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THE SERIES DATABASE OF RC ELEMENTS

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ABSTRACT

Within the FP7 project SERIES, a RC element structural database has been assembled from existing experimental data from literature, to provide researchers with the data needed to evaluate and develop seismic performance models for different RC load bearing elements. The database builds on previous work of the same or other research teams worldwide. It includes data on RC walls, columns and beams. In the paper the motivation, the basic structure of the three sub-databases, and some snapshots showing the applicability of the database, are presented.

INTRODUCTION

In the European Union's Seventh Framework Programme (FP7), the research project Seismic engineering research infrastructures for European synergies (SERIES) was carried out in the period 2009-2013 (SERIES, http://www.series.upatras.gr). 23 partners, including all major infrastructures in Europe and three industrial beneficiaries, were involved. The project offered to the European earthquake engineering research community and industry an opportunity to access large-scale research infrastructures; it also gave the opportunity to the infrastructures to develop further their experimental research. Within the project, a task was devoted to the development of a database of existing tests on reinforced concrete (RC) structural elements. The targeted data were available in the literature (papers in journals and conference proceedings, research reports, personal contacts, theses, etc.) or residing in individual laboratories in digital, albeit non-structured, form.

So far, the estimation of capacities of RC structural elements, like columns, walls and beams, relies mainly on empirical equations, as for example the formulas developed by Fardis and co-workers (Biskinis and Fardis 2010a, 2010b, Biskinis et al 2004) which were implemented in Eurocode 8, Part 3 (CEN, 2005). For the success of the empirical approach, an appropriate database of experimental results is needed. Decades ago, databases contained relatively few test data; moreover, most of them were available only in analogue form (e.g. report by Hirosawa, 1975). Recently, more comprehensive databases for RC members became available, such as the PEER database compiled at the University of Washington (Berry et al., 2004), the databases compiled by Fardis and co-workers (Panagiotakos and Fardis, 2001), updated by Biskinis et al. (2004), Biskinis (2007), Biskinis and Fardis (2010a, 2010b), Grammatikou (2013) and the databases by Lu et al. (2010) and Lignos and Krawinkler (2012, 2013).

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The existing databases are prepared in different recording formats (e.g. ASCII, XLS). Many of the databases are not accessible online through the world-wide-web; they are available only by a request to the authors. Links to original sources are possible only through the list of references, making it difficult to control the data obtained and experimental results. Results of older experiments are rarely digitized. They are rarely recorded and post-processed to enable a relatively easy and fast development of seismic performance models taking into account the common definitions of capacity parameters. Only in exceptional cases the results are shown in a graphical form, providing a visual information about an experiment, for example, on the overall behaviour, ductility or type of failure. Moreover, many databases have become outdated, as the authors have stopped to maintain them.

In spite of some shortcomings, the existing databases contain a large number of useful experimental data. The aim of the work performed within the SERIES project was to prepare a comprehensive, harmonised and user-friendly database of RC structural elements, using mostly the existing databases. The SERIES database builds on previous work carried out at the University of Washington (Berry et al., 2004), University of Patras (Panagiotakos and Fardis, 2001; Biskinis et al, 2004; Biskinis, 2007, Biskinis and Fardis, 2010a, 2010b, Grammatikou, 2013), Stanford University (Lignos and Krawinkler, 2012, 2013) and University of Ljubljana (Peruš et al., 2006; Poljanšek et al., 2009). It includes data on three different structural elements – RC columns, beams and walls (Perus et al., 2013; SERIES database, 2013).

In this paper, the motivation, the basic structure of the SERIES RC elements database, its data and some snapshots showing the applicability of the database are presented. The RC elements database is public at the SERIES Data Access Portal: http://www.dap.series.upatras.gr/

BASIC CONCEPTS OF THE SERIES DATABASE

In principle, different types of RC structural elements require different types and amounts of data, e.g., beams require more data than columns because of a larger variety of possible shapes (rectangular, T- and L- shaped cross sections) and because of asymmetric reinforcement. Different shapes are also characteristic of walls (rectangular, barbell and flanged cross sections). For columns, circular or some less common shapes (e.g. octagonal) are used. Therefore, the basic idea was to divide the RC element database into three sub-databases, which correspond to different types of RC elements: columns, beams and walls. In this way the databases are much more transparent and easier to use for automatic computational procedures. Of course, all databases should be consistent, having as many common parameters as feasible. Moreover, a further division of sub-databases, considering some specific forms of cross-section (for the same element) is made, e.g. columns of circular cross-section, beams with I cross-section, etc. In this way, the main databases include the most common types of these elements (square and rectangular cross-sections for columns, rectangular and T-shaped ones for beams, rectangular, barbell and flanged cross-sections for walls), whereas less common types (special cross-sections, e.g. circular, I- or L- shaped cross sections) have not been included yet in separate databases.

Microsoft Excel®, which has been widely used by the research and engineering community, enables intuitive and simple storing of the information. It offers also the possibility to perform quantitative analyses that range from statistical analyses to complex estimation tools, which are all equipped with user-friendly front ends. In addition, unlike many traditional statistical programs, it provides an intuitive interface. Therefore, it was decided to use Excel to store all the relevant information regarding the RC structural elements.

The main idea in structuring the sub-databases (RC column, beam and wall databases) was to divide the database in two main parts comprising: (1) the basic data, provided by the researchers in papers, reports, etc. and (2) the derived data, which may further assist researchers in their analyses (i.e. developing seismic performance models for different RC structural elements).

The first part (basic data) of any sub-database therefore consists of two sheets of an Excel file:

- *ReportedData,*
- *MetaData.*

The second part (derived data) of any sub-database consists of four sheets:

- *MetaData-SI_Units,*
- *MetaData-US_Units,*

- *CalculatedData-SI_Units,*
- *CapacityData-SI_Units.*

The structure of the RC elements database is shown in Figure 1. A more detailed description of each sheet is presented in the next section.

The original data reported in the literature use either SI or US customary units (see sheet *Metadata*). In order to reduce the possibility of errors, the same data, but expressed in different units, are presented in the sheets *MetaData-SI_Units* and *MetaData-US_Units*, respectively. In the sheet *CalculatedData-SI_Units* results of individual experiments are included in SI units (e.g., hysteretic response, peak points, envelope, dissipated energy). In the sheet *CapacityData-SI_Units* data and results of individual experiments are collected in a form that allows direct development of seismic performance models (derived input parameters that describe the mechanical and geometric parameters, e.g. shear span ratio, axial load ratio, etc., and the parameters of the deformation capacity, e.g. capping drift, ultimate drift etc.).

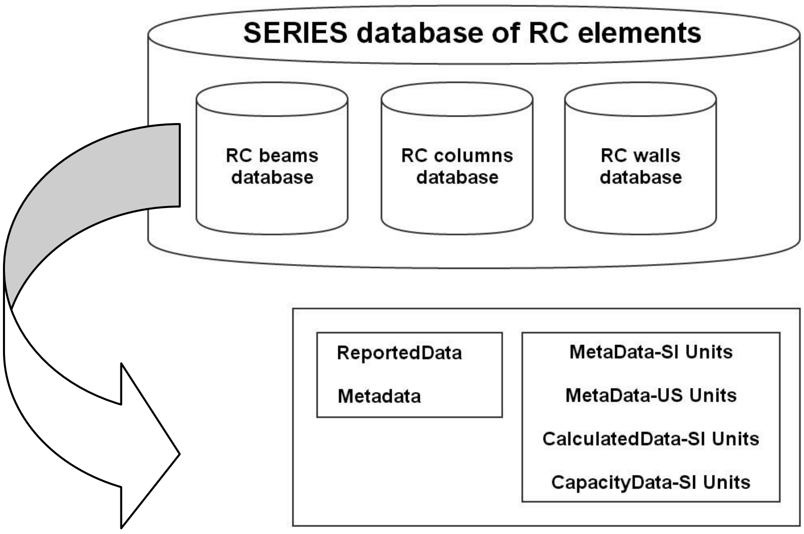

Figure 1. Schematic presentation of main modules of the SERIES RC elements database. Each module, related to the one of three sub-databases (i.e. beams, columns and walls), contains two main parts, including two and four Excel sheets, respectively.

For the time being, only the results of RC beams are post-processed to allow immediate further use for analyses (i.e. development of seismic performance models). Additional information on the post-processing of the results is given in the following two sections. Post-processed data are not yet available for the RC columns and RC walls sub-databases; however the information collected and recorded from the original source, including digitized force-displacement loops, permits the user to post-process the data him/herself.

DATA IN THE SERIES DATABASE

The most general data associated with the RC element specimens are described in the *ReportedData* Excel sheet. Besides the notation (e.g. *Serial number*, *Experiment campaign number*, *Test number*, *Test ID notation*), which uniquely define each specimen in the database, parameters such as *Reference*, *Comments*, *Digitized history*, *Axis units* and *Damage* relate the data to the original sources.

The data which define the main parameters of the tested specimen are presented in the *MetaData* sheet, and use original units (SI or US). They are related to the geometry of the specimens (e.g. cross-section dimensions, length of specimen, test configuration), axial load, type of loading, concrete properties, longitudinal , transverse and diagonal reinforcement, steel properties (yield stress and ultimate strength), reinforcement details (e.g. number of longitudinal bars, number of confinement hoops, bar diameters, concrete cover, embedment types, steel grades, etc.) and reported failure mode. Note that most parameters are the same for all three RC element types. The other parameters, which describe properties that distinguish one element type from another (e.g. cross-section properties of the flanged wall in relation to the rectangular column) are added accordingly.

In order to reduce the possibility of errors due to the use of different units, the same data are presented again in the sheets *MetaData-SI_Units* and *MetaData-US_Units*, consistently using either SI or US customary units, respectively.

More detailed data and data determined by processing the data are collected in the sheet *CalculatedData-SI_Units*. Hyperlinks to the files, which include numerical and graphical data on the digitized hysteretic loops, peak points, envelopes and hysteretic energy, are provided. For the time being, all collected RC specimens include graphical data on the digitized hysteretic loops, whereas only RC beam specimens include post-processed data on the capacity in terms of characteristic points, envelopes and bi-linear idealizations.

The sheet *CapacityData-SI_Units* provides data of individual specimens in a form that allows direct development of seismic performance models using different approaches. Provided are different derived input parameters that describe the mechanical and geometric parameters, e.g. shear span ratio, axial load ratio, longitudinal reinforcement ratio, transverse reinforcement ratio etc. In addition, for RC beam specimens, the parameters of the deformation capacity, expressed in terms of yield, capping and ultimate drift, are given alongside the corresponding strengths.

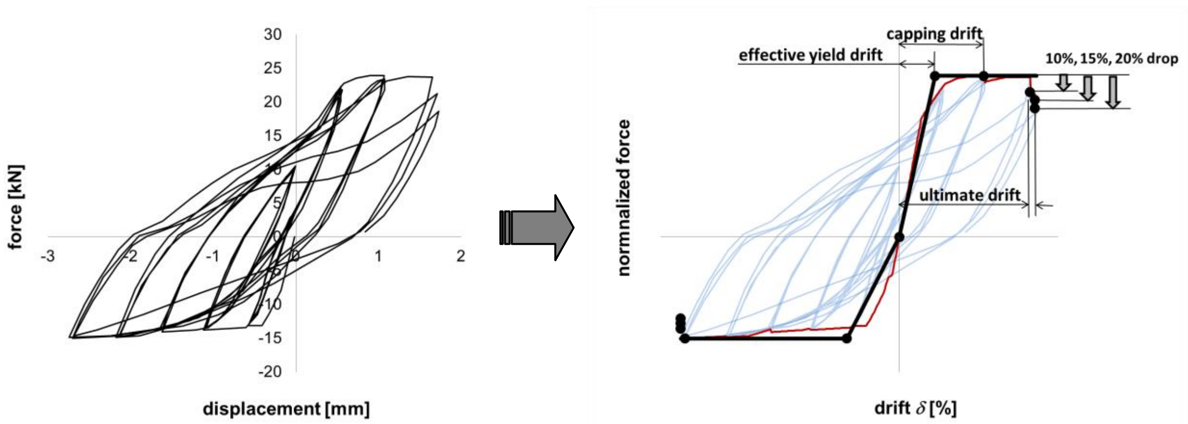

Figure 2. Example of post-processing of the hysteresis data for a beam specimen: (left) hysteretic force-displacement relationship for the tested specimen, (right) negative and positive envelope and idealized normalized force – drift relationship for the positive and negative envelope. The effective yield, capping and ultimate (at 10%, 15% and 20% strength drop) drifts are shown. In a symmetric case, the characteristic drifts are obtained from the mean envelope.

POST-PROCESSED RESULTS

Post-processed results include the determination of characteristic points, which define the capacity of an RC specimen. For example, the drift of the RC specimen (often called drift ratio), which is equal to the chord rotation, is obtained as the displacement at the top of an equivalent cantilever divided by the length of the cantilever (also called "shear span"). The characteristic drifts (see Figure 2), which represent specific points on the force – drift envelope, are the capping drift δ_c and the ultimate drift δ_u. In the case of asymmetric cross section, longitudinal reinforcement or loading (typically for beams), the characteristic drifts are defined separately in the positive and the negative envelope branch, whereas in symmetric case (typically for columns) the characteristic drifts are obtained from the mean envelope. The capping drift is the drift at maximum strength. The ultimate drift was conservatively assumed as the drift at the “near collapse” limit state, defined as the drift at a 20% drop below the maximum strength. In addition, the ultimate drift was determined also at a 15% and 10% drop in maximum strength. Other drift-related output parameters which have been determined, include the effective yield drift δ_y (determined from the bi-linear idealization using the equal-area rule) and the ductility ratio, μ_y, defined as the ratio between the ultimate and the effective yield drift. The ultimate drift according to this description is uniquely defined in the case of failure in a flexural mode. In the case of other failure modes, i.e. shear failure, axial load failure etc., the drop in shear resistance is more sudden and the drifts that correspond to 10%, 15% and 20% drop are usually the same. In most of these cases the capping point coincides with the ultimate drift point. As mentioned above, for the time being, only the RC beams database includes post-processed data on the capacity and the above defined envelops are applicable and available only to them. (compare Figure 6 where the force-displacement loop of an RC column is shown, with Figure 9, where the capacity data include also the envelope, characteristic points and bi-linear idealization of an RC beam).

THE SERIES RC COLUMN DATABASE

The RC column database includes data on 477 tested RC column specimens. It was developed at the University of Patras out of the database developed and used in the past by researchers there (e.g. Panagiotakos and Fardis, 2001; Biskinis and Fardis 2010a, 2010b) and from the PEER database developed at University of Washington (Berry et al., 2004). Displacement-force hysteresis loops not available at the PEER database were digitized manually.

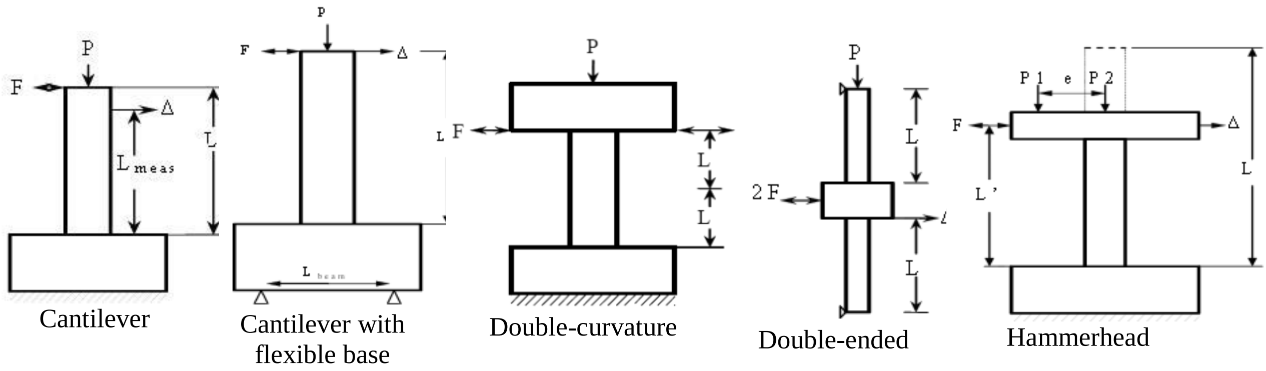

Figure 3. Typical test configurations for RC columns (Berry et al., 2004).

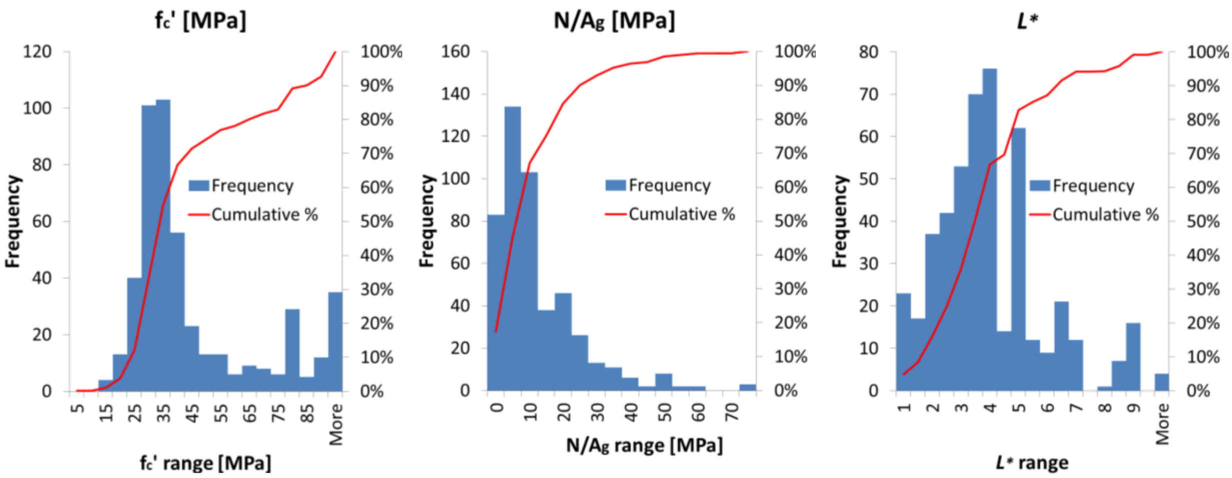

Figure 4. Distributions of specimen's concrete strength f_c, axial stress N/A_c and shear span ratio L* in the SERIES RC column database.

Most of the column specimens (475) were cyclically tested. 349 of the column specimens have square cross-section; the rest have rectangular. In the tests five different test configurations are found:

cantilever column, cantilever column with flexible base, double-curvature, double-ended and hammerhead (Figure 3).

Nine different types of confinement are included: interlocking ties; rectangular ties (around the perimeter); rectangular and interlocking ties; rectangular ties and U-bars; rectangular ties with J-hooks; rectangular and diagonal ties; rectangular and octagonal ties; rectangular and interlocking ties with J-hooks; and U-bars with J-hooks. The specimen concrete compressive strength ranges from 14 to 118 MPa, the compressive stress due to the vertical (axial) loading ranges amounts from 0 to 71 MPa, and the shear span ratio (equivalent cantilever length divided by the depth of the column cross-section) from 0.5 up to 10 (the shear span ratio is larger than 10 in only three column specimens). The data are graphically presented in Figure 4. 285 columns failed in flexure, 30 in shear and 53 in flexure-shear. In about 109 column specimens failure mode was not reported

Figure 5 shows an example of displacement-force history from the SERIES RC column database.

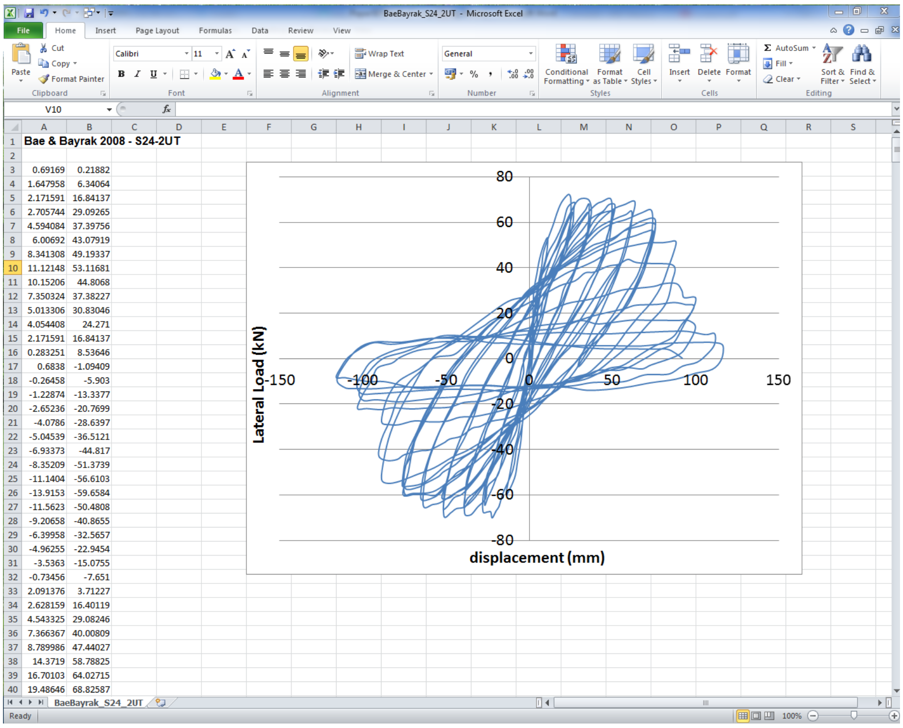

Figure 5. Example of digitized displacement-force history for column specimen from the SERIES RC column database (Specimen # S24-2UT).

THE SERIES RC WALL DATABASE

The RC wall database includes data on 350 tested RC wall specimens. It was derived from the database, which has been developed and used in the past at the University of Patras (e.g. Panagiotakos and Fardis, 2001; Biskinis, 2007; Biskinis and Fardis 2010a, 2010b; Grammatikou, 2013). The displacement-force hysteresis loops from Hirosawa's work (Hirosawa, 1975) were manually digitized at the University of Ljubljana, whereas all others were digitized at the University of Patras. Most of the wall specimens have rectangular (162) or barbell (162) cross-section; 11 have flanged cross-section and 15 of them have other types of cross-section. Six different test configurations were applied in the tests: cantilever wall; cantilever wall with flexible base; double curvature; double ended; hammerhead; and N-point loading (N is the number of loading points along the height of the wall). Nine different types of confinement were considered: interlocking ties; rectangular ties (around the perimeter); rectangular and interlocking ties; rectangular ties and U-bars; rectangular ties with J-hooks; rectangular and diamond ties; rectangular and octagonal ties; rectangular and interlocking ties with J-hooks; and U-bars with J-hooks. Wall specimens were tested cyclically (279) or monotonically

(71). 107 specimens failed in flexure, five in shear-tension, 33 in shear-compression, 18 in sliding shear and three had a lap-splice failure. For 118 specimens which failed in shear and 33 in flexure-shear the exact failure mechanism (shear-tension or shear-compression) was not reported. About 33 specimens did not fail during the experiment. The specimen's concrete compressive strength ranges from 13.5 to 109.1 MPa, compressive stress due to the vertical (axial) loading is from 0 to 34.3 MPa; the shear span ratio (equivalent cantilever length divided by the length of the wall cross-section) is from 0.35 up to 4.1(see also Figure 6).

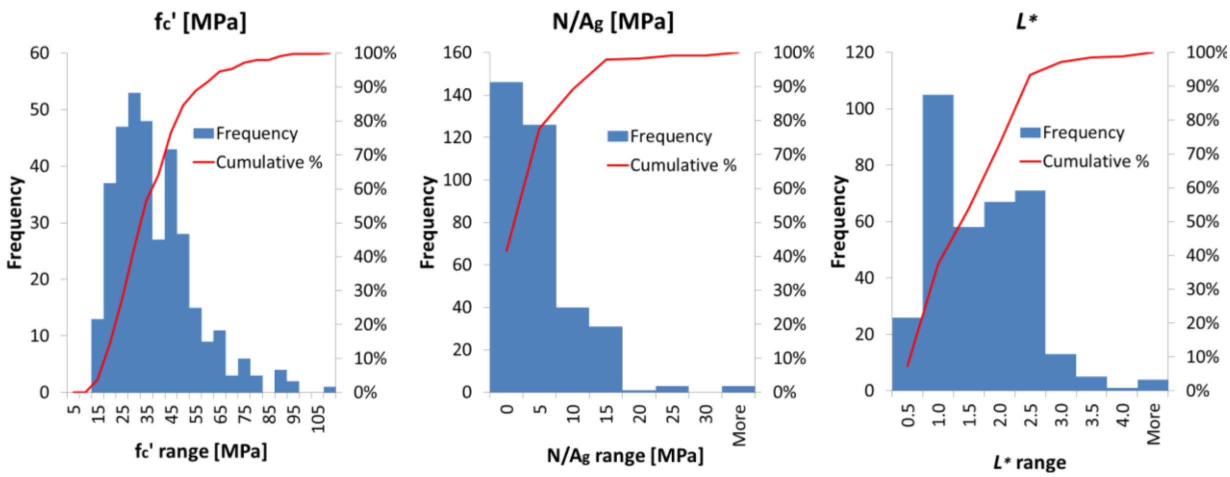

Figure 6. Distributions of specimen concrete strength f_c, axial stress N/A_c and shear span ratio L* in the SERIES RC wall database.

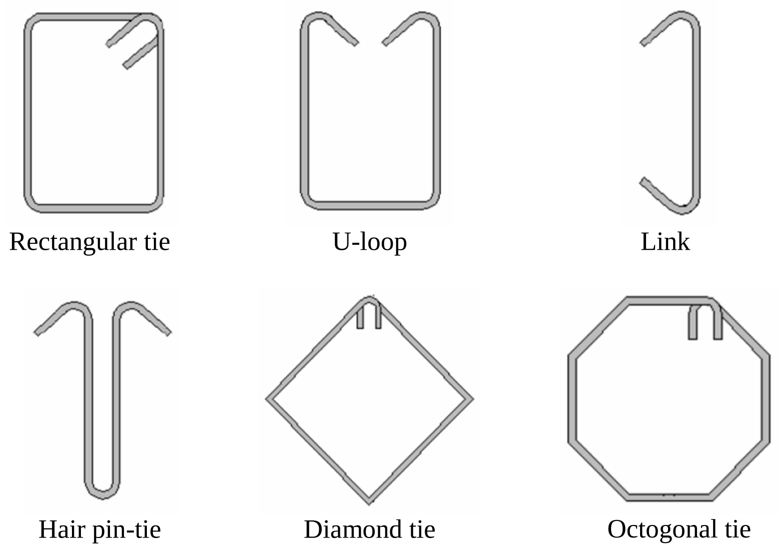

Figure 7. Typical shear reinforcement and notation used in the SERIES RC beam database (Lignos and Krawinkler, 2012, 2013).

THE SERIES RC BEAM DATABASE

The RC beam database includes data on 128 tested RC beam specimens. It was derived from a database developed and used at Stanford University (Lignos and Krawinkler, 2012 2013). Included are only specimens with the available digitized force-displacement hysteresis loops. The digitization was performed at Stanford University. Most of the beam specimens have rectangular cross-section (88) or square cross section (33), whereas 7 of them have T-shaped cross-section. Nine different test configurations were applied in the tests: cantilever beam; cantilever beam with flexible base;

cantilever beam with column pre-stressed; double ended; double curvature; simply supported beam with one or two point loads; and two types of Japanese double curvature assemblies.

Ten different types of confinement were defined (see Figure 7): peripheral rectangular ties; horizontal rectangular tie (longer dimension of the tie along the smaller dimension of the specimen); vertical rectangular tie (longer dimension of the tie along the larger dimension of the specimen); U-loop; link; hair pin tie; diamond shape tie; vertical link (along the longer dimension) and horizontal link (along the smaller dimension); and octagonal tie. 115 of the beam specimens were cyclically tested and 13 monotonically. For most specimens the type of the failure was not reported by the authors. Among those for which the failure mode is known, are three specimens. which failed in flexure, four in shear and one in flexure-shear. The specimen's concrete compressive strength ranges from 19.6 to 54.2 MPa, and the yield stress of corner longitudinal bars is from 276 to 1451 MPa. Since the capacity data for RC beams have been already post-processed, the extracted data on the ultimate drifts are available. They range from 2% up to 10% (see also Figure 8).

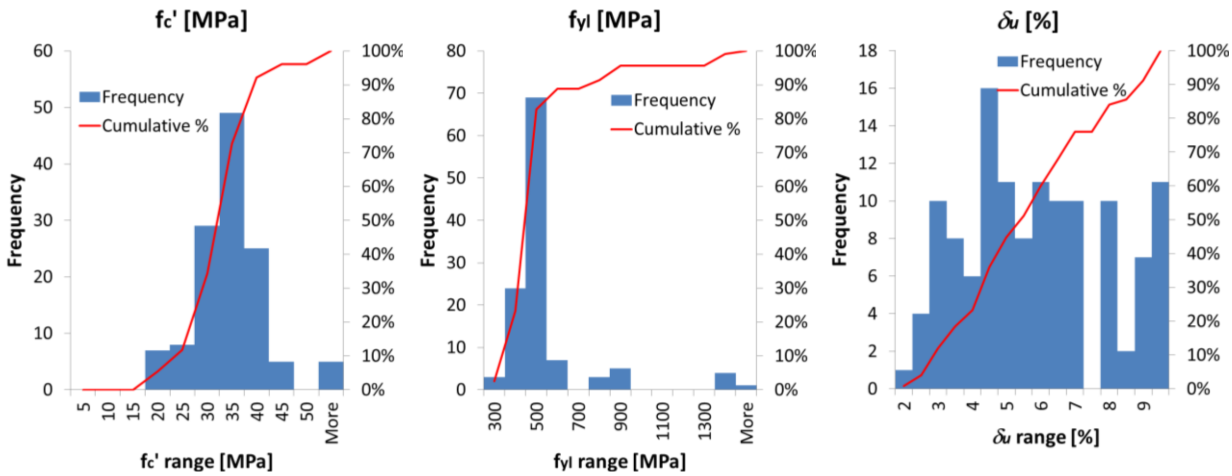

Figure 8. Distributions of specimen concrete strength f_c, yield stress of corner longitudinal bars f_{yl} and ultimate drift δ_u at 20% drop in the SERIES RC beam database.

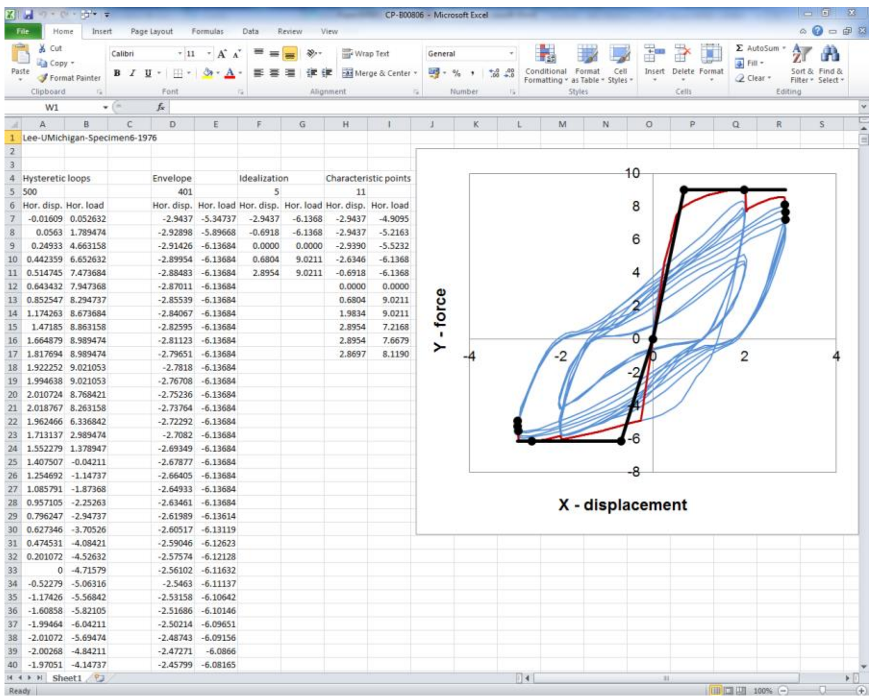

Figure 9. Example of digitized displacement-force history and post-processed envelope, and characteristic points for beam specimen from the SERIES RC beam database (Specimen # 6).

In Figure 9 an example of a digitized displacement-force history and a post-processed envelope, with characteristic points for a beam specimen from the SERIES RC beam database is shown. Owing to the asymmetric longitudinal reinforcement (and sometimes an asymmetric cross-section), different characteristic points are defined for the top and bottom side of the beam specimen.

USING THE DATABASE AND DEVELOPMENT OF THE SEISMIC PERFORMANCE MODELS

The intuitive interface of MS Excel enables relatively easy use of the SERIES database and further data manipulation. By clicking on the headers in any of the sheets (see for example Figure 10; line 4, column *L* for description of *P-Δ*), the user can obtain a more detailed description of each parameter. For some of the more complex parameters, a click on *Help* offers even more detailed description or image that is associated with the description of that parameter. A click on *Manual* opens the manual, which describes the database.

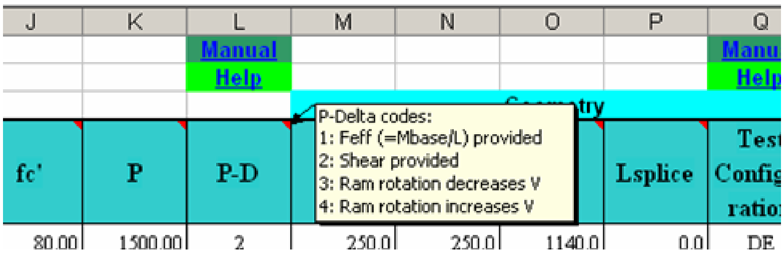

Figure 10. Snapshot of the database – description of the parameter.

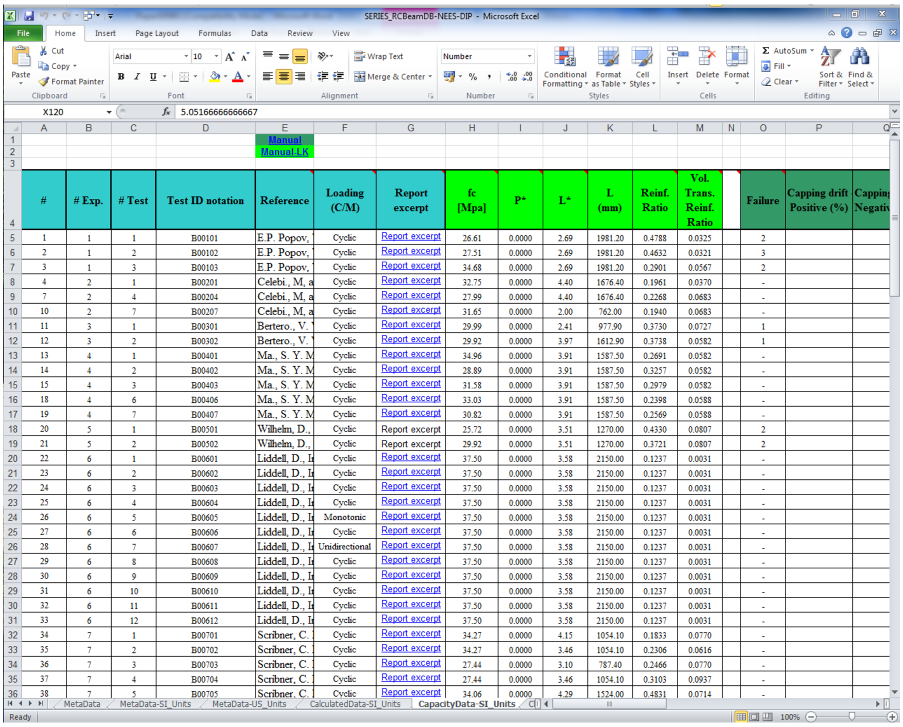

Figure 11. Snapshot of the sheet *CapacityData-SI-Units*. Users can view and/or extract data, needed for analysis.

A mouse click on the cells in the columns *Digitized history*, *Peak points* and *Envelope* (sheet *CalculatedData-SI_Units*) brings up the graphical visualization of the displacement-force hysteresis, and, wherever available, the characteristic points, bi-linear idealization and envelope, respectively.

The User can identify in a simple way the important input parameters, which influence the seismic performance of the structural element. Typical normalized parameters, e.g. the concrete compressive strength, the shear span ratio, the normalized axial force, the ratio of the longitudinal reinforcement and the confinement ratio (parameters defined by green headers in Figure 11) can be extracted directly. However, by extracting additional parameters from *Metadata-SI_Units* or *Metadata-US_Units*, a user can define her/his own influential input parameters. These data, together with the data on capacity, may serve as a database for further analyses with standard statistical tools (i.e. Excel, Matlab etc.). Thus, the most demanding step in the development of seismic performance models is, instead of time-consuming collection of data, the selection of representative specimens and then the choice of the appropriate method (e.g. multivariate statistical regression, already applied by Biskinis and Fardis, 2010a, 2010b; Biskinis et al., 2004; Panagiotakos and Fardis, 2001; CAE method, already applied by Perus at al, 2006; Poljansek et al., 2009, or a semi-empirical approach already applied by Lignos and Krawinkler 2012, 2013).

CONCLUSIONS

In the paper the RC structural element database, developed within the SERIES project, was presented. The SERIES RC element (columns, beams and walls) structural database has been assembled to provide researchers with the data needed to evaluate and develop seismic performance models for different RC structural elements. The database is public at the address http://www.dap.series.upatras.gr/ .

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