Low-damage Structural Systems, Principals for the Unique Moment-Rotation Behavior of Unbonded Post-tensioned Precast Concrete Systems and Introduction to a Program Written to Obtain It

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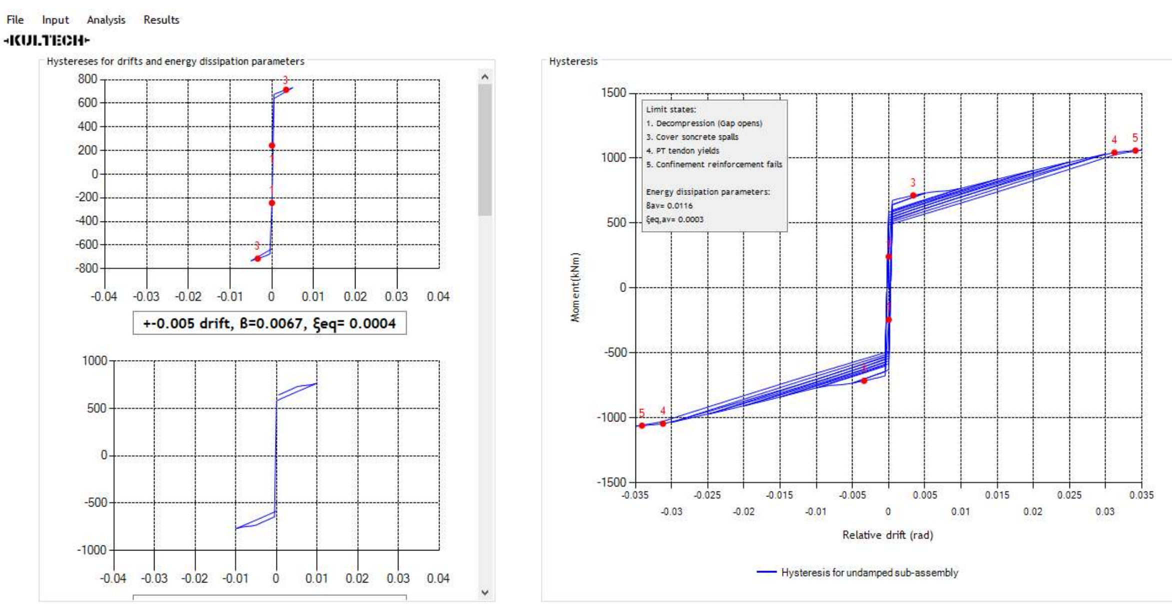


'Strength is essential, otherwise unimportant.'

Hardy Cross

Summary

Traditional structural seismic design approach is to design buildings so they behave inelastically and to provide sufficient ductility to prevent brittle failure of structural members, joints, and eventually the whole system. The inelastic behavior of buildings manifests itself by way of significant structural damage post-earthquake. This structural damage can at times require very high repair costs or can prevent functionality of the building for a considerable time. Rather than designing the building to have structural damage which is to be repaired later, recent advancements in earthquake engineering include increasing use of low-damage design philosophy. Low-damage design is by definition designing buildings so there is minor, negligible or easily repairable structural damage in a building subjected to design level earthquake. One of the most efficient low-damage seismic systems is Unbonded Post-tensioned Precast Concrete (UPPC), in which structural damage is concentrated in a specially designed joint interface. Moreover, post-tensioning strands are designed to remain elastic, which causes the building to re-center after the seismic event, thus minimizing residual deformations. However, this system has unique aspects which prevent it to be modelled and analyzed with conventional methods and computer software. In addition, performance criteria cannot be defined for these systems as it is defined for conventional systems. The gap-opening behavior, un-bonded nature of strands and low energy dissipation capacity require special analytical and modelling techniques for these systems. This article explains in detail the peculiarities of Unbonded Post-tensioned Precast Concrete systems and introduces the reader to a computer program written to obtain their moment-rotation behavior.

What is Low-damage Design?

Structural engineers are responsible for designing structures to withstand any loads they are likely to be subjected to, and they are professionally obliged for doing it in the most economical way.

Consider the force-deformation relation given for a structural system in Figure 1. Theoretically it is possible to design any type of building to behave elastically when subjected to design earthquake, but for most situations it is economically not viable.

Mainly for this reason (and for other reasons we will mention later) the conventional design philosophy is to let the building to 'yield', but make sure it does not fail in a brittle manner (provide sufficient ductility).

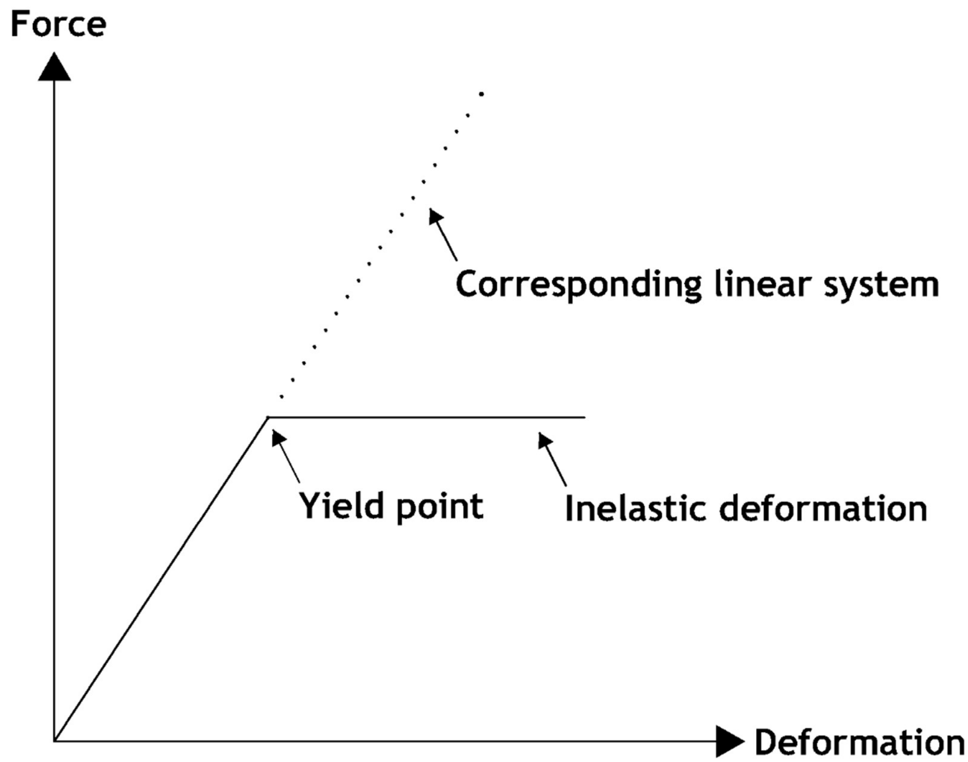


Figure 1 – Idealized bilinear elasto-plastic behavior of structural systems

Letting the building to yield obviously means letting it have inelastic deformations. Inelastic deformations are by definition residual, which means they remain after the earthquake. The state of the building in terms of the level of structural damage is defined by a concept called Performance-Based Seismic Engineering, but this topic is beyond the scope of this article. We will suffice in stating that taking into acount various parameters (occupancy type etc..) the seismic performance is evaluated according to structural damage level. In other words, structural damage IS allowed in most cases in seismic design.

If the building in question is a production facility that cannot tolerate a temporary closure for retrofit operations, or a residential building for that matter, repairing structural damage sounds not feasible. So why not design the building from the beginning to have minimum structural damage that does require very little repair operation or no repair at all?

The Most Beautiful Low-Damage System: UPPC

Enters to the scene a beautiful structural system: Unbonded Post-tensioned Precast Concrete, UPPC.

First, let's examine a little more closely where structural damage occurs in conventional cast-in-situ reinforced concrete buildings. For brevity, let's focus on a relatively simple (isostatic) cantilever beam. For further brevity, let's consider applying an incremental vertical static load at the top of the beam. Reinforcing steel at the bottom is mainly constructive, hence the primary tensile reinforcing steel is the one at the top. (Figure 2)

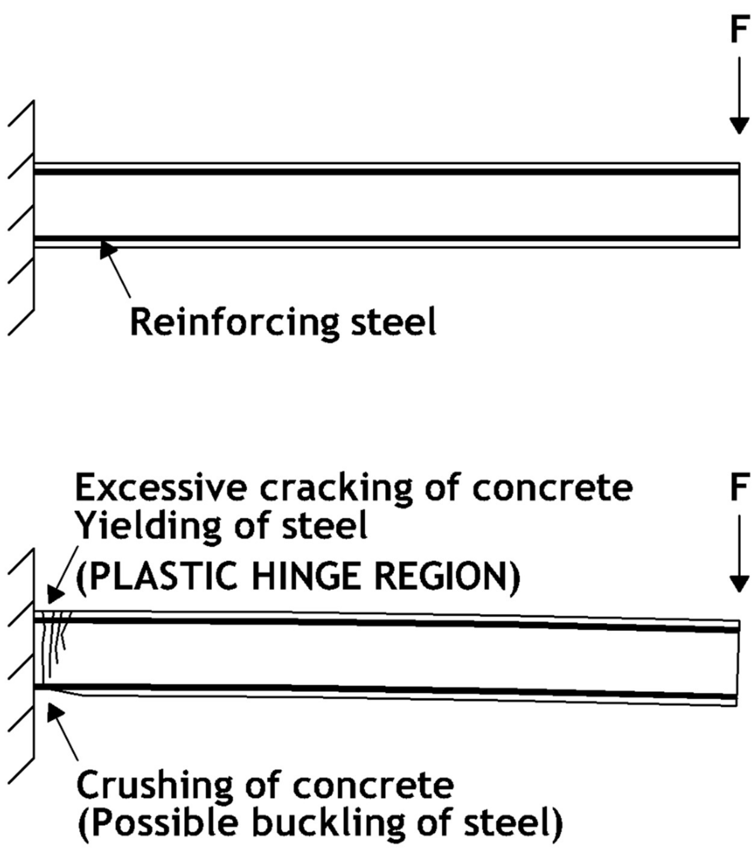


Figure 2 – Plastic hinge region of a cantilever beam with point force at the end

When the beam reaches its yield point, much of further deformation that takes place is inelastic(plastic). This plastic deformation is distributed to a length which is called *plastic hinge length*. Within this plastic hinge length and not necessarily confined to it, inelastic deformations are exhibited in the beam member, protruding to a significant distance towards mid-span. These inelastic deformations are predominantly yielding of mild steel and cracking or spalling of concrete. An example of such deformations can be observed in Figure 3a.

One last thing to stress about this conventional joint is that it is basically monolithic, which means that the beam-column joint is (in most cases assumed to be) full rigid and that structural damage is not concentrated to a surface but propagates to a significant length.

Now let's move directly to Figure 3, which clearly demonstrates the difference between structural damage observed in cast-in-situ joint and UPPC joint.

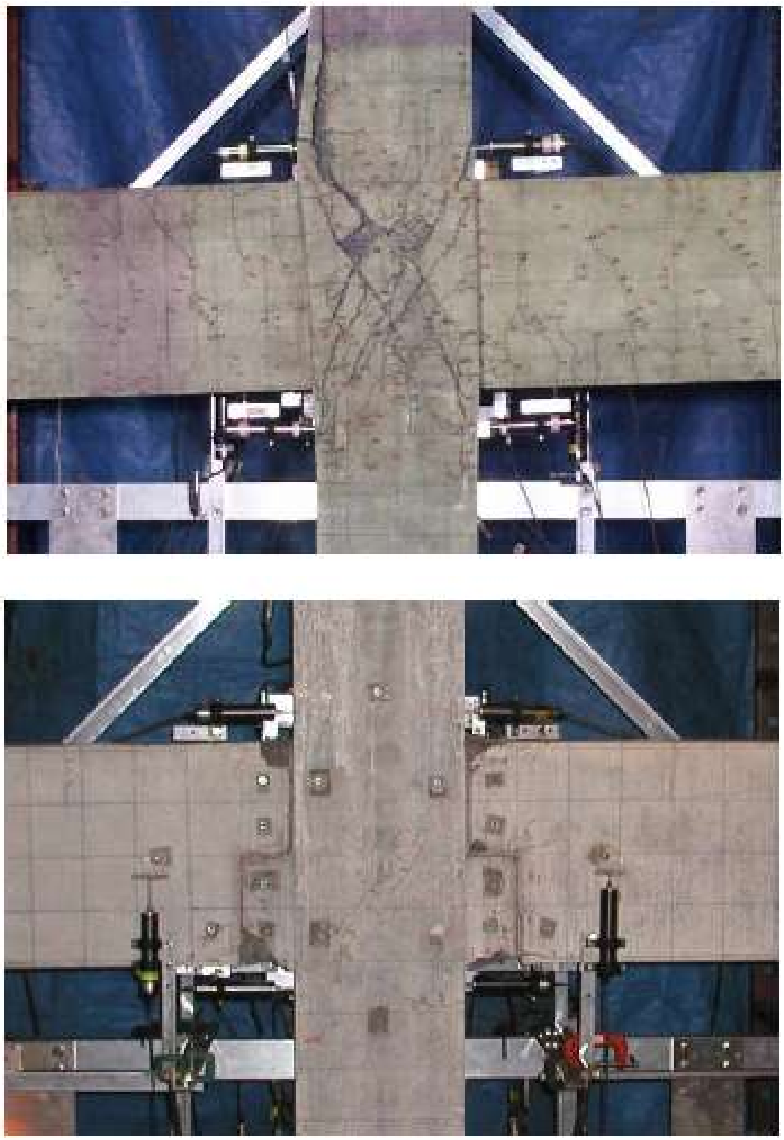


Figure 3 – Structural damage at a) Cast-in-situ joint b) UPPC joint [1]

As can be clearly observed, structural damage is concentrated at local joint interface in UPPC and it is much lighter than the substantial damage in cast-in-situ joint, which shows itself mainly in joint panel region and proceeding towards column member.

What makes UPPC unique?

Let's look at the unique characteristics of UPPC which make them low-damage systems.

Gap-opening

One of the first things that are taught in reinforced concrete courses is that 'plane sections remain plane'. It comes with 'strain compatibility' principle, which assumes there is perfect bonding between reinforcing steel and concrete. This phenomenon allows the analyst to equate the strain at concrete fiber at rebar level to rebar strain.

Let's consider the cantilever beam once again. Figure 4 illustrates the strain compatibility principle and section equilibrium for a cast-in-situ joint interface/section. Please note that unconfined and confined concrete distinction is not displayed for brevity.

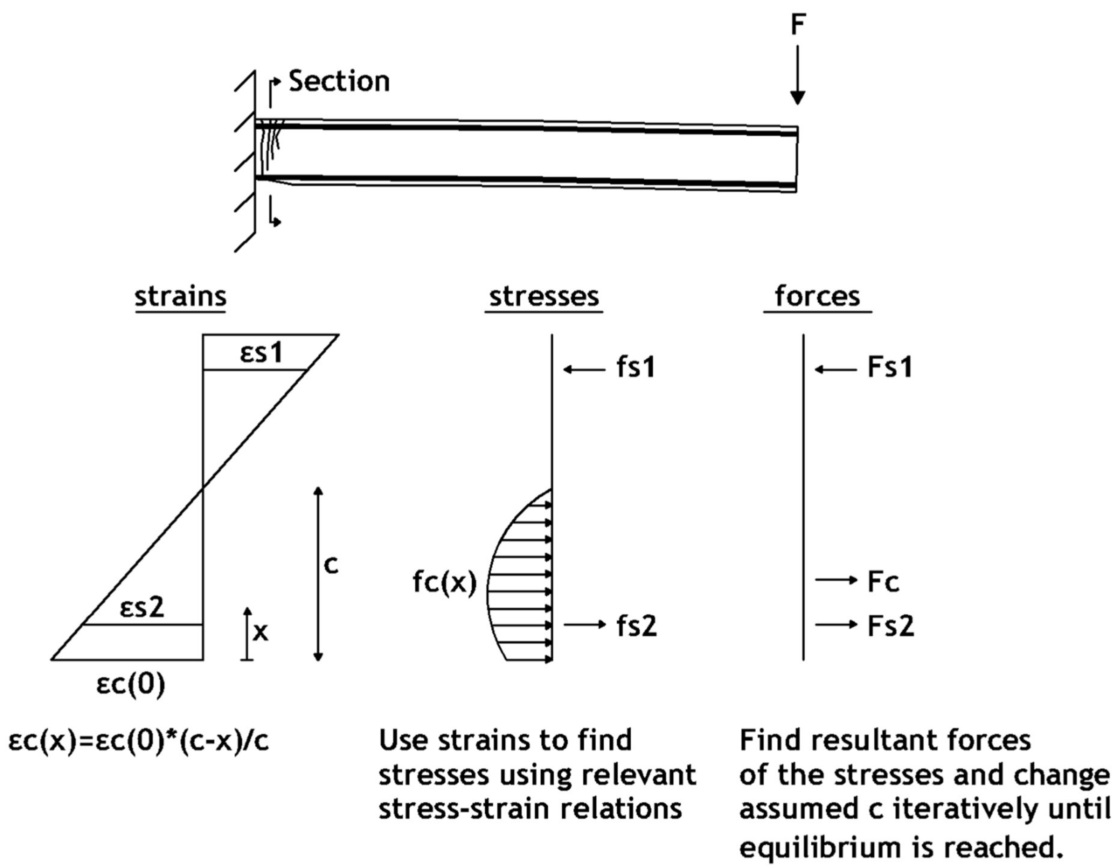


Figure 4 – Section analysis parameters for conventional member section

This phenomenon does not apply to UPPC systems. Precast systems, by definition, are produced as individual members in the production facility and they are connected at the site. Although it is possible to design and construct them 'emulating' monolithic construction, this is not the case in UPPC systems. In UPPC systems, individual precast members (mainly beams and columns) are connected by post-tensioning strands which typically have no anchorage to the members along the length. When the load is applied at the tip of the cantilever beam, a gap opens at the beam-column joint interface, imposing elongation at the post-tensioning strands. There is no strain compatibility. Figure 5 illustrates the gap-opening concept.

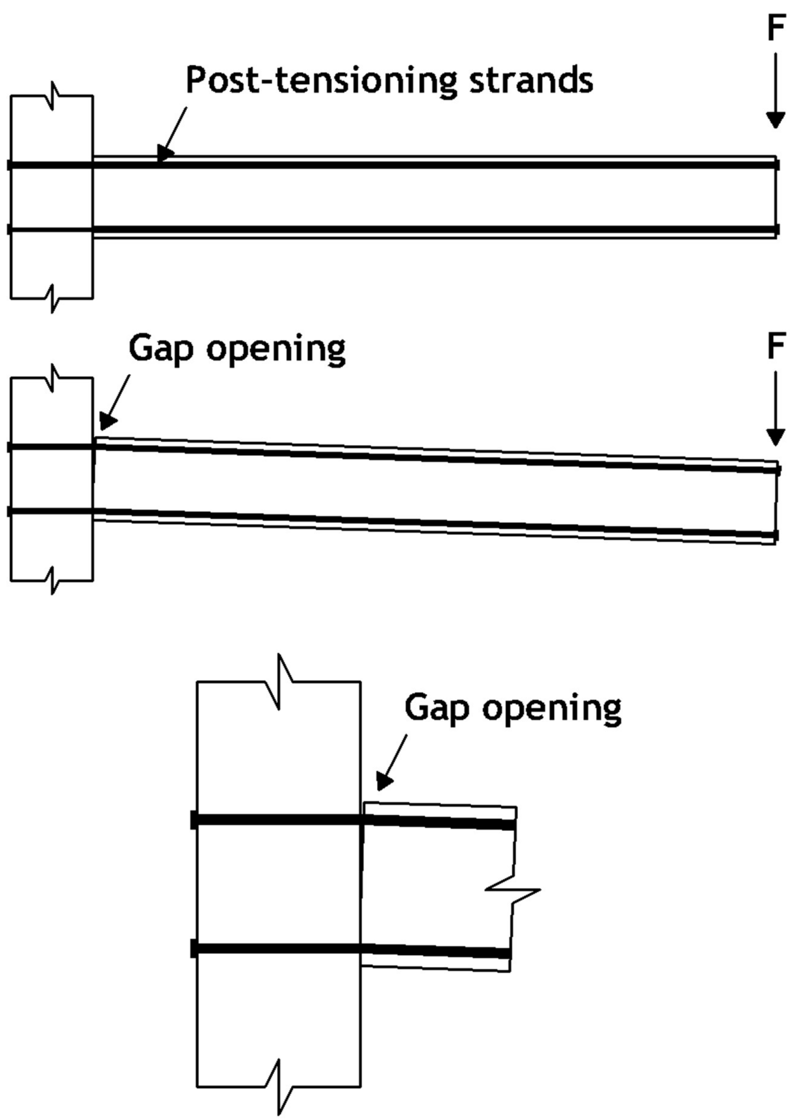


Figure 5 – Gap opening in UPPC systems

When seismic forces impose gap opening at the joint, tensile stresses are resisted by the post-tensioning strands. Compressive stresses are resisted by concrete reaction forces, which cause stress concentrations near the joint region. This joint region is typically specially designed (using fiber reinforced concrete or alternative materials) to reduce the structural damage to a tolerable degree. Furthermore, post-tensioning strands are designed to remain elastic under design earthquake demand, which enables them to 'self-center' the system.

Elastic post-tensioning strands

The post-tensioning strands can be considered as a nonlinear elastic truss member because they are not bonded to the surrounding members throughout their length. Obviously, the forces acting on them are a function of the stresses acting on them, which in turn are a function of the longitudinal strains they have. These longitudinal strains can be easily calculated by the basic strain relation (See Figure 6):

$$\varepsilon = \frac{\Delta_L}{L_i}$$

Where ε is the longitudinal strain in the strands, Δ_L is the total change in length of the strand (in our case always elongation), and L_i is the initial length of the strand between the anchorages.

The logic of prestressing comes with the fact that the strands are by definition 'pre'stressed. In other words, they have an initial longitudinal strain ε_i due to jacking before any forces act on them. The gap-opening imposes additional strains on them, as shown in Figure 6.

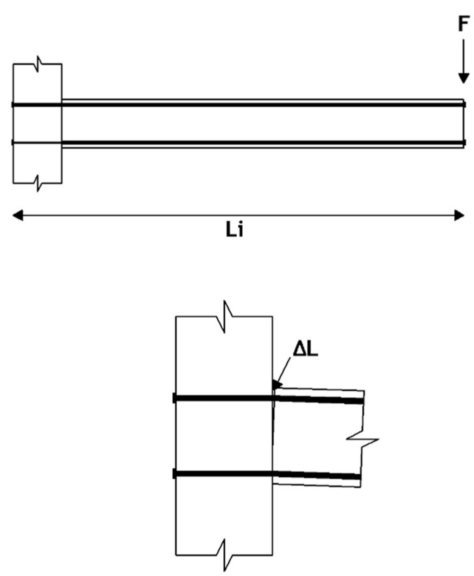


Figure 6 – Strain imposed on strands by gap opening

The stress-strain relation for pre-stressing strands is given in Figure 7. [2] As can be seen, when the proportionality strain limit is exceeded, we can no longer talk about elasticity in the strands. However, elasticity can be described as ‘tendency to take original shape after the forces are removed’. And in our case it is particularly useful because if we make such a design that the strands are still in the elastic range at design earthquake level, we can achieve ‘self-centering’ effect which dramatically reduces residual deformations. This is one of the phenomena which make UPPC low-damage systems.

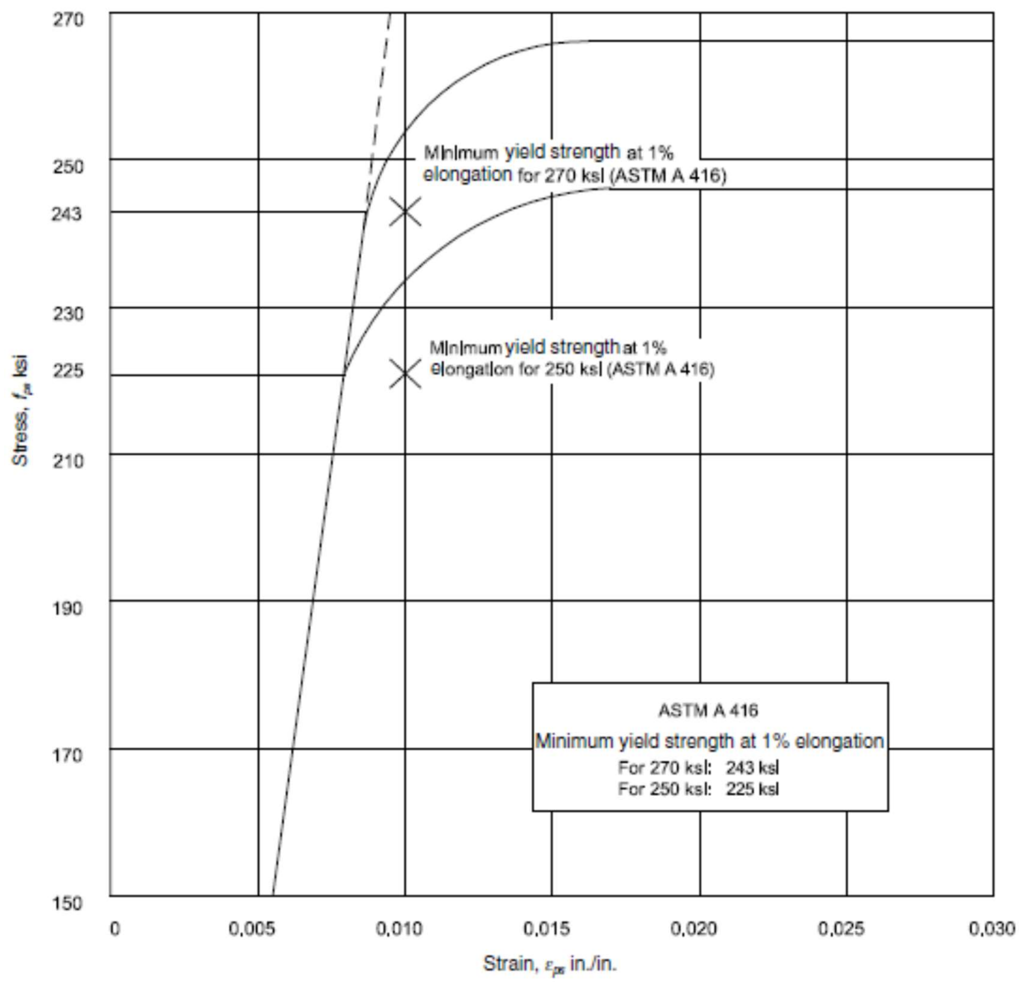


Figure 7 – Stress-strain relation for prestressing steel

One last thing to point out about post-tensioning strands, in UPPC systems where strands are placed at top and bottom of the beam, because strain demands are high due to the location of the strands, the initial jacking stress is limited to 50% of the ultimate strength.

Equivalent viscous damping ratios ξ_{eq}

Since damping is a phenomenon which is extremely difficult to quantify and idealize, common practice is to use assumed values for it. The widely accepted equivalent viscous damping ratio for conventional reinforced concrete structures is 5.00%. However, this number generally does not apply for UPPC systems, since they have lower energy dissipation capacity than cast-in-situ systems. Since these systems are by definition 'low-damage', the mechanisms which are assumed to take place in reinforced concrete systems to possess ξ_{eq} of 5.00% are not present for them. For this reason, the equivalent viscous damping ratios for these systems should be calculated exclusively.

The equivalent energy dissipation ratio ξ_{eq} is given by Chopra [5] with the following relation:

$$\xi_{eq} = \frac{1}{4\pi}\frac{E_D}{E_{so}}$$

This energy dissipation issue is very important and it will be covered in detail in the next article. The parameter defined by ACI T1.1-01 [6], relative energy dissipation ratio ß will also be discussed in detail in the upcoming article.

Performance criteria for UPPC systems

Performance criteria specified by international building codes to determine seismic performance level of structures cannot be used for UPPC systems because of the unique aspects we have outlined. For this reason, special performance criteria for UPPC systems should be defined.

Before outlining performance criteria, let us examine the 5 limit states a typical UPPC moment-rotation curve has. El-sheikh et al [3] define these limit states as follows:

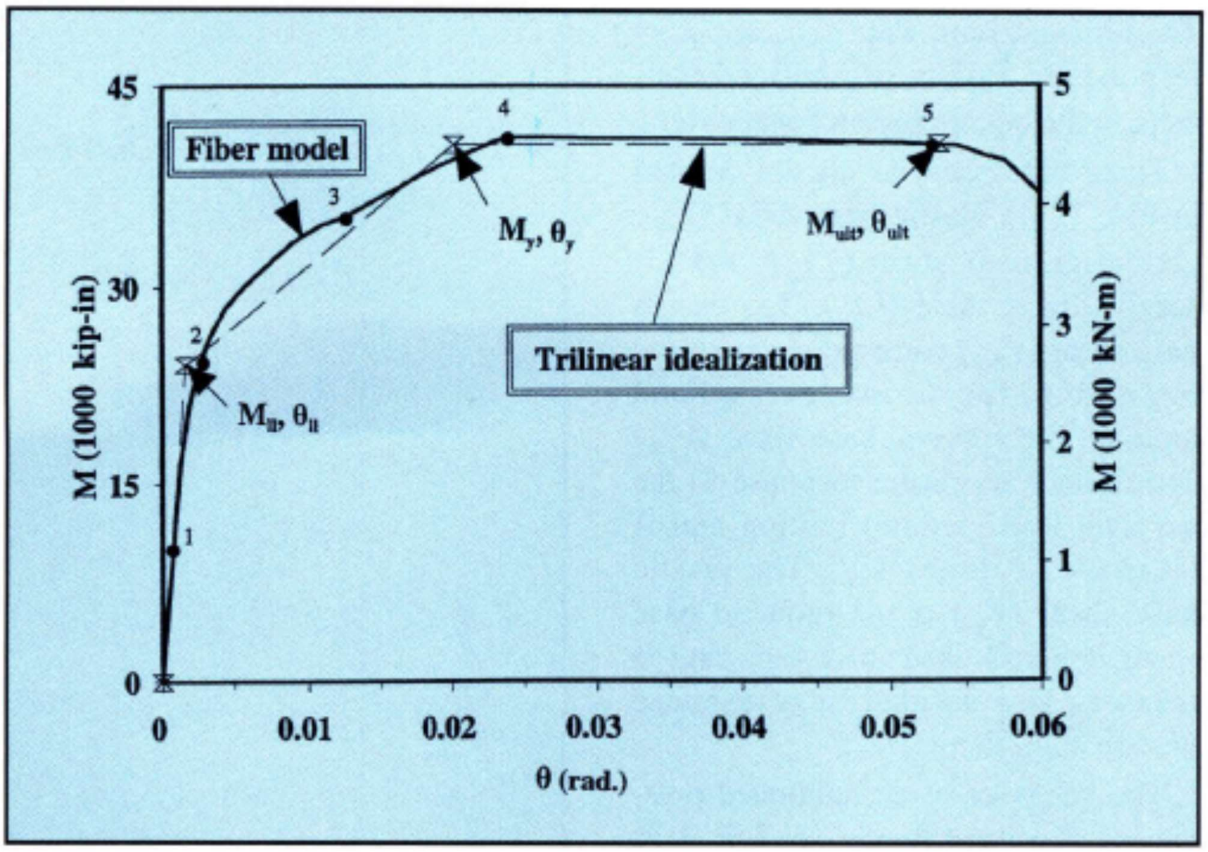


Figure 8 – Typical moment-rotation curve for UPPC [3]

State 1: Decompression limit state. Gap-opening begins. Beyond this point moment-rotation behavior is softened due to a) propagation of gap opening along the section b) an increase in concrete stress and strain which softens concrete

State 2: Linear limit state. After this point moment-rotation behavior significantly deviates from the initial linear part.

State 3: Cover spalling limit state. The state at which unconfined concrete cover spalls. Rapid decrease in unconfined concrete stress occurs, which decreases the slope of the moment-rotation curve.

State 4: Yield limit state. Post-tensioning strand reaches the limit of proportionality, beyond which point strands begin to deform inelastically.

State 5: Ultimate limit state. Strain at the extreme fiber of confined concrete reaches its ultimate strain. Confining reinforcement fails. A brittle failure is expected.

Now let us see how Kurama [4] defines performance criteria for UPPC systems:

Immediate Occupancy Performance Level:

- Decompression at beam-column interface (State 1)
- Slip of friction dampers (This is specific to the case with dampers)
- Hairline cracking near beam-to-damper and column-to-damper connections (This is specific to the case with dampers)

Life-safety Performance Level:

- Crushing of unconfined concrete (State 3)
- Flexural hinging at column base

Collapse Prevention Performance Level:

- Yielding of post-tensioning strands (State 4)
- Confined concrete on the verge of crushing (State 5)

Analytical modelling of UPPC systems

The gap-opening behavior and the unbonded post-tensioning strands also require unique modelling techniques to represent the behavior of UPPC systems in the most correct way. Kurama [4] once again provides very useful insight into how to model such systems. In this article, we will only mention two principles which are essential to the unique aspects we have mentioned.

The most realistic way to model post-tensioning tendons is to model them as truss members with bilinear stress-strain relationship. The location of the truss member is chosen according to the location of the strands with respect to section's neutral axis. The jacking stresses can be modelled as initial internal stresses. The anchors of strands are modelled by kinematically constraining truss nodes at the end to the relevant nodes at beam ends.

The gap-opening behavior is modelled by equating tensile strength and stiffness of concrete fibers to zero. This way, the reduction of stiffness due to gap opening is taken into account by the fact that concrete fibers subjected to tensile strains have no stiffness.

A computer program: KULTECH UPPCv0.0

The unique aspects of UPPC systems outlined above require a nonconventional approach in analyzing them. In addition to that, an alternative of modelling these systems as global frames is to define the moment-rotation behavior as zero-length rotational spring elements. For this reason, we at KULTECH have developed a computer program that analyzes cyclic moment-rotation behavior taking into account cyclic concrete compressive stress-strain relationship and prestressing steel stress-strain relationship. The program applies cyclic beam chord rotations with ±0.50%, ±1.00%, ±1.50%, ±2.00%, ±2.50%, ±3.00% and ±3.50%. It plots moment-rotation relationships for all beam chord rotation ratios and calculates the relative energy dissipation ratio β (as defined by ACI T1.1-01 [6]) for each ratio. It also presents detailed results in tabular form and concrete and prestressing steel behavior in graphical form.

The capabilities of UPPCv0.0 is listed below:

- It gets user input about geometrical disposition of the system (beam length, height, width, column width, strand eccentricity)
- It gets user input necessary to obtain cyclic nonlinear stress-strain relationships for unconfined concrete, confined concrete and prestressing steel. (Clear cover, area and distancing of confining reinforcement, concrete strength, initial jacking stress, longitudinal reinforcing steel area)
- It forms the analysis model and applies the beam chord rotation protocol (±0.50%, ±1.00%, ±1.50%, ±2.00%, ±2.50%, ±3.00%, ±3.50%)
- It incrementally (and for returning cycles decrementally) applies beam chord rotation value and at each increment, it analyzes the section. For section analysis, it assumes a value for concrete compressive stress block and finds resultant forces for both prestressing tendons and concrete according to the assumed concrete compressive stress. For concrete, it takes Mander's cyclic model for unconfined and confined concrete. It uses Newton-Raphson method to find the compressive block depth value that satisfies section equilibrium with a tolerable error.
- After section equilibrium is reached, it calculates the moment resistance of the section and points it on the plot.
- At the end of the analysis, it plots general hysteresis for the whole beam chord rotation values.
- For each limit state that defines seismic performance of such systems, it marks the limit state point.
- In addition to the general hysteresis, it plots hystereses for all beam chord rotation values separately, and calculates and displays the relative energy dissipation ratio β and equivalent viscous damping ratios ξ_{eq} for all beam chord rotations.
- It provides graphical and tabular information regarding nonlinear stress-strain reactions of concrete and prestressing tendons.

An example solved by KULTECH UPPC v0.0

Let's do a tutorial demonstrating the capabilities of the program. Let's consider we are to design a residential structure using UPPC system. We will work on the 2D frame shown in Figure 9.

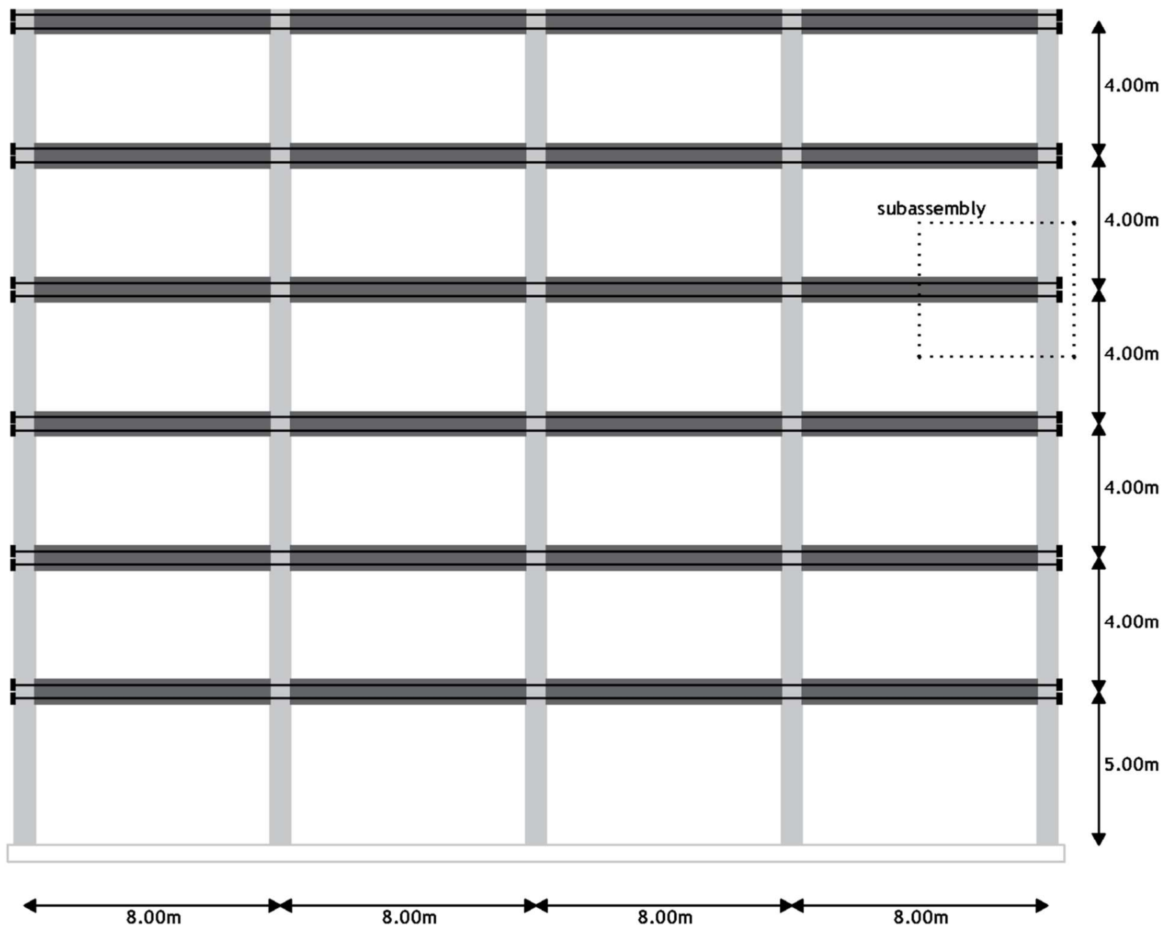


Figure 9 – Sample UPPC frame for tutorial

Let's consider we have made a preliminary analysis for gravity and seismic loads and obtained a design moment.

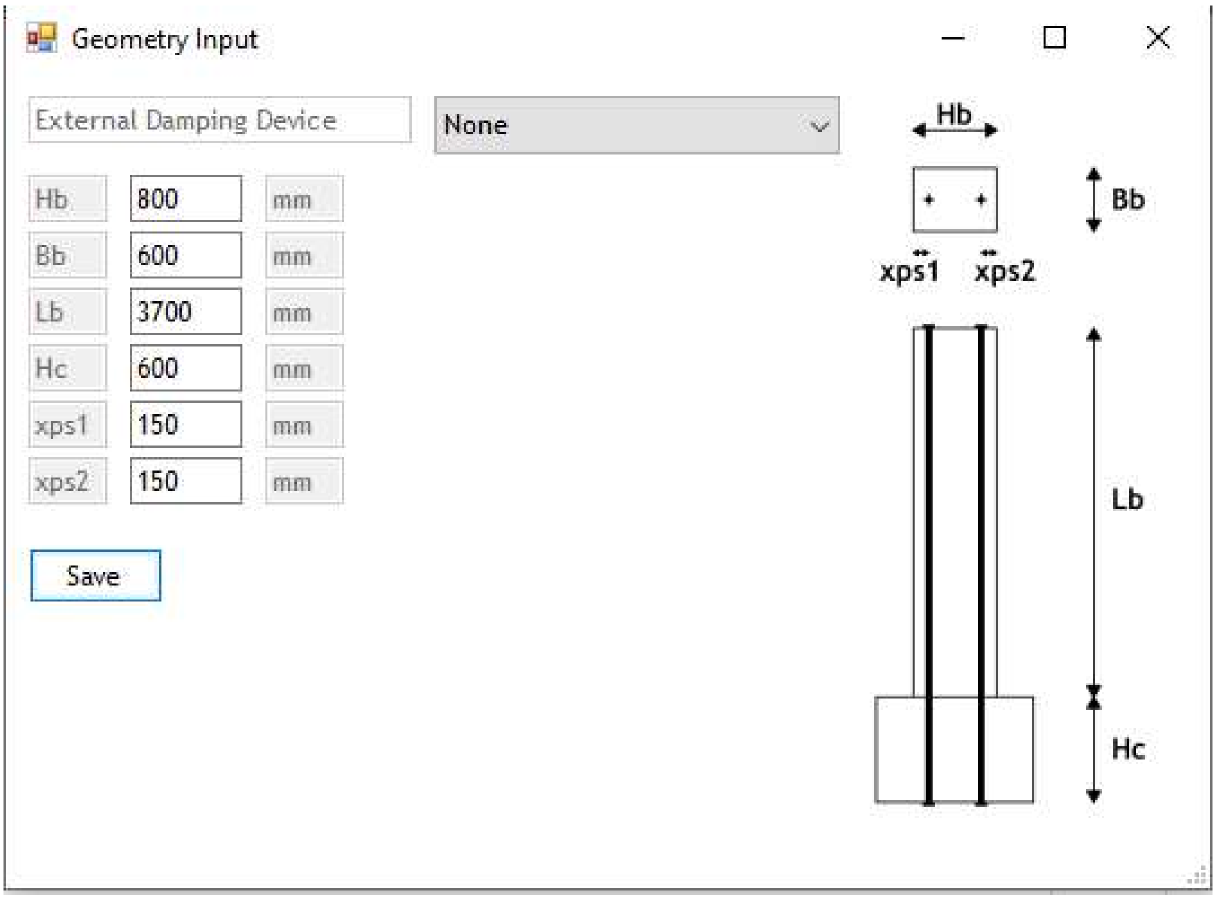
With KULTECH UPPCv0.0, we will choose analysis parameters such as dimensions, strand areas and material strengths, and make a detailed analysis of the joint. We will also see the drift levels at which performance levels are exceeded and obtain energy dissipation ratios ß and equivalent viscous damping ratios ξ_{eq}.

The subassembly we take is the exterior beam-column joint of third floor. Beam and column members are ‘cut’ from the middle (the assumed contra-flexure points) as shown in Figure 9.

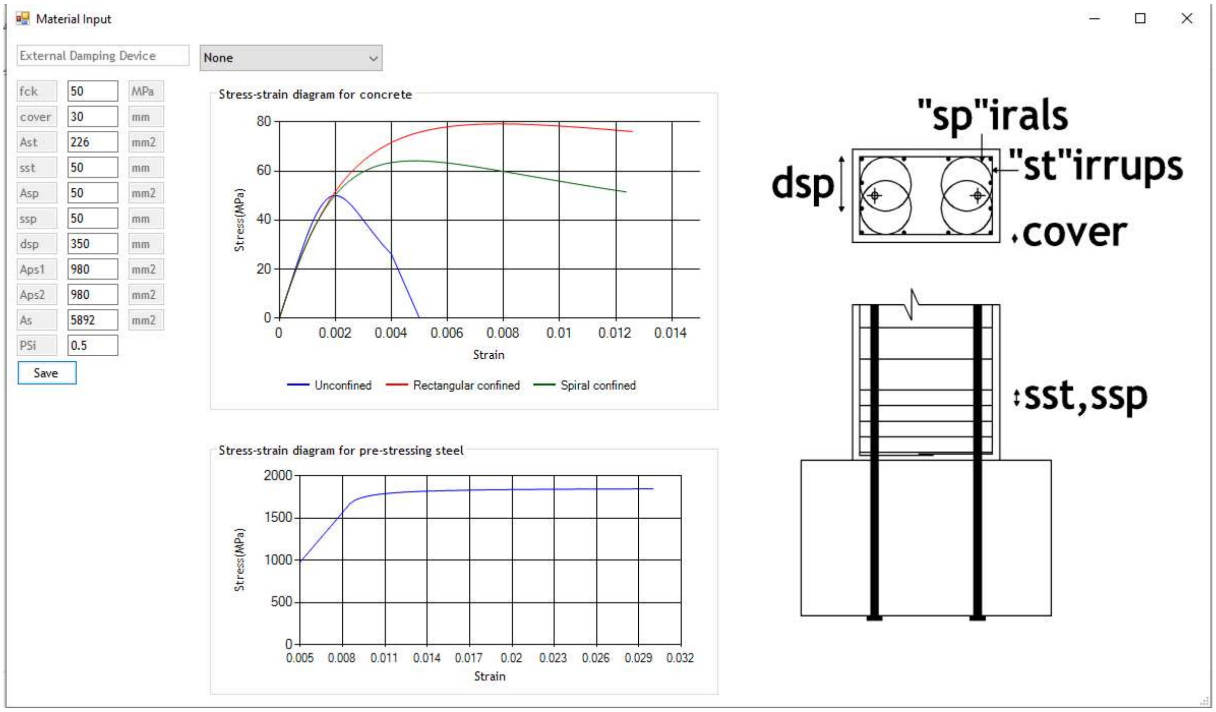
From now on, let’s proceed with ‘tutorial form’.

1. When KULTECH UPPCv0.0 main form is opened, click on ***Input*** on the main menu bar. Then click on ***Geometry Input***.

2. Fill the Geometry Input form with the following values. (Please note the beam length is chosen to be as half the beam clear length). Click on ***Save***. Exit the Geometry Input form.



3. Click on ***Input*** on the main menu bar once again. Now click on ***Material Input***. Fill the form with the input below and click on ***Save*** to see the material stress-strain curves.



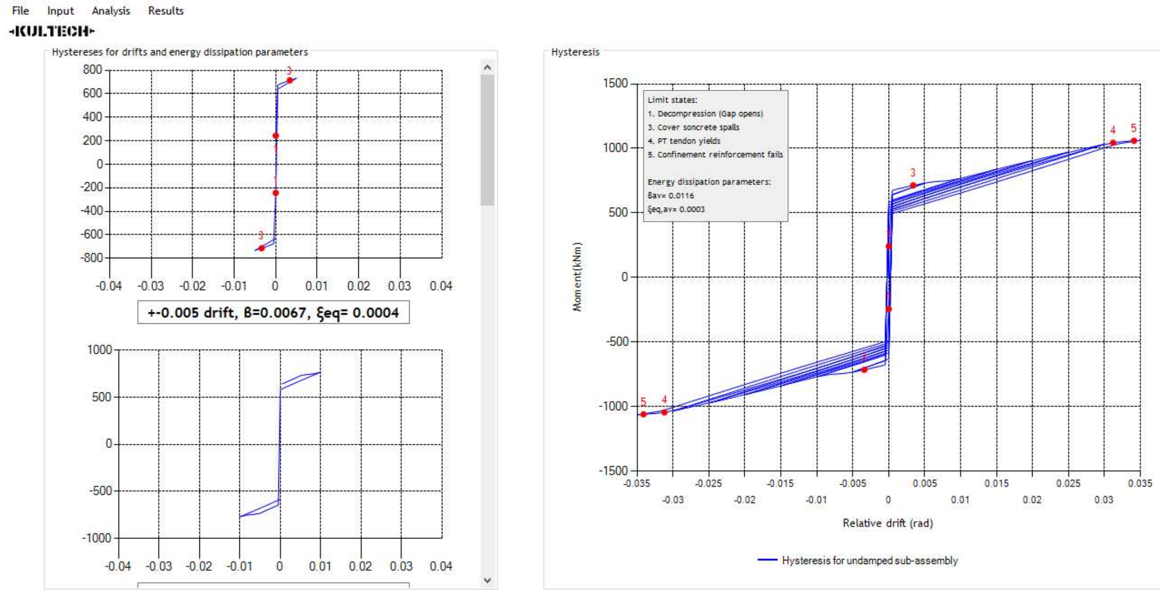
4. Click on ***File*** on main menu. Click on ***Save*** to save the file.

5. Click on ***Analysis*** on main menu. Click on ***Analyze***.

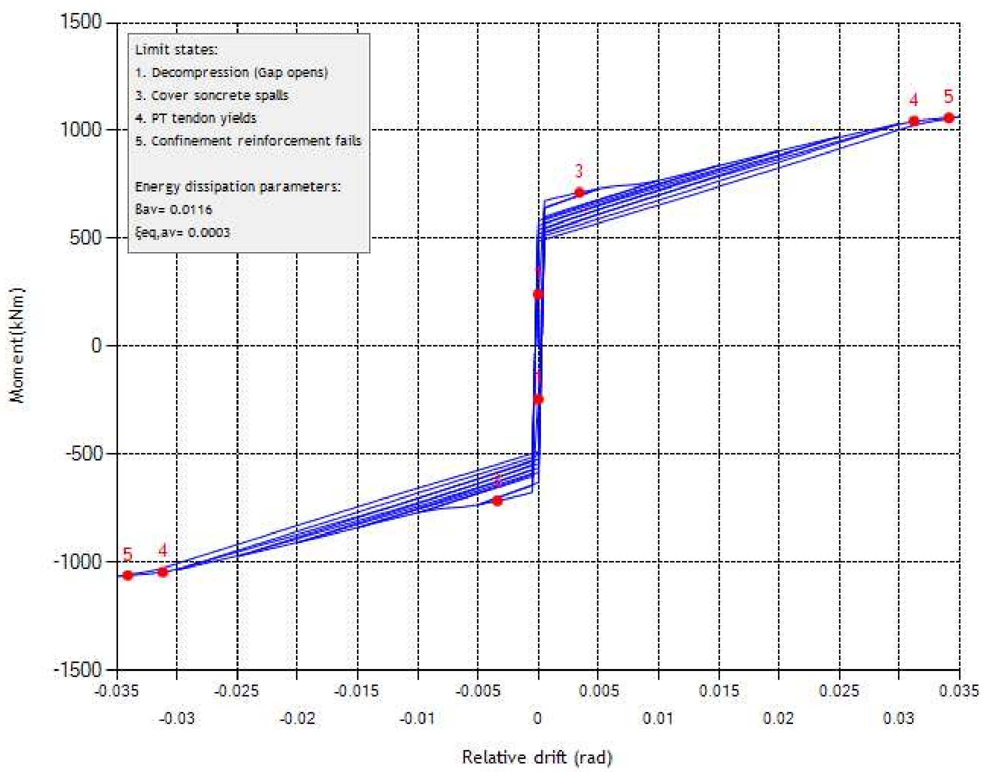
Note: Although in the user interface for Material Input monotonic concrete stress-strain relation is displayed, the program uses cyclic Mander model for unconfined and confined concrete to capture the limited energy dissipation capacity of the joint.

Output and interpretation of results

Once you click the Analyze button, the program performs the analysis and fills the main form as follows:

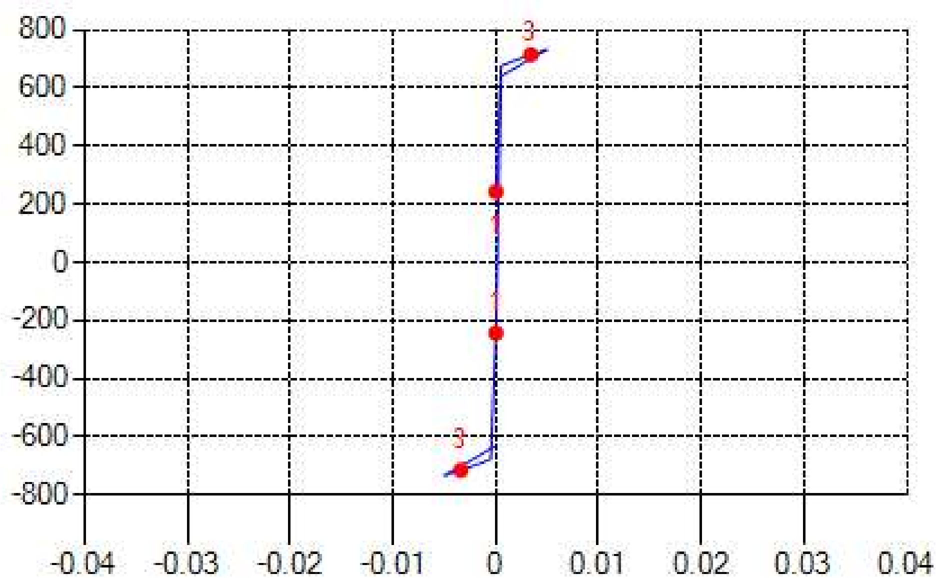


Let's focus on the right part first:

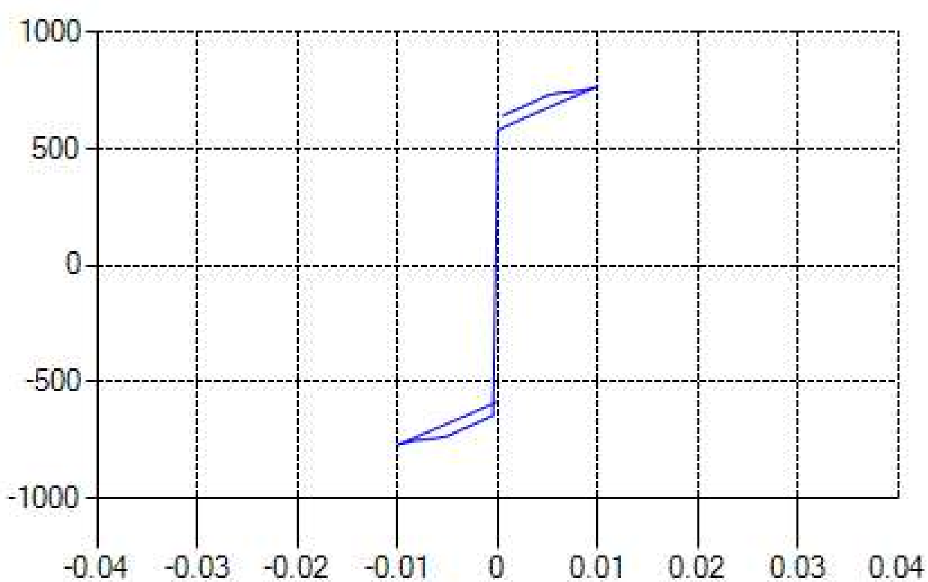


As can be seen, limit states are marked and labeled in the cyclic hysteresis plot. Limit state 2 is not shown since it does not define a clear performance point and it is used to capture deviation from linearity which is naturally captured in the hysteresis. The average energy dissipation parameters along with the definition of limit states are shown at top left part.

On the left part, hysteresis for all drift ratios are shown separately. In addition, energy dissipation parameters for that drift ratio is also given.



+-0.005 drift, ß=0.0067, ξeq= 0.0004

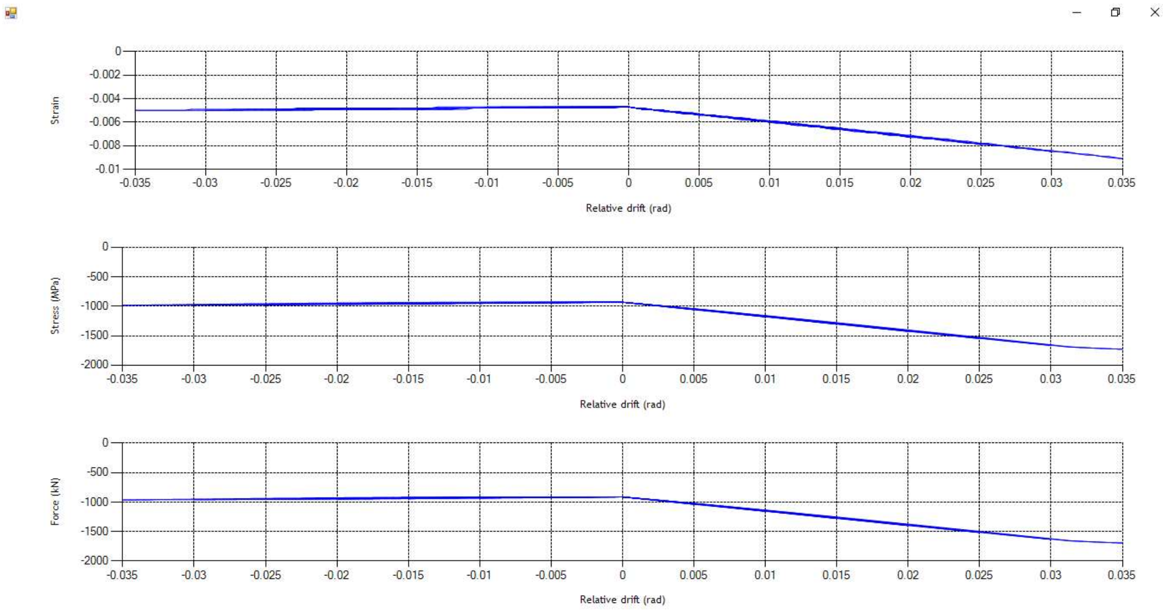


Now let's see the results in table form.

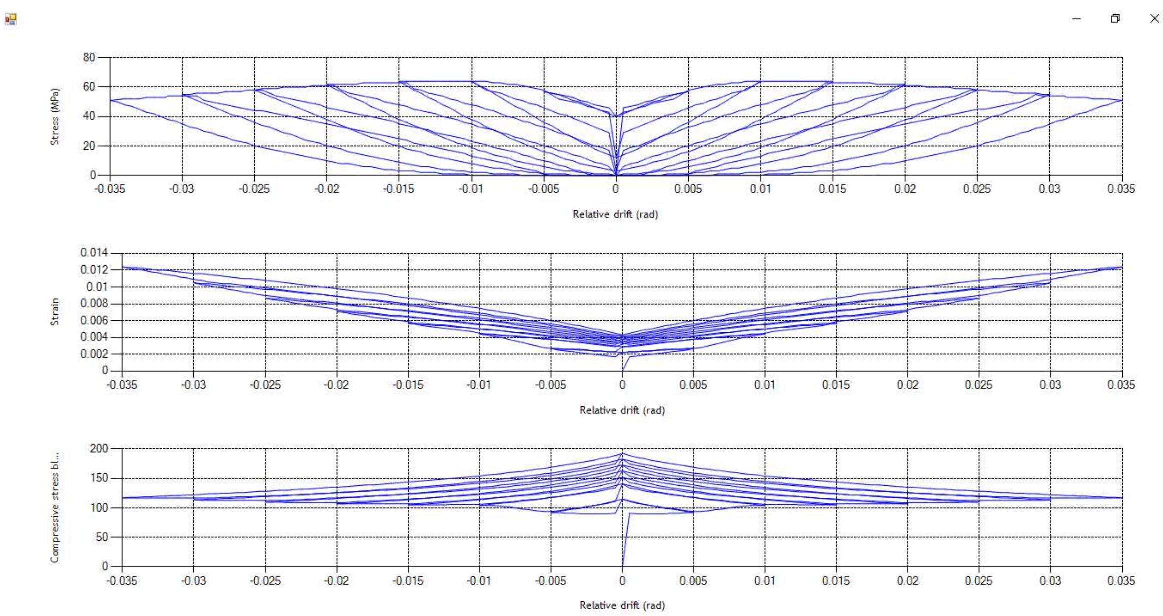
6. Click on ***Results***. Click on ***Tables***. You will see the following form. With this form you can navigate through all the data.

θhys	Mhys	c	εc0	Fc	εps1	Fps1	εps2	Fps2
rad	kNm	mm		kN		kN		kN
0	243	0	0	0	-0.0047	-912	-0.0047	-912
0.0005	675	90.9	0.0026	1838	-0.0048	-925	-0.0047	-914
0.001	683	90.3	0.0027	1852	-0.0049	-937	-0.0048	-915
0.0015	690	89.9	0.0029	1866	-0.0049	-950	-0.0048	-916
0.002	696	89.9	0.003	1880	-0.005	-962	-0.0048	-918
0.0025	703	90	0.0032	1894	-0.0051	-975	-0.0048	-919
0.003	709	90.3	0.0034	1908	-0.0051	-987	-0.0048	-920
0.0034	714	90.6	0.0035	1919	-0.0052	-998	-0.0048	-921
0.004	720	91.2	0.0037	1935	-0.0053	-1012	-0.0048	-923
0.0045	726	91.8	0.0039	1949	-0.0053	-1025	-0.0048	-924
0.005	732	92.4	0.0041	1962	-0.0054	-1037	-0.0048	-925
0.0045	722	94	0.004	1948	-0.0053	-1024	-0.0048	-923
0.004	712	95.7	0.0039	1933	-0.0053	-1012	-0.0048	-922
0.0035	702	97.5	0.0038	1919	-0.0052	-999	-0.0048	-920
0.003	692	99.5	0.0037	1905	-0.0051	-986	-0.0048	-919
0.0025	682	101.6	0.0036	1891	-0.0051	-974	-0.0048	-918
0.002	671	103.8	0.0035	1877	-0.005	-961	-0.0048	-916
0.0015	661	106.2	0.0034	1864	-0.0049	-949	-0.0048	-915
0.001	651	108.8	0.0033	1850	-0.0049	-936	-0.0047	-914
0.0005	640	111.6	0.0032	1837	-0.0048	-924	-0.0047	-913
0	-243	114.6	0.0031	1824	-0.0047	-912	-0.0047	-912

7. To see plot for post-tensioning strands, click on ***Results***. Now click on ***PT strands***.



8. To see the results for concrete fibers, click on ***Results***. Now click on ***Concrete***.



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