Grid4Build: A High Performance Grid Framework for the 3D Analysis and Visualisation of Building Structures

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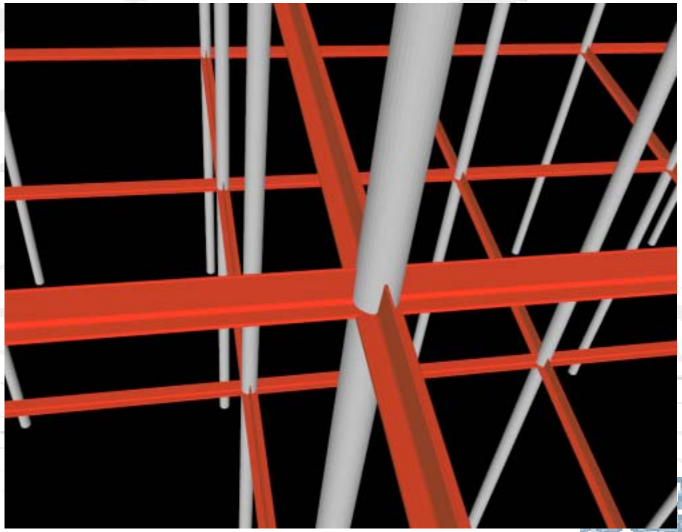
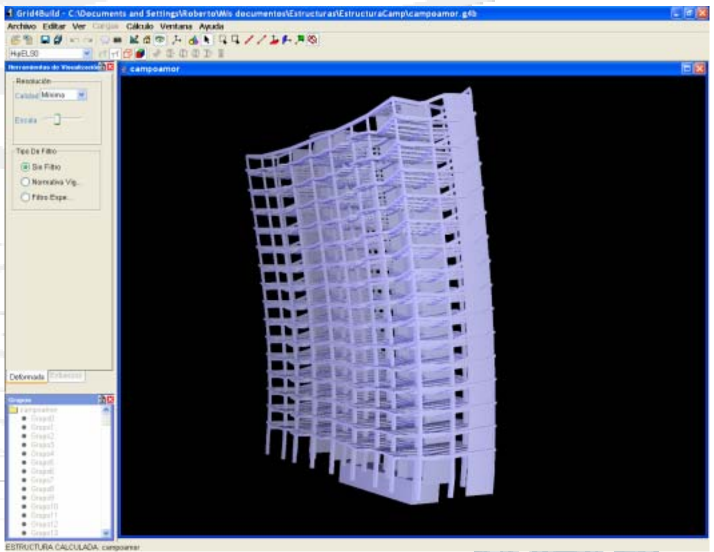


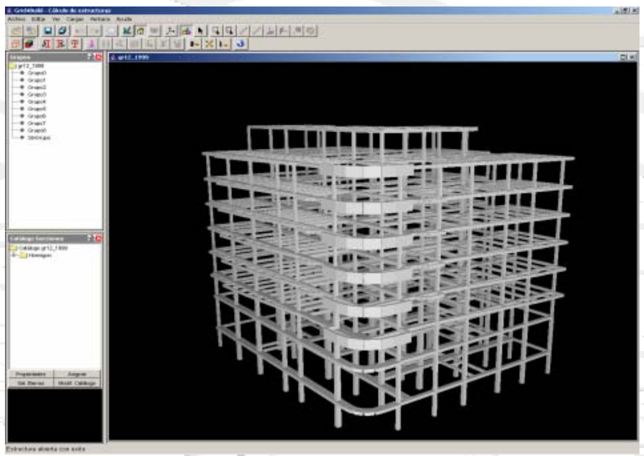
Advanced Computational Techniques in Structural Analysis

- Structural analysis of buildings is the process to determine the response of a structure to different applied loads.
- 3D dynamic analysis of buildings is a time-consuming and memory intensive problem.
- Simplifications have been carried out:
  - Reduce computation and memory requirements.
  - The number of nodes considered and the number of dof have been severely restricted.
  - Inadequate for asymmetric and complex structures.



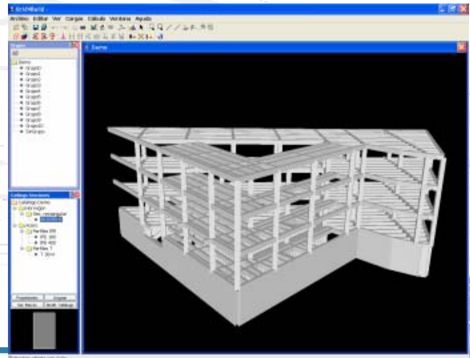
Advanced Computational Techniques in Structural Analysis

- Seismic analyses are model dependent:
  - A need for realistic 3D analytical models.
  - Calculations must be performed accurately, complying criteria of safety, cost limitations and construction constraints.
- The amount of computations and memory required in a 3D realistic analysis can be too intensive for a single PC.



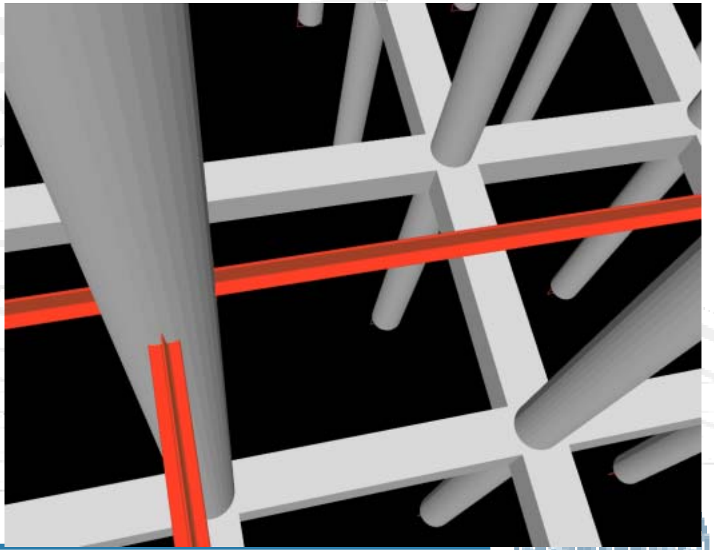
Advanced Computational Techniques in Structural Analysis

- A high number of alternatives must be simulated:
  - A structural designer simulates different preliminary solutions (distinct layouts, section members, etc.).
  - Spanish Earthquake-Resistant Construction Standards (NCSE-02): Each building must be analysed at least with five earthquakes.
- The computational requirements of the problem are enlarged by several orders of magnitude.
- Usage of parallel computing is recommended:
  - Simulate buildings by means of several computers.
  - Tackle in a realistic way large-scale structural problems.
  - Reduce the computational time.
  - Simulate larger buildings.
  - Employ cost-effective cluster of PCs.



The Parallel Structural Simulator

- A parallel application has been developed:
  - 3D realistic analysis (6 degrees of freedom and all the nodes are considered).
  - Static and dynamic (direct time integration methods and modal analysis techniques) simulations.
  - All the computation stages are parallelised (MPI).
  - It employs state-of-the-art public domain numerical libraries.
  - Usually run on a cluster of PCs but highly portable to other platforms.



The Parallel Structural Simulator

- Static Structural Analysis. The Stiffness method:
  - Obtain its group of nodes and structural members.
  - Generate the Stiffness matrix K.
  - Generate the external load matrix F.
  - Impose the initial conditions.
  - Solve the system of linear equations for joint displacements KD=F.
  - Calculate the member end forces.
  - Compute the stresses and deformations at any point of the structure.

The Parallel Structural Simulator

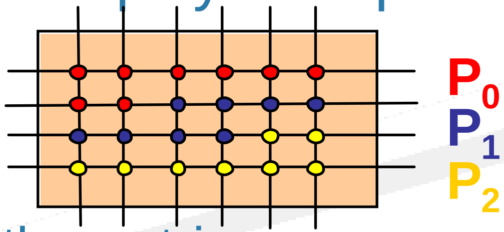
- Dynamic Analysis. Direct Time Integration methods:
  - Obtain its group of nodes and structural members.
  - Generate the Stiffness, Mass and Damping matrices.
  - Obtain the Effective Stiffness matrix Kefect.
  - Impose the initial conditions.
  - For each time step t=Δt, 2Δt, ..., TMax:
    - Evaluate the effective dynamic load vector Fefect.
    - Compute displacements (solve a system of linear equations): Kefect*d=Fefect.
    - Compute velocities and accelerations.
    - Calculate the member end forces.
    - Compute the stresses and deformations at any point of the structure.

The Parallel Structural Simulator

- Dynamic Analysis. Modal Analysis techniques:
  - Obtain its group of nodes and structural members.
  - Generate the Stiffness and Mass matrices.
  - Compute the natural frequencies (w) and the natural mode shapes of vibration (Φ) by solving the eigenvalue problem: $K\Phi=w^2M\Phi$.
  - For each time step $t=\Delta t, 2\Delta t, \ldots, TMax$:
    - Evaluate the effective dynamic load vector.
    - Solve a set of independent equations of one degree of freedom.
    - Compute the displacements, velocities and accelerations at joints.
    - Calculate the member end forces.
    - Compute the stresses and deformations at any point of the structure.

Parallelisation Strategy

- The data parallelism paradigm has been employed to parallelize the problem:
  - *N/p* contiguous nodes are assigned to each processor.



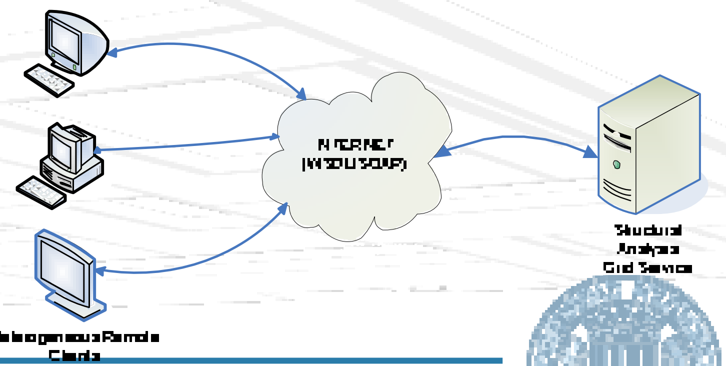
  - Each processor computes its local part of the matrices (stiffness, mass) and vectors (displacements, velocities, ...).
  - Data required for the simulation are partitioned following a rowwise block-striped distribution.
- Moments and deformations are calculated in parallel:
  - B/p contiguous structural elements are assigned to each processor.
  - Each processor computes:
    - 12 internal forces at the ends of its members and the reactions in points attached to the foundation.
    - Moments and deformations at any point of the structural elements.

Numerical Libraries Employed

- Systems of linear equations:
  - WSMP (Watson Sparse Matrix Package): Parallel factorisation based on Cholesky Multifrontal algorithm.
  - MUMPS (MUltifrontal Massively Parallel Solver): Parallel Multifrontal technique based on LDLT factorisation.
  - PETSc (Portable, Extensible Toolkit for Scientific Computation): Krylov subspace methods and preconditioners.
- Eigenvalue problem:
  - SLEPc (Scalable Library for Eigenvalue Problem Computations). Large sparse standard and generalized eigenvalue problems:
    - Implementations of different methods.
    - Transparent access to external software package: ARPACK (ARnoldi Package).

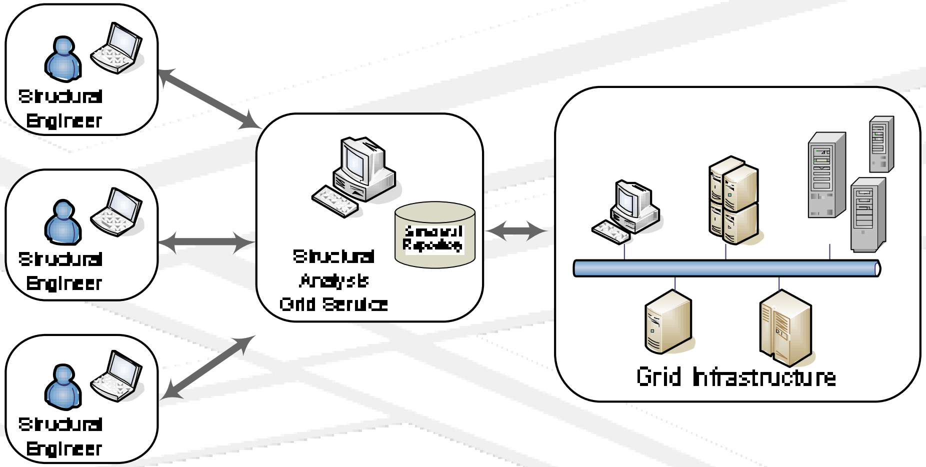
Advanced Computational Techniques in Structural Analysis

- Studios for engineering do not own parallel platforms:
  - Simulations on standard PCs. It limits the size of the problem to be treated.
  - Do not want to invest in clusters because of the physical space required and maintenance problems.
- A need to resort to other advanced computational techniques (Grid Computing).
- To expose the functionality of the Parallel Structural Simulator over the Internet, in the shape of service-oriented systems to perform on demand analysis over computational Grids.
- Heterogeneous clients could analyse their structures using standard protocols (SOAP, WSDL, HTTP).



Grid Models Applicable to Structural Analysis

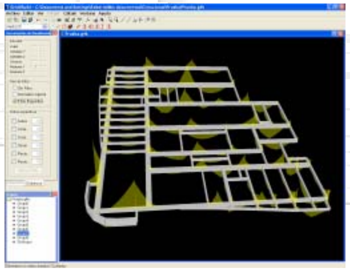
- Client-Service:
  - A machine offers a reliable structural analysis service.
  - A client sends their simulations.

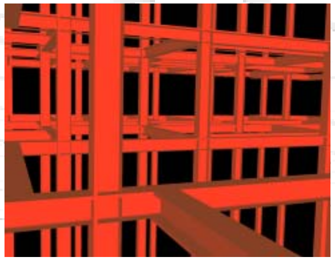


- High Throughput:
  - Multiple heterogeneous clients employ concurrently the service.
  - Lots of different structural solutions are analysed in the Grid resources at the same time.
  - Objective: To compute as many simulations as possible.

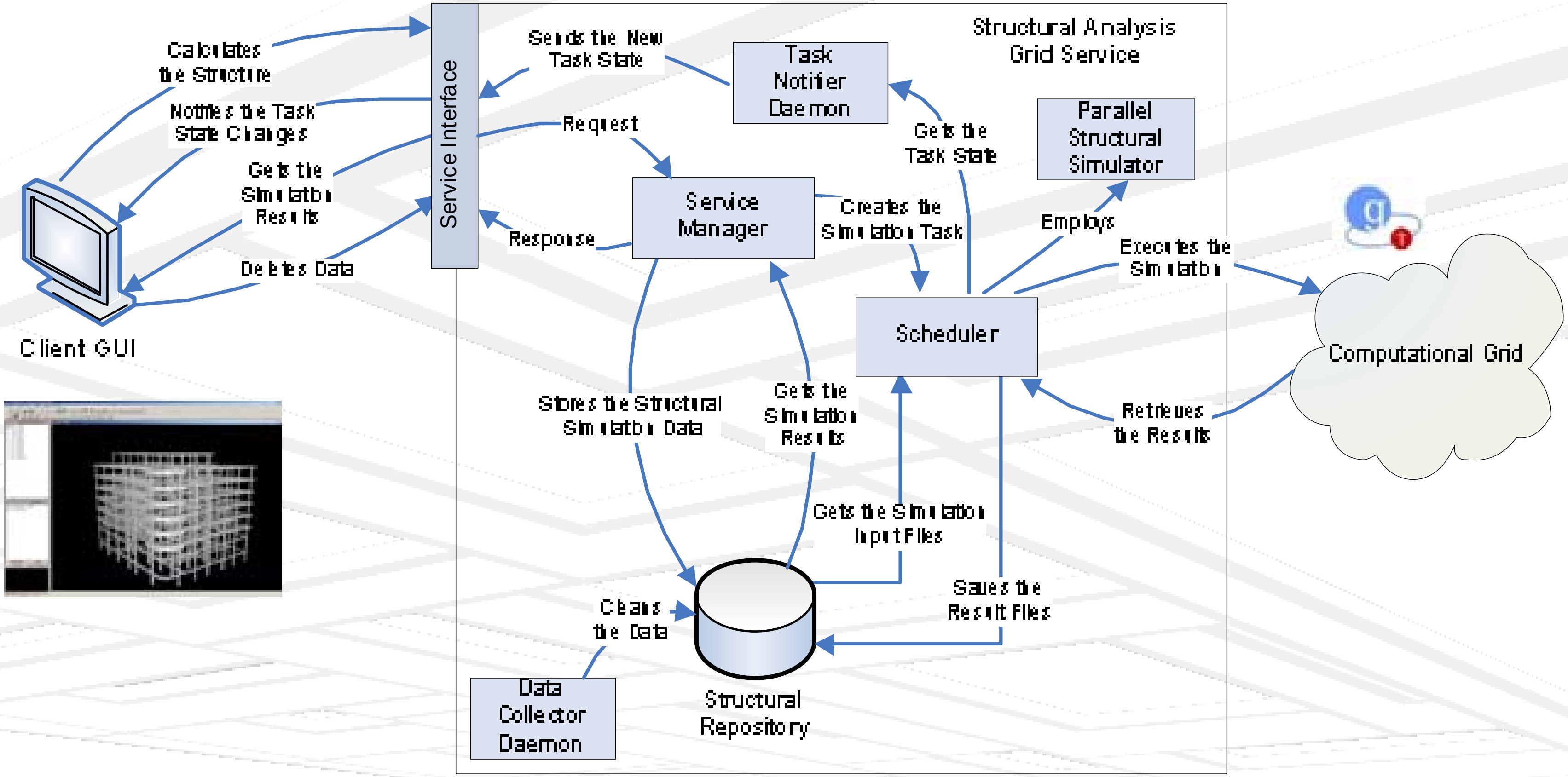
The Structural Analysis Grid Service

- A Structural Analysis Grid Service has been developed.
- It implements a Service Oriented Architecture (SOA).
- It is based on a high throughput Grid model.
- It offers static and dynamic 3D on demand structural analysis by means of the Parallel Application.
- It is based on Globus Toolkit 4.
- Heterogeneous clients access the service via standard protocols (SOAP, WSDL, HTTP).
- The most appropriate computational resource of a Grid infrastructure is employed for each simulation.





Architecture



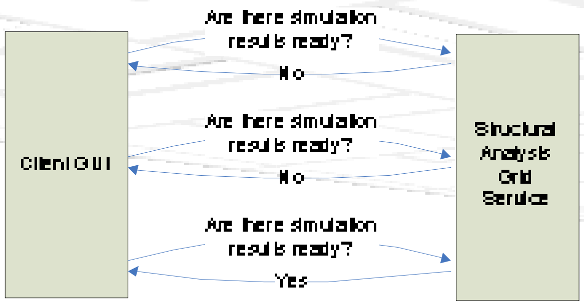
Client-Service Communications

- One of the main problems related to a SOA.
- SOAP messages:
  - XML files. Text files introduce a non-viable overload in the communications. An efficient alternative approach has been developed:
    - Use of a hexadecimal codification for embedding binary data inside the SOAP message.
    - Important reduction in message sizes and in time of communications.
- GridFTP protocol:
  - The clients have direct access to the Structural Repository.
  - They can download directly the binary result files.
  - More efficient alternative for large volume of results.

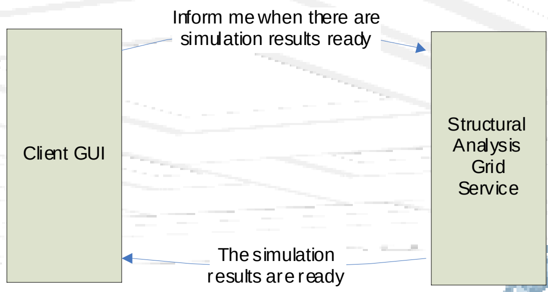
Notifications

- A notification based-strategy has been employed.
- Software design pattern that enable to inform the client about changes in its simulations (waiting, in execution, failed, finalized, ...):
  - The client no longer consults the state of the simulations but it is informed by the service.
  - The overload in the service is reduced (specially in case of multiple clients).
  - For each simulation, the services creates a notification item. The client subscribes to this item and it is informed about any simulation change.

Without Notifications



With Notifications



Result Transfers

- Static Analysis:
  - The scheduler retrieves the results once the task has finished.
  - The client is informed.
  - The client invokes a “Get Results” request.
- Dynamic Analysis:
  - Large volume of data in multiple time steps.
  - Result transfers to the scheduler and to the client are overlapped with computations.
  - The client is informed when the service has available a determined amount of output data.
  - The client invokes multiple “Get Results” requests.

Fault Tolerance

- Several fault tolerance levels have been implemented.
- It is guaranteed that all simulation requests will be successfully attended.
- Client:
  - A simulation identifier is stored for each analysis.
  - In case of failure client or if the client application is closed, the results can be retrieved later (asynchronous result transfer).
  - The client will be subscribed again to the notifications.
  - Results will be transferred when ready.
  - In dynamic analysis, results will be retrieved from the last time step successfully received.
- Grid Service:
  - An in course task persistence schema has been implemented.
  - One file stores the service state and all the information needed to re-launch the pending simulations tasks after a failure.
  - Task execution failures will be managed by the Grid scheduler.

Security Aspects

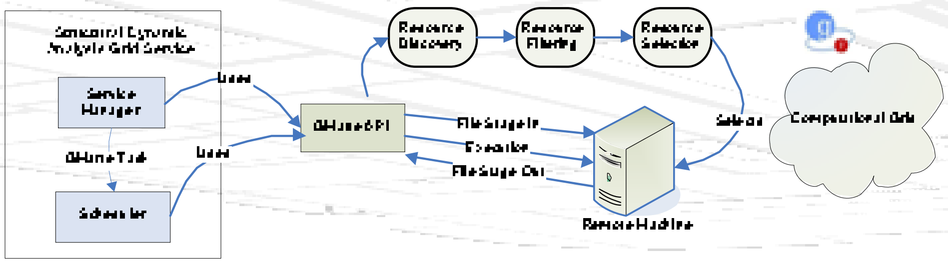
- The security layer involves aspects like user authorization and authentication as well as data privacy and integrity.
- User authorization and authentication mechanisms:
  - Special file containing the allowed clients (authorization).
  - The allowed users are matched with internal service users conferring different privileges.
  - The user credentials (authentication process) are specified via a X.509 certificate.
- Data privacy and integrity:
  - A public/private key encryption schema is used to transport the data between the client and the service.

Grid Scheduling

- The allocation of simulations to resources are managed by a Grid metascheduler.
- For each simulation, the best resource must be selected.
- It has a clear impact on the service performance.
- GMarte (Grid Middleware for Abstract Remote Task Execution) metascheduler has been employed:
  - Client-side object-oriented middleware which enables the execution of scientific applications on Globus 2.x and 4.x based-resources.
  - It provides a Java API.

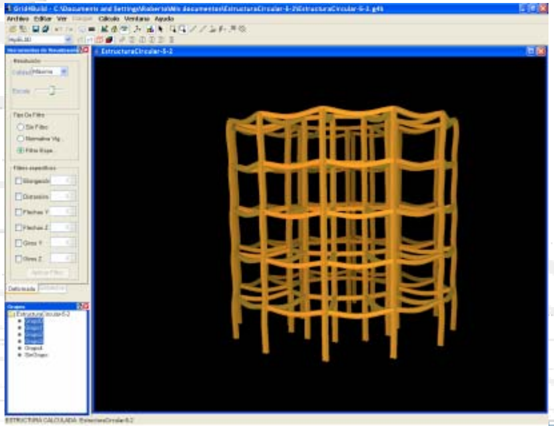
Grid Scheduling

- Resource discovery, resource filtering, scheduling, fault tolerance, job monitoring, data transfer management, etc.
- It considers application requirements, the dynamic resource state and the network.
- It incorporate a multi-threaded metascheduler (faster scheduling times and high throughput).
- Fault tolerance among Grid Service and resources.
- Partial result support. Not present in other middlewares:
  - Periodic retrieval of data at the time of their generation.
  - No need to wait for the dynamic simulations to finish completely.
  - Overlapping of the data communications and the execution of the simulation.



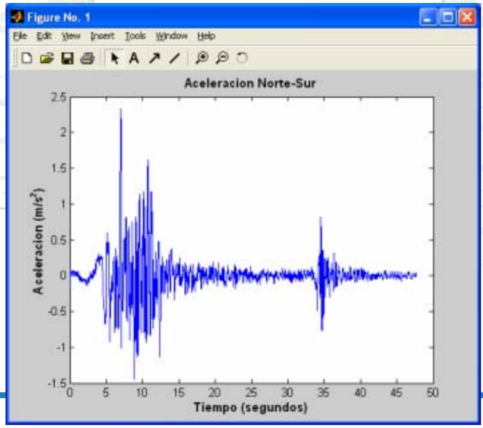
The Client GUI

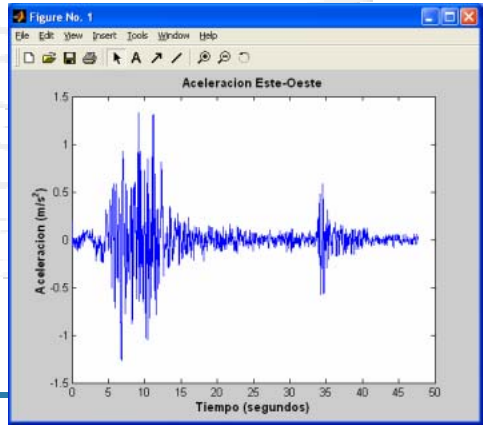
- Developed over Java 3D libraries.
- User-friendly preprocessing and post processing stages.
- The user can interact with the structure (rotations, translations, zooms). High level of interactivity.
- Several structural elements selection tools.
- Preprocessing phase:
  - Assign different properties to structural members (initial conditions, sections, static and dynamic external loads, etc.).
  - Simulation parameter definition.
- Post processing stage:
  - Stresses and deformations.
  - Graphical and numerical information.
  - Videos.
- Analyses the structure by means of the Grid Service.

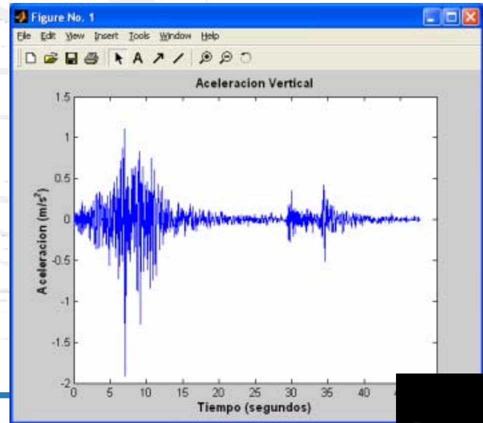


Example of Result Visualisation

- August 17, 1999.- Earthquake occurred in Izmit (Turkey): 35.000 dead, 30.000 injured y 15.500.000 affected. Magnitude: 7,4 Richter.







Conclusions

- A high performance Grid Computing framework has been developed.
- The GUI Client assists the structural engineers in the pre-processing and post-processing stages.
- The HPC-based parallel stimulator: 3D parallel static and dynamic structural analysis of large buildings.
- The Structural Analysis Grid Service:
  - Based on Globus Toolkit 4. It employs GMarte metascheduler.
  - It fulfils the requirements of a multilevel system available via the network: Robustness, reliability, security and fault tolerant.
  - It offers a parallel simulator to the structural scientific community:
    - ➢ Takes advantage of geographically distributed resources.
    - ➢ No need to invest in hardware, software and to be worried about new updates.
- Grid4Build framework is being exposed during this week in Construmat 2007 International Building Exhibition.