ point** | **-0.0025** | -0.0025 |
| **4$^{th}$ point** | **0.0015** | 0.0045 |
| **5$^{th}$ point** | | -0.0065 |
| **6$^{th}$ point** | | 0.0065 |
| **7$^{th}$ point** | | -0.0085 |
| **8$^{th}$ point** | | 0.0085 |
| **9$^{th}$ point** | | -0.0105 |

**Table1. Cyclic Loading Scenarios**

Based on ***Table2,*** 21 loading cases are studied In ***Chapter2*** to ***Chapter6***. In order to explain these cases, it is important to note that 5 Hardening type are considered into account and for each hardening type, 2 models of rate-independent and rate-dependent are considered. For any of which some sensitivity analysis is studied that can be checked in detail in ***Table2***.

| Hardening Type | RATE INDEPENDENT | | | RATE DEPENDENT | |
|---|---|---|---|---|---|
| | Main case | Sensitivity analysis 1 | Sensitivity analysis 2 | Sensitivity analysis 1 | Sensitivity analysis 2 |
| **Perfect Plasticity** | ***Case 1*** | | | ***Case 2*** - η | ***Case 3*** - t |
| **Linear Isotropic** | ***Case 4*** | ***Case 5*** - K | | ***Case 6*** - η | ***Case 7*** - t |
| **Nonlinear Isotropic** | ***Case 8*** | ***Case 9*** - δ | ***Case 10*** - σu | ***Case 11*** - η | ***Case 12*** - t |
| **Linear Kinematic** | ***Case 13*** | ***Case 14*** - H | | ***Case 15*** - η | ***Case 16*** - t |
| **Nonlinear Isotropic + Linear Kinematic** | ***Case 17*** | ***Case 18*** - δ | ***Case 19*** - H | ***Case 20*** - η | ***Case 21*** - t |

**Table2. Numerical simulation cases**

***Table3*** is related to different values of parameters in the sensitivity analysis done on different cases. In this table **Main** parameters are mentioned in the left column and 3 variants are introduced for each one, as well.

| | Main | Var_1 | Var_2 | Var_3 |
|---|---|---|---|---|
| **K** | 50,000 | 25,000 | 50,000 | 100,000 |
| **H** | 50,000 | 25,000 | 50,000 | 100,000 |
| **δ** | 20,000 | 5,000 | 20,000 | 80,000 |
| **σu** | 350 | 250 | 450 | 550 |
| **η** | 5,000 | 1,000 | 5,000 | 10,000 |
| **t** | 1 sec | 10 sec | 1 sec | 0.5 sec |

**Table3. Sensitivity analysis values**

In each part, first of all, the step by step curve is plotted in 3 colors, each color for one path of loading. Then the sensitivity analysis results are plotted and discussed. For the rate-dependent models, the stress-strain and the stress-time curves are going to show the influence of the viscosity parameter and the loading rate. It is evident and also experienced in all cases that the rate-independent response can be recovered from the rate-dependent results using very small values for the viscosity or high values for the loading time (low loading rate).

## 2. Perfect Plasticity

For the first case, the perfect plasticity model is considered in which all hardening parameters are set to zero. The Stress-strain curve for a rate-independent elastoplastic model with linear elastic and perfect plastic response is provided in ***Figure1***. As it is supposed the material yields exactly when it reaches the yield stress limit (200 MPa) and after this threshold it would not experience any kind of hardening. In other word, after yielding the material would experience more and more strains without any increase in bearing capacity. However, it is in theory and in fact after reaching some specific point which is the ultimate stress point the material would break. Here we can clearly observe the changes of loading direction which are shown by blue marks and see that material does not go further the yield stress (200 MPa) due to the perfect plastic nature.

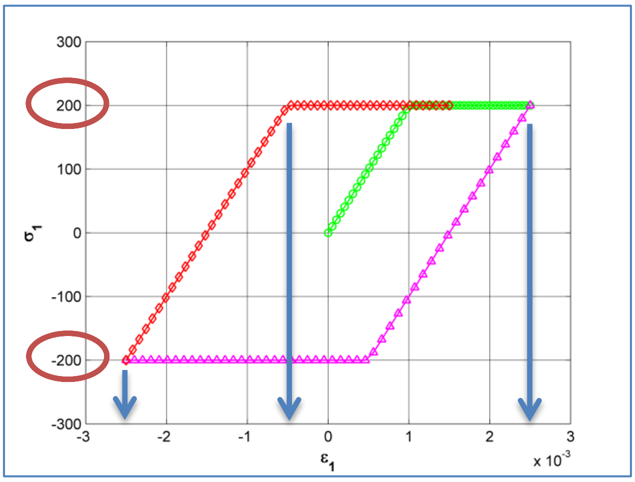


**Figure1. rate-independent perfect plasticity.**

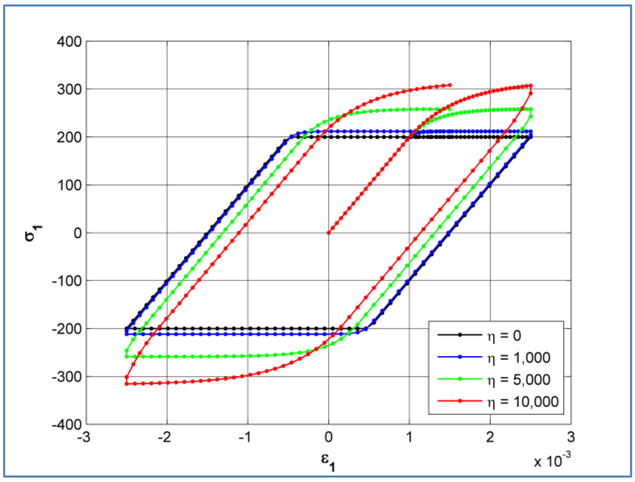


**Figure2. Effect of viscosity parameter on the bahavior of rate-dependent perfect plastic model.**

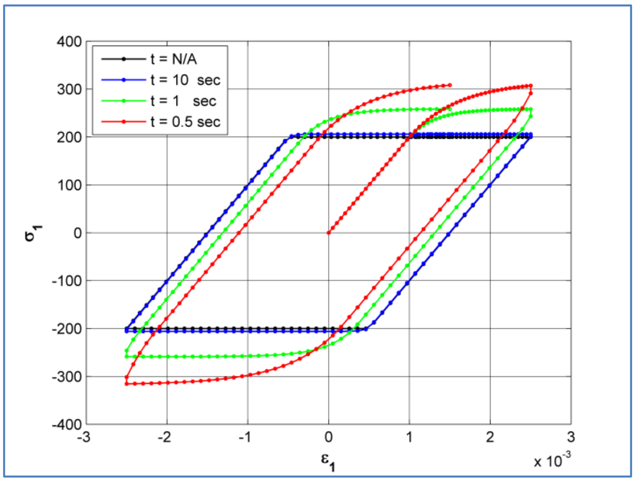


**Figure3. Effect of loading duration on the bahavior of rate-dependent perfect plastic model.**

For the rate dependent models, we can observe in **Figure2** to **Figure4** that as lower the viscosity parameter would be or as higher the duration of loading would be (blue line), the closer the results would be to the rate independent case (black line) because load is being applied gradually. As a general rule, one can interpret the behavior of rate dependency to an additional hardening added to model, but in high strain rates.

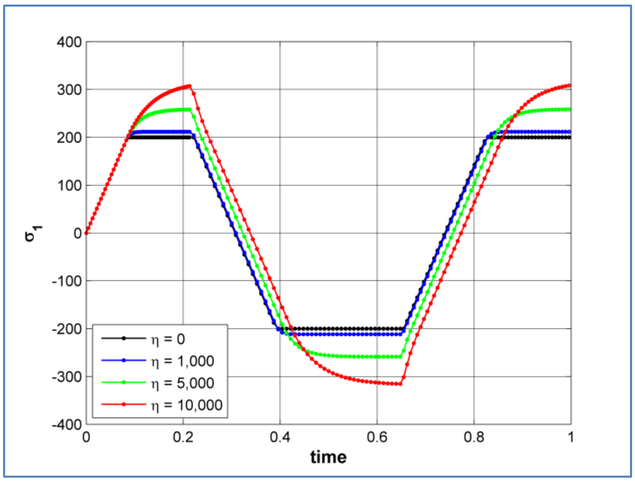


**Figure4. Effect of viscosity parameter on the bahavior of rate-dependent perfect plastic model.**

# 3. Linear Isotropic Hardening Plasticity

## 3.1. Rate Independent response

The effect of expansion in yield surface due to the isotropic hardening is clearly portrayed in ***Figure5*** in which the stress data in first blue mark (+250 = end of $1^{st}$ path) is transferred to the $2^{nd}$ path and material here yields in -250 MPa instead of -200 MPa. This increased capacity is due to the nature of this plasticity model and the same rule goes for two orange circle marks where the $3^{rd}$ path also expands and starts to yield in +350MPa instead of +200MPa, because of previous stress history.

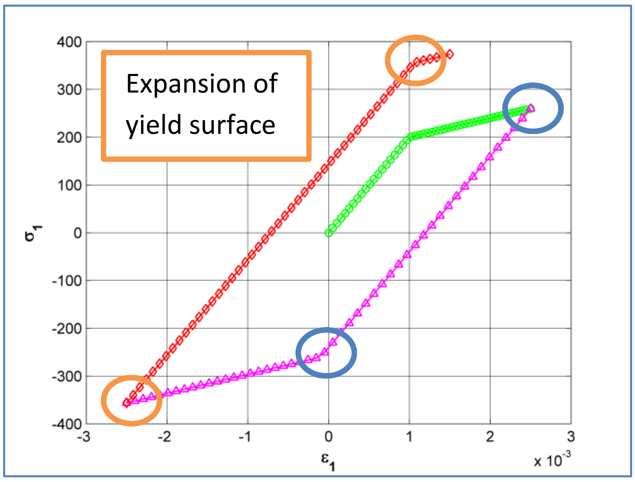


**Figure5. rate-independent linear Isotropic hardening plasticity**

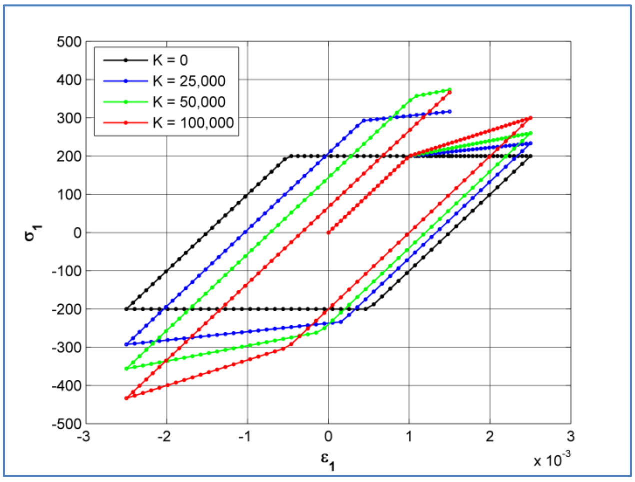


**Figure6. Effect of K on the bahavior of rate-independent Isotropic hardening plasticity**

***Figure6*** also delivers a good perspective related to the effect of Isotropic hardening value (K) on the behavior of this model. So, increasing the value of K would dramatically affect the expansion rate.

## 3.2. Rate Dependent response

For the rate dependent models, we can observe in **Figure7** and **Figure8** that as lower the viscosity parameter would be or as higher the duration of loading would be, the closer the results would be to the rate independent case (black line) because load is being applied gradually

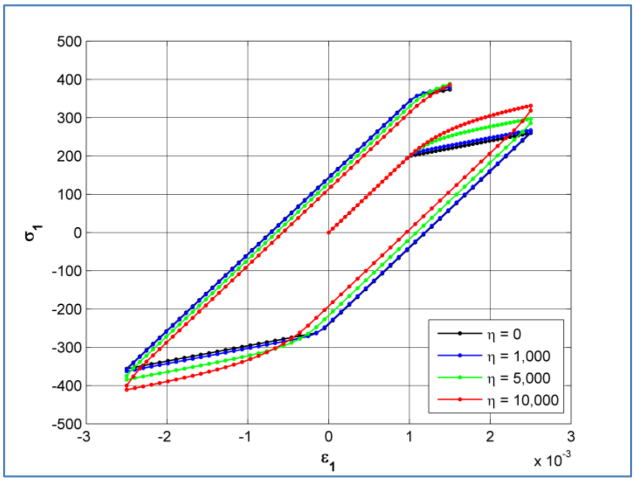


**Figure7. Effect of viscosity parameter on the bahavior of rate-dependent isotropic hardening plasticity**

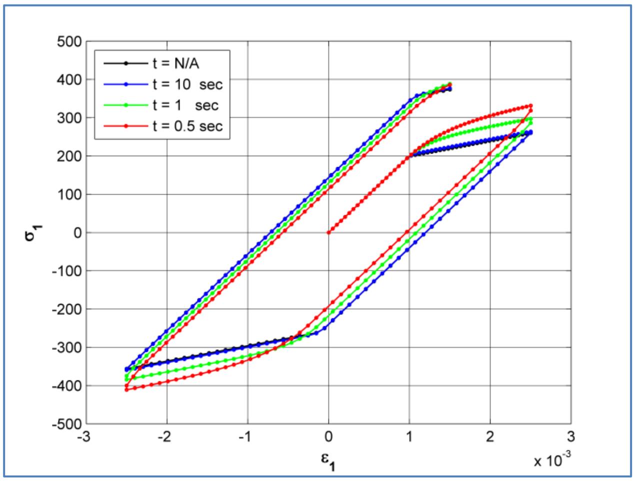


**Figure8. Effect of loading duration (strain rate) on the bahavior of rate-dependent isotropic hardening plasticity**

An interesting point in comparing previous figures (**Figure7** and **8**) is that by doubling the strain rate from one side and making the viscosity parameter half from the other side, the behavior of material would not undergo any change. This fact is studied by comparing red curves in ***Figure7*** and ***Figure8***.

And finally ***Figure9*** exhibits effect of increasing viscosity on the shape of stress-time curve, in order to study the increased stress peaks.

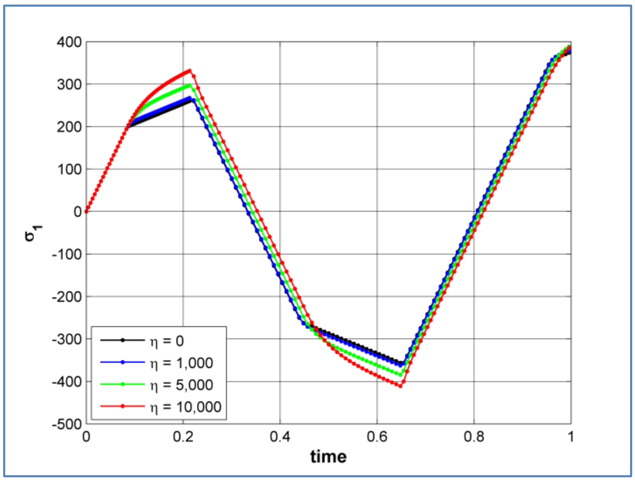


**Figure9. Effect of viscosity parameter on the bahavior of rate-dependent isotropic hardening plasticity**

## *4. Nonlinear Isotropic Hardening Plasticity*

### *4.1. Rate Independent response*

For the nonlinear isotropic hardening a nonlinear exponential saturation law + linear part for the isotropic hardening is studied in the code and for this purpose the well-known "Newton-Raphson" iterative method is considered in order to calculate the gamma.

***Figure10*** shows that in nonlinear isotropic models there is no a distinguishable yield point and yield procedure does not occur exactly on sigma-Y. The blue arrow shows the +200 MPa which was supposed to be the yield stress point, but we see that stress curve is going further and the blue circle describes the nonlinear convergence to the asymptotic value of stress.

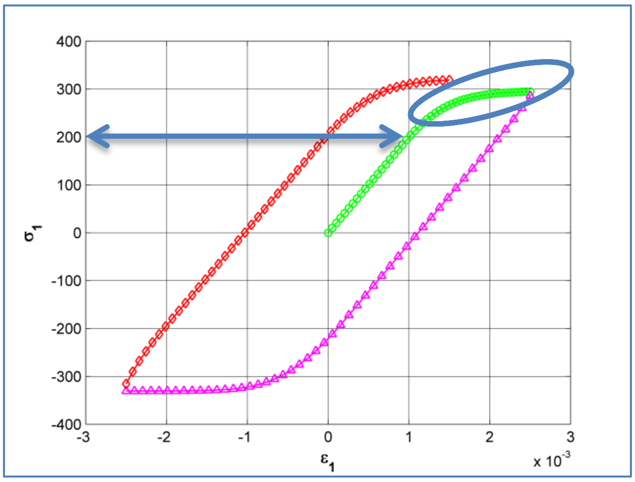


**Figure10. rate-independent nonlinear isotropic hardening plasticity**

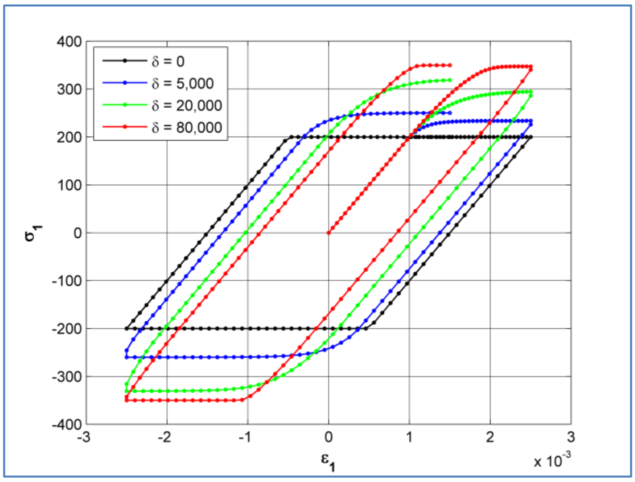


**Figure11. Effect of delta parameter on the bahavior of rate-dependent nonlinear isotropic hardening plasticity**

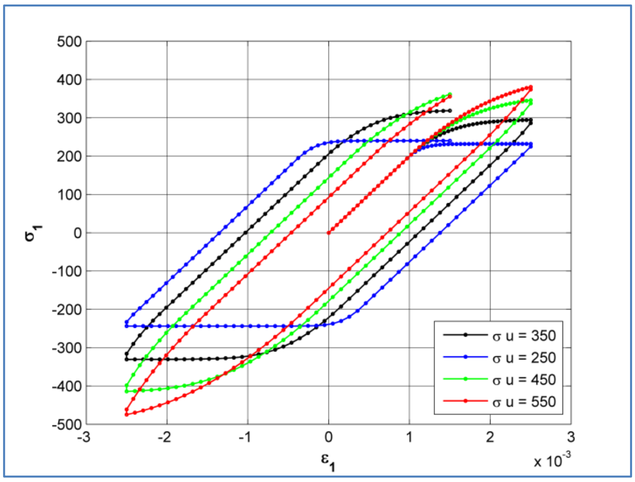


**Figure12. Effect of sigma infinity on the bahavior of rate-dependent nonlinear isotropic hardening plasticity**

***Figure11*** describes the effect of exponential coefficient (delta) on models behavior. It is evident that by increasing the delta value the rate at which stress-strain curve attain the asymptotic value of the yield stress (sigma infinity) is increased dramatically. Delta=20000 is chosen for the rest of this part.

An interesting point in ***Figure11*** is that by increasing the value of delta, material reaches to the sigma infinity so soon. So, the capacity of nonlinear behavior of material goes to end and in next cycles we would witness less and less nonlinear effect (red curve), because the asymptotic value of the yield stress is reached so early and the threshold is filled.

On the other hand ***Figure12*** shows the crucial effect of choosing a proper guess for the asymptotic value of the yield stress (sigma infinity). It demonstrates that if the difference between yield stress and asymptotic value of the yield stress is too low (blue curve) then the nonlinear effect would not have any visible effect rather than the linear isotropic hardening plasticity model. So as the consequence of this study the proper value of 350 MPa is chosen for this study in order to study the effect of nonlinear isotropic hardening plasticity in the rest of this report.

## *4.2. Rate Dependent response*

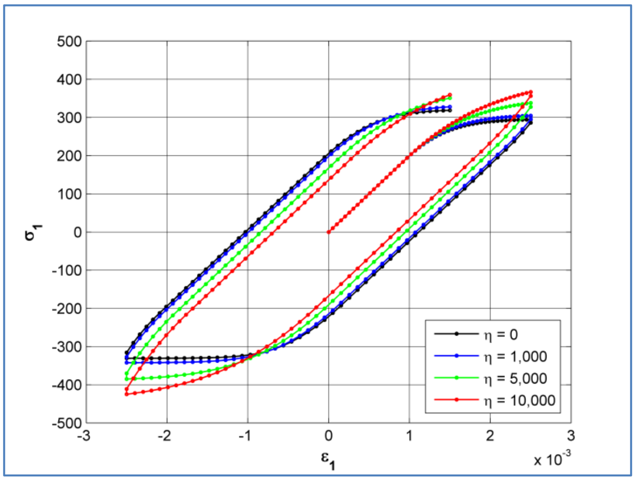


**Figure13. Effect of viscosity parameter on the bahavior of rate-dependent nonlinear isotropic hardening plasticity.**

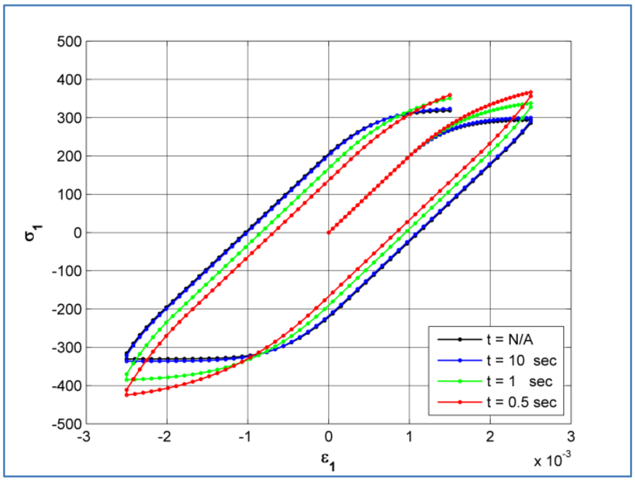


**Figure14. Effect of loading duration on the bahavior of rate-dependent nonlinear isotropic hardening plasticity.**

In this report we use nonlinear model of exponential saturation model and drop out the term corresponding to the linear part (K) in order to capture exactly the exponential gradient.

**Figure13** to **Figure15** shows that the rate independent results (black line) would be achieved if a low viscosity parameter or a high duration of loading is chosen (blue line).

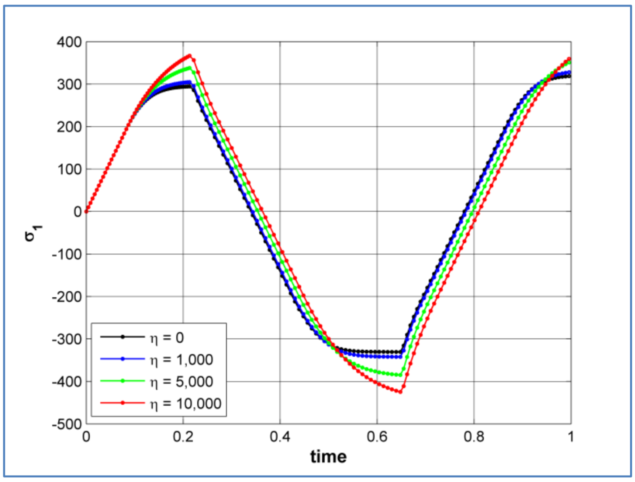


**Figure15. Effect of viscosity parameter on the bahavior of rate-dependent nonlinear isotropic hardening plasticity.**

# 5. Linear Kinematic Hardening Plasticity

## 5.1. Rate Independent response

The kinematic hardening causes translation in yield surface and this effect is portrayed in ***Figure16*** where the stress data in first blue mark (+250 = end of 1st path) is caused the 2nd path to yield much earlier (in -150 MPa instead of -200 MPa). This is due to the nature of this plasticity model and the same rule goes for two orange marks which makes the 3rd path also shifts and starts to yield in +150MPa instead of +200MPa.

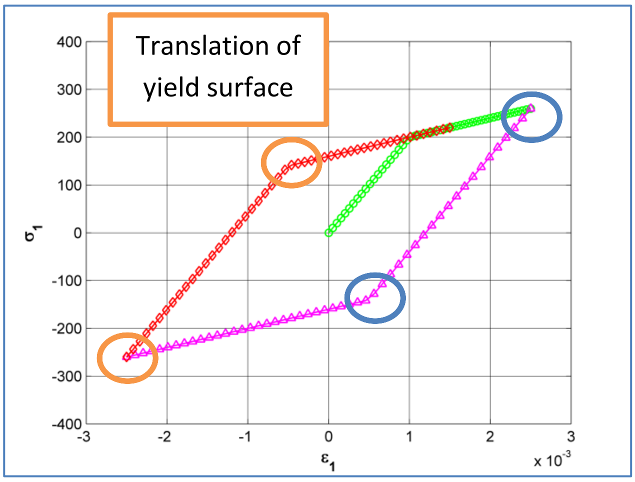


**Figure16. rate-independent linear kinematic hardening plasticity**

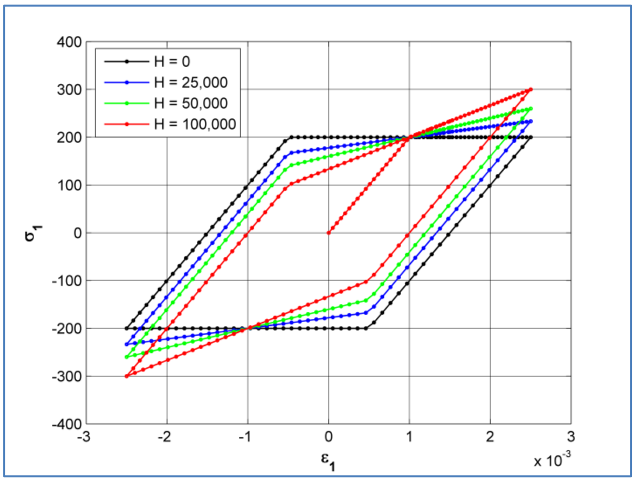


**Figure17. Effect of H value on the bahavior of rate-independent kinematic hardening plasticity**

***Figure17*** also gives a perspective related to the effect of kinematic hardening value (H) on the behavior of this model. So, increasing the value of H would affect the translation rate.

## 5.2. Rate Dependent response

For the rate dependent model, we can observe in **Figure18** and **Figure19** that like previous cases as lower the viscosity parameter would be or as higher the duration of loading would be, closer the results would be to the rate independent case (black line) because load is being applied gradually.

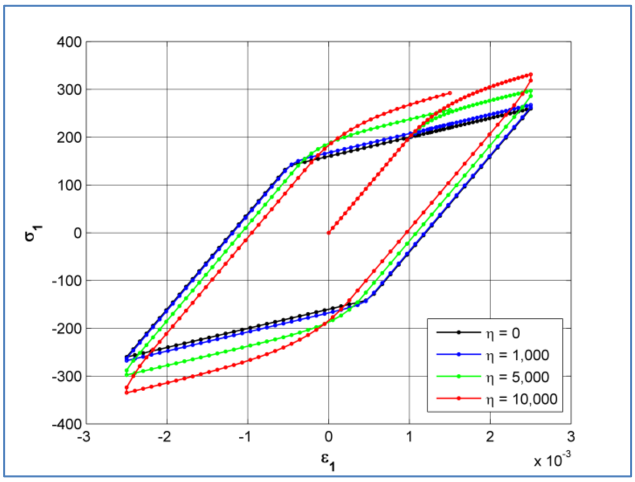


**Figure18. Effect of viscosity parameter on the bahavior of rate-dependent linear kinematic hardening plasticity.**

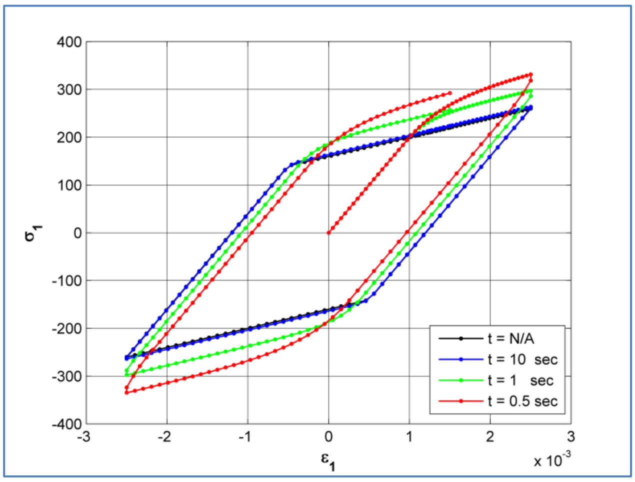


**Figure19. Effect of loading duration on the bahavior of rate-dependent linear kinematic hardening plasticity.**

**Figure20** plots the stress-time curve for the linear kinematic hardening and as we can see the increase in viscosity parameter would case higher peaks in stress capacity both in tension and compression and as lower the viscosity parameter would be, closer the results would be to the rate independent case (black line).

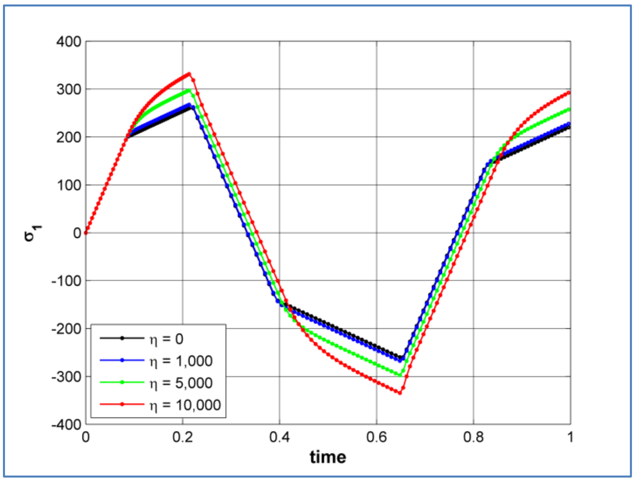


**Figure20. Effect of viscosity parameter on the bahavior of rate-dependent linear kinematic hardening plasticity.**

One of the main reasons of using cyclic loading in this report is to compare the isotropic and kinematic hardening effect together. Comparing ***Figure16*** to ***Figure5*** and ***Figure18*** to ***Figure7*** clearly demonstrate the main differences between these two models. As for the isotropic case we have expansion and in kinematic case we have translation in the yield surface. Both are sensitive to viscosity parameter and strain rate in the rate dependent models.

## *6. Nonlinear Isotropic and Linear Kinematic Hardening Plasticity*

### *6.1. Rate Independent response*

This is the most complete model studied in this report. It includes both isotropic (nonlinear) hardening and kinematic (linear) hardening. ***Figure21*** has both effects and is comparable with ***Figure10*** for only nonlinear isotropic and ***Figure16*** for only linear kinematic cases.

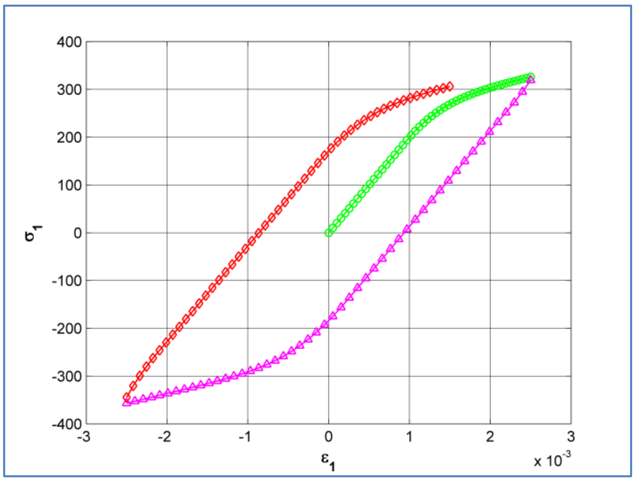


**Figure21. rate-independent nonlinear isotropic + linear kinematic hardening plasticity**

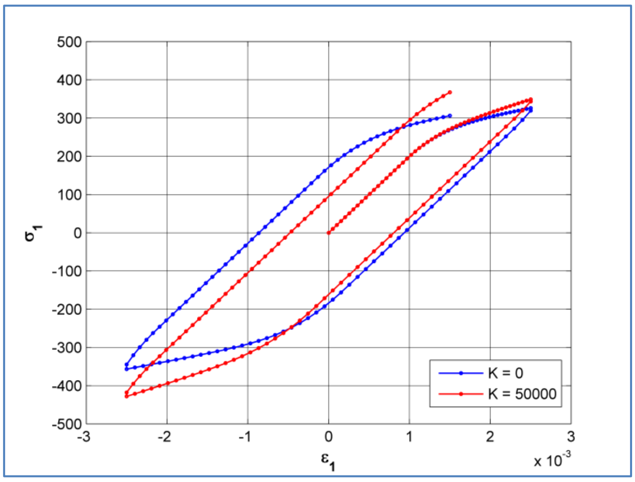


**Figure22. Effect of linear term K in the behavoir of rate-independent nonlinear isotropic + linear kinematic hardening plasticity**

On the other hand, as it was mentioned earlier in this report we use nonlinear model of exponential saturation model and drop out the term corresponding to the linear part (K) in order to capture exactly the exponential gradient. However, ***Figure22*** clearly shows the huge impact of adding the linear term (K) in nonlinear isotropic hardening model. Comparing to ***Figure24*** in next page we can observe that the effect of K is completely meaningful in relation with the effect of H parameter.

And finally, Figure23 describes the effect of exponential coefficient (delta). Like chapter 4.1 it is again obvious that by increasing the value of delta the rate at which stress-strain curve reaches the asymptotic value of the yield stress (sigma infinity) is increased dramatically.

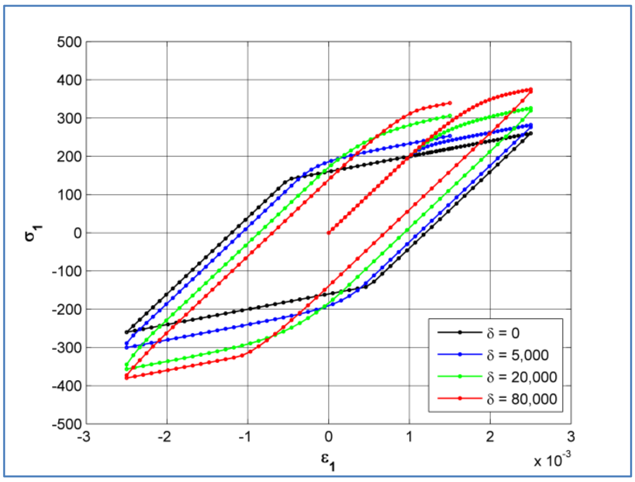


**Figure23. Effect of delta on the bahavior of rate-dependent nonlinear isotropic hardening plasticity**

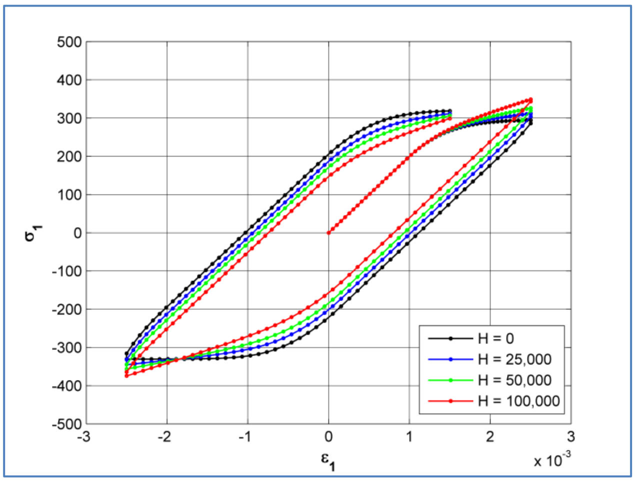


**Figure24. Effect of H value on the bahavior of rate-independent kinematic hardening plasticity**

## *6.2. Rate Dependent response*

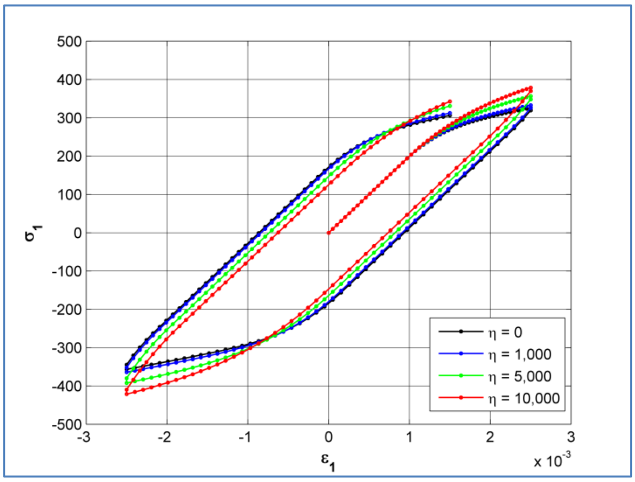


**Figure25. Effect of viscosity parameter on the bahavior of mixed perfect plastic model.**

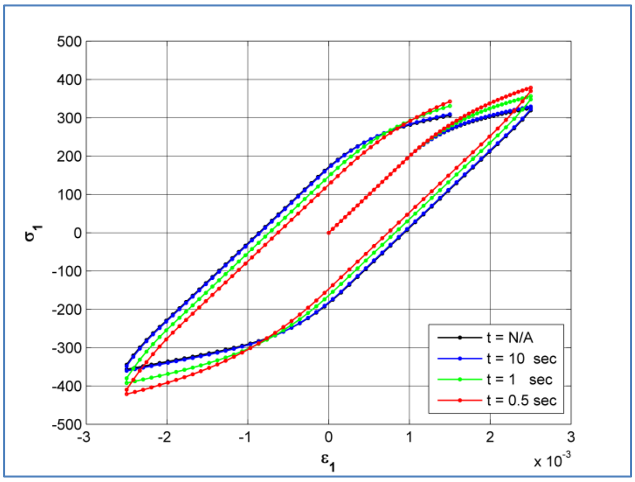


**Figure26. Effect of loading duration on the bahavior of rate-dependent mixed plastic model.**

The rate dependent behavior is somehow predictable from chapter4 and 5. **Figure25** to **Figure26** shows again that as lower the viscosity parameter would be or as higher the duration of loading would be (blue line), the closer the results would be to the rate independent case (black line) because load is being applied gradually.

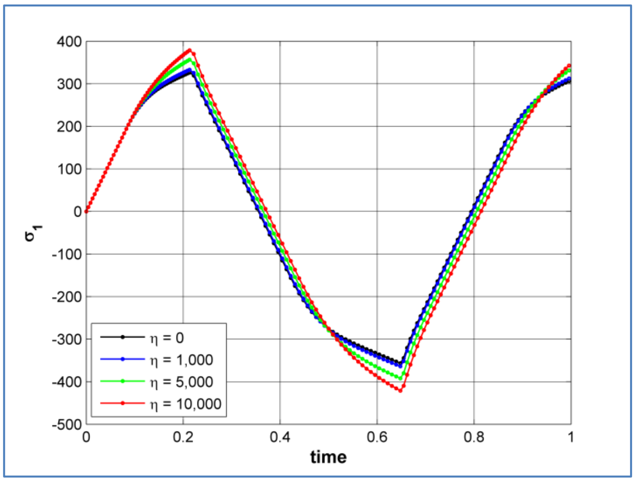


**Figure27. Effect of viscosity parameter on the bahavior of rate-dependent mixed plastic model.**

## 7. *Full Cyclic Loading*

As mentioned in the introduction, here the 2nd loading scenario as a full 9 path cyclic loading is considered. ***Figure28*** and ***Figure29*** studies the effect of **expansion** of linear isotropic hardening model and **translation** of linear kinematic hardening model compared to the perfect plastic model (black line). In this special case K and H is chosen equally as 25000. And no rate dependency is considered for the comparison.

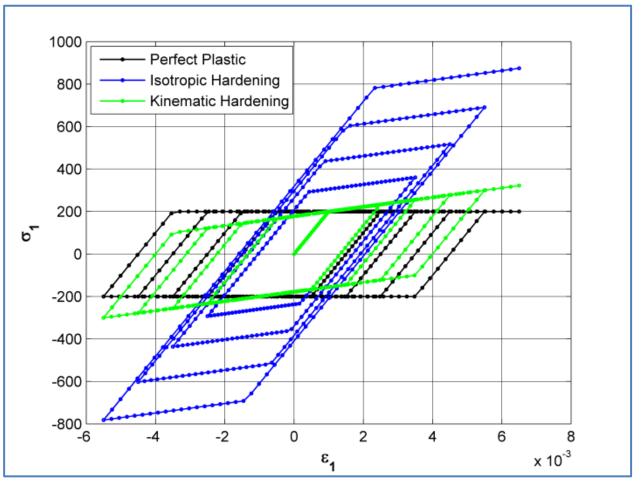


**Figure28. stress-strain comparison of hardenig plasticity models in full cyclic load**

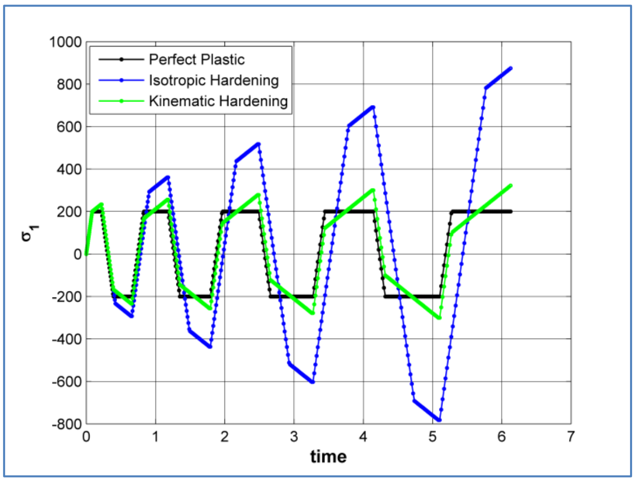


**Figure29. stress-time comparison of hardenig plasticity models in full cyclic load**

Moreover, to study the behavior of nonlinear isotropic hardening model and in order to captures the convergence of model to final asymptotical stress value, ***Figure30*** and ***Figure31*** are provided.

Here delta is chosen 2000 (K=0) and as we see, the value of sigma infinity (350MPa) is almost reached after 2 complete cycles and from there the value of tolerated stress would not go above more. This fact is the opposite point of linear hardening models in which there is no theoretical limit for maintaining the final stress.

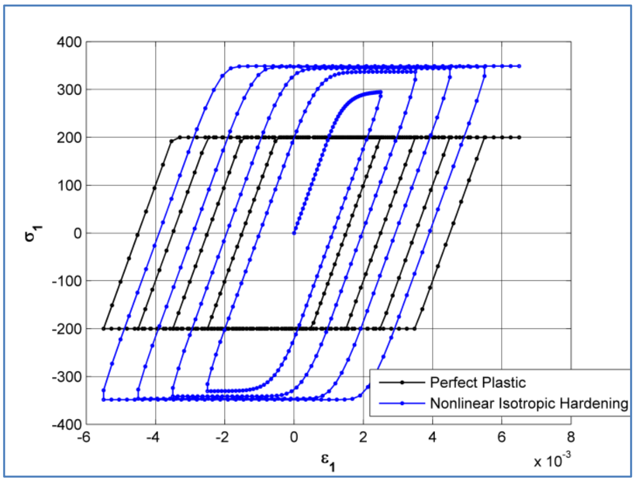


**Figure30. Effect of nonlinear isotropic hardening plasticity on the stress-strain curve**

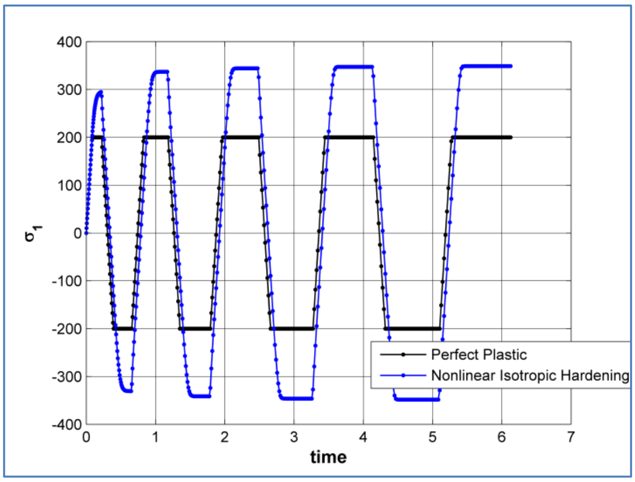


**Figure31. Effect of nonlinear isotropic hardening plasticity on the stress-time curve**

## ❖ *Appendix: Code*

```
%% 1D Plasticity Model

%==============================================================%
%           Linear isotropic hardening plasticity              %
%        Nonlinear isotropic hardening plasticity              %
%           Linear kinematic hardening plasticity              %
%==============================================================%
%                                                              %
%--INPUTS------------------------------------------------------%
%                                                              %
%  SIGy         : Yield Stress                                 %
%  SIGu         : Ultimate Stress                              %
%  E            : Young's Modulus                              %
%  K            : Isotropic Hardening Modulus                  %
%  H            : Kinematic Hardening Modulus                  %
%  Delta        : Exponential Parameter                        %
%  Eta          : Viscosity Coefficient                        %
%  nPath        : Number of Loading path                       %
%  nStep        : Number of time steps in each path            %
%  Strain_rate  : Number of time steps in each path            %
%  EPS_input    : Strain Cyclic Loading [INPUT DATA]           %
%                                                              %
%--OUTPUTS-----------------------------------------------------%
%                                                              %
%  EPS          : Strain Evolution                             %
%                 {epsilon , 0 , 0 }                           %
%  EPS_p        : Plastic Strain Evolution                     %
%                 {epsilon plastic , exi , exi_bar}            %
%  SIG          : Stress Evolution                             %
%                 {sigma , q , q_bar }                         %
%  EPS_p_tr     : Trial Plastic Strain                         %
%  EPS_e_tr     : Trial Elastic Strain                         %
%  SIG_tr       : Trial Stress                                 %
%  EPS_Hist     : Strain History                               %
%  SIG_Hist     : Stress History                               %
%                                                              %
%--------------------------------------------------------------%
clc; clear all; %close all;

colors = input('colors = 1:black - 2:blue - 3:green - 4:red ');
axislimit    = 4;

SIGy         = 200;
SIGu         = 350;
E            = 200000;
K            = 50000*0;
H            = 50000*0;
Delta        = 20000*0;
Eta          = 1000*0;
nPath        = 9;
nStep        = 50;
% Strain_rate  = 0.00115;     % for t = 10 sec
Strain_rate  = 0.01150;     % for t = 1 sec
% Strain_rate  = 0.02300;     % for t = 0.5 sec

EPS_input(1) =  0.0000;     %Strain Cyclic Loading Points [INPUT DATA]
EPS_input(2) =  0.0025;     %max number = nPath+1
EPS_input(3) = -0.0025;
EPS_input(4) =  0.0035;
EPS_input(5) = -0.0035;
```

**Input data by user**

**Cyclic loading Strain points**

```
EPS_input(6) =  0.0045;
EPS_input(7) = -0.0045;
EPS_input(8) =  0.0055;
EPS_input(9) = -0.0055;
EPS_input(10)=  0.0065;


%% DEFINING STRAIN & STRESS ARRAY

TotStep  = nPath*nStep;          % Total number of steps after full cycle
StepTime = zeros(nPath,1);       % Time of loading in each path
dt       = zeros(TotStep,1);     % Delta t in each loading step
Timing   = zeros(TotStep,1);     % Time Step Evolutions
EPS_Path = zeros(nPath,nStep);   % Evolution of strain in each path

for i=1:nPath
    StepTime(i) = abs(EPS_input(i+1) - EPS_input(i)) / Strain_rate;
    dt( (i-1)*nStep+1 : i*nStep ) = StepTime(i) / nStep;
    EPS_Path(i,:) = linspace( EPS_input(i) , EPS_input(i+1) , nStep );
end
TotTime = sum(StepTime(:));      % Time of loading after full cycle

for i=2:TotStep
    Timing(i) = Timing(i-1) + dt(i);
end
```

**Building required arrays for strain and stress evolution**

```
SIG_Hist = zeros(TotStep,1);     % Strain History
EPS_Hist = EPS_Path(1,:)';       % Stress History
for i=2:nPath
    EPS_Hist = [EPS_Hist ; EPS_Path(i,:)'];
end

%-------------------------------------------------------------------------
EPS   = zeros(TotStep,3);        % Strain Evolution
EPS_p = zeros(TotStep,3);        % Plastic Strain Evolution
SIG   = zeros(TotStep,3);        % Stress Evolution



% The Loading Cycle Loop
```

**Loop for each loading step**

```
EPS(:,1) = EPS_Hist;

for i=2:TotStep
%---------------------------------------------------------------Trial State
    EPS_p_tr = EPS_p(i-1,:);
    EPS_e_tr = EPS(i,:) - EPS_p_tr;
    SIG_tr   = [E * EPS_e_tr(1) , K * EPS_e_tr(2) , H * EPS_e_tr(3)];

    F_tr     = abs( SIG_tr(1) - SIG_tr(3) ) - (SIGy - SIG_tr(2));
    if  F_tr <= 0
    %----------------------------------------------------------Elastic Part
        EPS_p(i,:) = EPS_p_tr;
        SIG(i,:)   = SIG_tr;
        E_ep = E;
        Gam  = 0;
    else
    %----------------------------------------------------------Plastic Part
        if Delta==0        %===== Linear  Hardening =====%
            Gam = F_tr / ( E + K + H + Eta/dt(i) ) / dt(i);
```

**Linear hardening**

**Nonlinear hardening**

**Newton-Raphson algorithm**

```
        else                  %===== Nonlinear Hardening ==
            tol = 1e-6;
            g   = 0.01;
            Gam = 0;
            while g>=tol
                X1    = EPS_p(i,2);
                X2    = EPS_p(i,2) + Gam * dt(i);
                Pi1   = ( SIGu-SIGy ) * ( 1 - exp(-Delta * X1) ) + K * X1;
                Pi2   = ( SIGu-SIGy ) * ( 1 - exp(-Delta * X2) ) + K * X2;
                Pii2  = ( SIGu-SIGy ) * Delta * exp(-Delta * X2) + K ;

                g     = F_tr - Gam*dt(i) * ( E+H+Eta/dt(i) ) - (Pi2-Pi1);
                Dg    = -dt(i) * ( E + Pii2 + H + Eta/dt(i) );
                DGam  = -g / Dg;
                Gam   = Gam + DGam;
            end
        end
```

**Final stress and strain value at step**

```
        X1  = EPS_p(i,2);
        X2  = EPS_p(i,2) + Gam * dt(i);
        Pi1 = ( SIGu - SIGy ) * ( 1 - exp(-Delta * X1) ) + K * X1;
        Pi2 = ( SIGu - SIGy ) * ( 1 - exp(-Delta * X2) ) + K * X2;

        SIG(i,1)    = SIG_tr(1) - Gam*dt(i) *E * sign(SIG_tr(1)-SIG_tr(3));
        SIG(i,2)    = SIG_tr(2) - (Pi2-Pi1);
        SIG(i,3)    = SIG_tr(3) + Gam*dt(i) *H * sign(SIG_tr(1)-SIG_tr(3));

        EPS_p(i,1) = EPS_p(i-1,1) + Gam*dt(i) * sign(SIG_tr(1)-SIG_tr(3));
        EPS_p(i,2) = EPS_p(i-1,2) + Gam*dt(i);
        EPS_p(i,3) = EPS_p(i-1,3) - Gam*dt(i) * sign(SIG_tr(1)-SIG_tr(3));

        E_ep=E*(1 - E * (E-(SIGu-SIGy)*Delta*exp(-Delta* (EPS_p(i-1,2)+Gam*dt(i))
)+ H + Eta/dt(i))^(-1) );

    end

    SIG_Hist(i,1) = SIG(i,1);
end

%% Plot
plotcurves_1D(EPS_Path,EPS_Hist,SIG_Hist,Timing,nStep,colors,axislimit);
```

**Plotting**

**Plot function**

```
function plotcurves_1D(EPS_Path,EPS_Hist,SIG_Hist,Timing,nStep,colors,axislimit)

%-----------------------------------------------------------
figure(1);
plot(EPS_Path(1,:),SIG_Hist(1          :  nStep,1)
,'g','LineWidth',1,'Marker','o','MarkerSize',5); grid on; hold on;
plot(EPS_Path(2,:),SIG_Hist(1+  nStep :2*nStep,1)
,'m','LineWidth',1,'Marker','^','MarkerSize',5); grid on; hold on;
plot(EPS_Path(3,:),SIG_Hist(1+2*nStep :3*nStep,1)
,'r','LineWidth',1,'Marker','d','MarkerSize',5); grid on; hold on;
switch axislimit
    case 1; axis([-0.003,0.003,-300,300])
    case 2; axis([-0.003,0.003,-400,400])
    case 3; axis([-0.003,0.003,-500,500])
    case 4;
end
xlabel('\epsilon_{1}','FontSize',12,'FontWeight','bold')
ylabel('\sigma_{1}','FontSize',12,'FontWeight','bold')
set(gca,'GridLineStyle','-');

%---------------------------------------------------------------------------
switch colors
    case 1; cc='k'; mm='o';
    case 2; cc='b'; mm='d';
    case 3; cc='g'; mm='^';
    case 4; cc='r'; mm='.';
end
```

**Color selection**

```
%---------------------------------------------------------------------------
figure(2);
plot(EPS_Hist,SIG_Hist ,cc,'LineWidth',1,'Marker','o','MarkerSize',2); grid on;
hold on;
switch axislimit
    case 1; axis([-0.003,0.003,-300,300])
    case 2; axis([-0.003,0.003,-400,400])
    case 3; axis([-0.003,0.003,-500,500])
    case 4;
end
xlabel('\epsilon_{1}','FontSize',12,'FontWeight','bold')
ylabel('\sigma_{1}','FontSize',12,'FontWeight','bold')
legend('bbb');
set(gca,'GridLineStyle','-');
```

**Stress-strain**

```
%---------------------------------------------------------------------------
figure(3);
plot(Timing,SIG_Hist ,cc,'LineWidth',1,'Marker','o','MarkerSize',2); grid on; hold
on;
xlabel('time','FontSize',12,'FontWeight','bold')
ylabel('\sigma_{1}','FontSize',12,'FontWeight','bold')
legend('bbb');
set(gca,'GridLineStyle','-');

end
```

**Stress-time**