Development of a Computer Program for Direct Displacement-Based Design

T.J. Sullivan,
University of Pavia, Pavia, Italy

F. Bono, F. Magni
EUCENTRE, Pavia, Italy

G.M. Calvi
IUSS Pavia, Pavia, Italy

SUMMARY:
The Direct displacement-based seismic design (DBD) procedure is now well developed for most structural systems and material typologies. However, there do not appear to be any software applications incorporating the procedure. As such, a three year Italian research project has recently seen the realisation of a computer program, named DBDSoft, that permits the Direct DBD of regular reinforced concrete buildings. Development of the program required several conceptual programming challenges to be addressed. This paper explains how the challenges have been overcome for RC frame and wall buildings through the realisation of a program in which designers assign strength proportions to plastic hinge locations and then equilibrium analyses are undertaken in order to arrive at required design strengths, in line with the Direct DBD approach. The current limitations of the software are identified and important areas for future research are discussed.

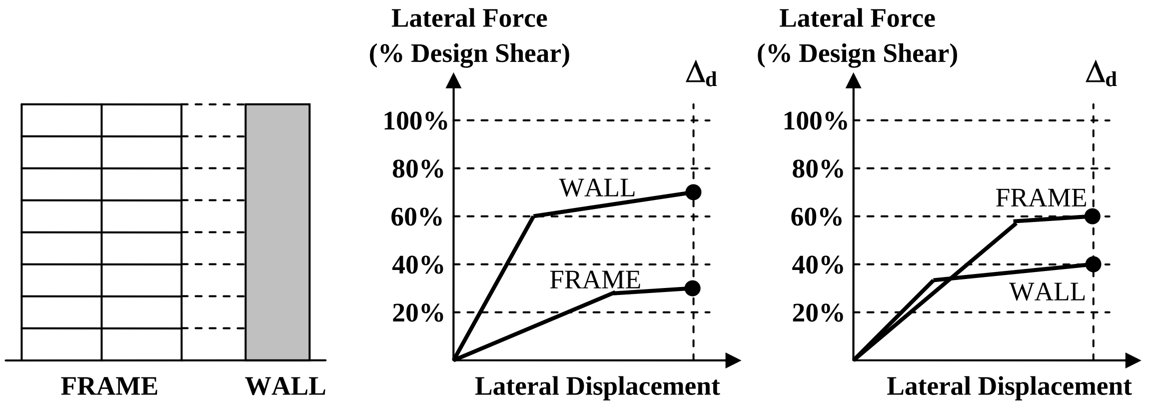
Keywords:, displacement based design, software, DBD program.

1. INTRODUCTION

In 1993, Priestley (1993) identified a number of serious conceptual shortcomings with current code “force-based” seismic design methods. In order to address these shortcomings, which are also detailed in Priestley et al. (2007), a large number of Displacement-based seismic design (DBD) procedures have been developed and tested over the past two decades (see, for example, the methods reviewed in Sullivan et al. 2004). However, to the authors’ knowledge, no computer software has, until now, been developed for the application of any of the various DBD procedures. The Direct DBD approach of Priestley and co-researchers is currently the most developed DBD method, with a text on the subject (Priestley et al. 2007) and more recently a model code (Sullivan et al. 2012a), and in this paper the advances that have been made towards the realisation of a computer program for Direct DBD are presented. The paper focuses only on aspects of the DBD methodology that are relevant for the DBD software development, and for the background and detailed description of the Direct DBD methodology, refer to Priestley et al. (2007).

2. THE ROLE OF STRENGTH PROPORTIONS IN DIRECT DBD

As explained by Sullivan et al. (2005), strength proportions can be assigned at the start of a Direct DBD procedure as part of an innovative seismic design strategy. The assignment of strength proportions relies on concepts of equilibrium and displacement compatibility. Any distribution of strength proportions that is in equilibrium with the total applied forces and respects displacement compatibility (with checks that the deformation capacities of individual elements of the structure are not exceeded for a given system displacement) provides a valid distribution for design. In typical building configurations, such as buildings possessing frames and wall linked by RC floor slabs, the displacement demands on the frames will be practically the same as those on the walls. As such, the total lateral resistance of the building for a given design displacement, Δ_d, can be assumed to be equal to the sum of the resistances offered by the frame and wall elements for the same level of displacement demand. In line with this, and as explained by Pauly (2002) and Sullivan et al. (2005), designers can choose the strength proportions they prefer, with two different plausible strength distributions illustrated for a frame-wall structure in Figure 2.1.



(a) Elements of Lateral Load Resisting System

(b) One plausible distribution of design strength proportions for the system

(c) Another plausible distribution of design strength proportions for the same system

Figure 2.1. An example of permissible distributions of design strength proportions for a RC frame-wall building.

The actual required total design base shear for the two different distributions of strength proportions shown in Figure 2.1 could differ owing to the different amounts of energy dissipation that could be provided by the structural elements at the design displacement. As the wall indicated in the example of Figure 2.1 yields at a displacement considerably smaller than the frame, it is subject to larger ductility demands and arguably, by assigning a greater proportion of strength to the wall in this system, a lower total design base shear could be obtained. However, optimum design solutions are not always driven by the need for a minimum total base shear and it may be preferable to limit the same of the walls for architectural reasons, in which case a higher contribution from the frames would be preferred, even if maybe not the most efficient option structurally.

The freedom to assign strength proportions in this manner is now incorporated within various aspects of the Direct DBD approach. For example, note that according to Priestley et al. (2007), the yield drift of a RC frame, θ_y, can be estimated using the following expression:

$$\theta_y = \frac{2\varepsilon_y L_b}{h_b} \tag{2.1}$$

Where ε_y is the yield strain of the longitudinal reinforcement, L_b is the beam length and h_b is the beam section depth. This very practical expression can be extended to the case where a frame has *n* bays of different length and beams of different depth by computing the yield drift of each bay and then finding an average storey yield drift, $\theta_{y,avg}$, using the flexural strength proportions ($M_{b,i}$) as shown in Eq.(2.2):

$$\theta_{y,avg} = \frac{\theta_{y,1}M_{b,1} + \theta_{y,2}M_{b,2} + ... + \theta_{y,n}M_{b,n}}{\sum_{i=1}^{n} M_{b,i}} \tag{2.2}$$

Another example in which strength proportions are used is in the estimation of the displaced shape of frame-wall structures, as explained by Sullivan et al. (2005). By increasing the proportion of strength assigned to the frames, the point of contraflexure in the walls will be lowered and this in turn will dictate the displaced shape of the building. Furthermore, in order to combine equivalent viscous damping values of two or more systems working in parallel, a work-done approach that relies on proportions of strength can be used (see Priestley et al. 2007 and Sullivan et al. 2012a).

3. CHALLENGES FACING THE REALISATION OF A COMPUTER PROGRAM FOR DIRECT DBD

Standard structural analysis programs utilise traditional concepts of structural mechanics in order to form a stiffness matrix which relates the displacements of the structural degrees of freedom to the internal forces. For modal response spectrum seismic analyses, the stiffness matrix is used together with the mass matrix to identify the period and shape of different modes of vibration. The periods of each mode are used to read off response spectrum ordinates which, together with the participating mass of each mode, can then be used to identify modal force and deformation components for the structure.

While the stiffness matrix approach is based upon sound principles for elastic response, it possesses a shortcoming for the design of RC structures; the cracked section properties of a RC element will depend on the strength assigned of the section, not only the section dimensions, and therefore cannot be known until the end of the design process. This characteristic of RC sections, that has only been recognised in recent years, results from the observation that the yield curvature of RC sections tends to be independent of the strength of the section, depending principally instead on the section depth and reinforcement yield strain (for evidence see Priestley et al. (2007) amongst others). As such, because the stiffness of a RC section can be obtained by dividing the section flexural strength by the section yield curvature (which gives the product of the concrete section modulus (E) with the cracked second moment of inertia, I_{cr}) the stiffness of RC sections depends on the flexural strength of the sections, implying that sections of the same dimension can offer very different levels of stiffness if their reinforcement or the axial force in the section differs significantly. This aspect of RC sections is illustrated in Figure 3.1 (after Priestley et al. 2007) where the idealised moment-curvature response of the same RC section with different quantities of longitudinal reinforcement is illustrated.

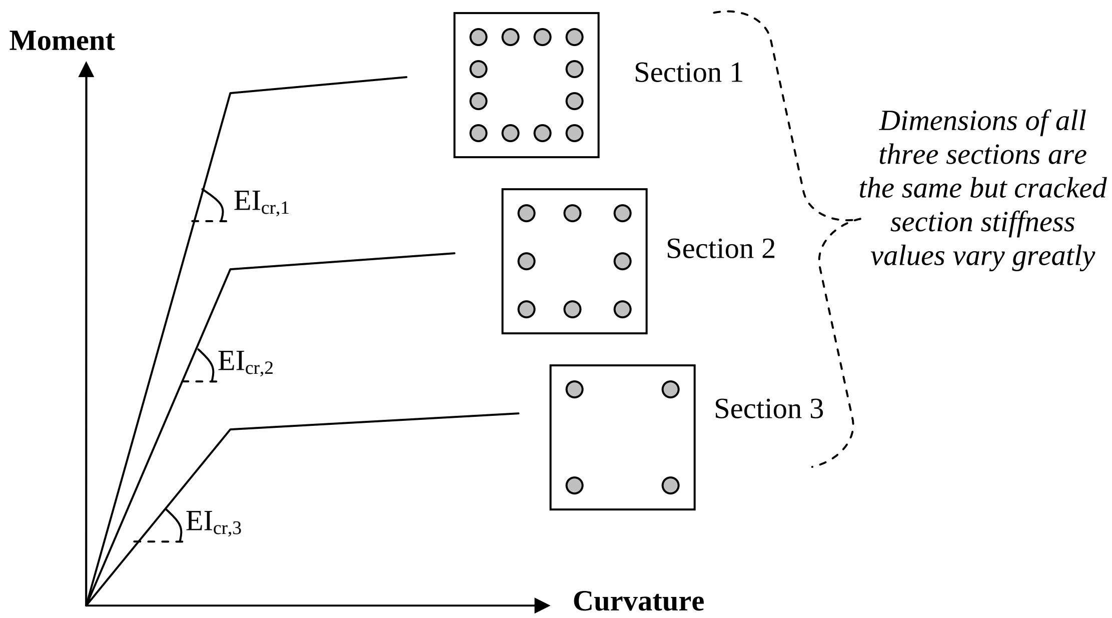


Figure 3.1. Idealised moment-curvature response of an RC section with three different quantities of reinforcement (modified from Priestley et al. 2007).

In Direct DBD, there is no need to estimate the section cracked stiffness since the procedure identifies the required effective (secant) stiffness required to satisfy design deformation limits. However, just as this very aspect of the design procedure helps it overcome shortfalls with current force-based design, it also implies that a new means of undertaking structural analysis must be programmed if software for Direct DBD is to be developed.

Another challenge facing the development of a computer program for Direct DBD relates to the fact that Direct DBD is, by its very nature, intended as a design tool and not an analysis procedure. If the programming of Direct DBD is to be successful, then the user should not loose the ability to direct and dictate the design solution that is obtained. For example, as was discussed earlier with respect to Figure 2.1, it should be clear that an almost infinite number of viable seismic design solutions can exist for a frame-wall building of specific dimensions, owing to the fact that different proportions of strength can be assigned to the frame and wall sub-systems. The designer should be free to set the strength proportions and develop the design solution best suited to the task at hand. Note that in contrast to Direct DBD, such freedom is not available with traditional seismic analysis tools owing to the fact that the stiffness values used in traditional structural analysis are dependent only on the section dimensions, suggesting that once the section dimensions are set, the stiffness is also fixed, which, as was previously discussed with reference to Figure 3.1, is not true for RC sections.

4. OVERVIEW OF THE NEW DBD SOFTWARE

Despite the challenges facing the development of a computer program for Direct DBD, a trial program, DBDsoft (Sullivan et al. 2012) has recently been completed at the EUCENTRE as part of a 3-year research project for the Italian Civil Protection Department. An overview of the current version of the software is provided in the sub-sections that follow.

4.1. Structural Geometry and Material Properties

Before beginning to design the structure in DBDsoft (Sullivan et al. 2012), the engineer should first decide on the location of lateral load resisting elements and identify preliminary section sizes. Preliminary section sizes can usually be set based on the requirements of non-seismic load cases or using engineering judgement. To proceed with the design in DBDsoft, the engineer must then input the material properties and geometrical layout in a similar manner to a traditional structural analysis package. Specifically, a number of tabs are followed (see Figure 4.1) in which the user defines the Material Properties, Section dimensions, Element Classes, Nodes, Element Connectivity, and any restraints or releases.

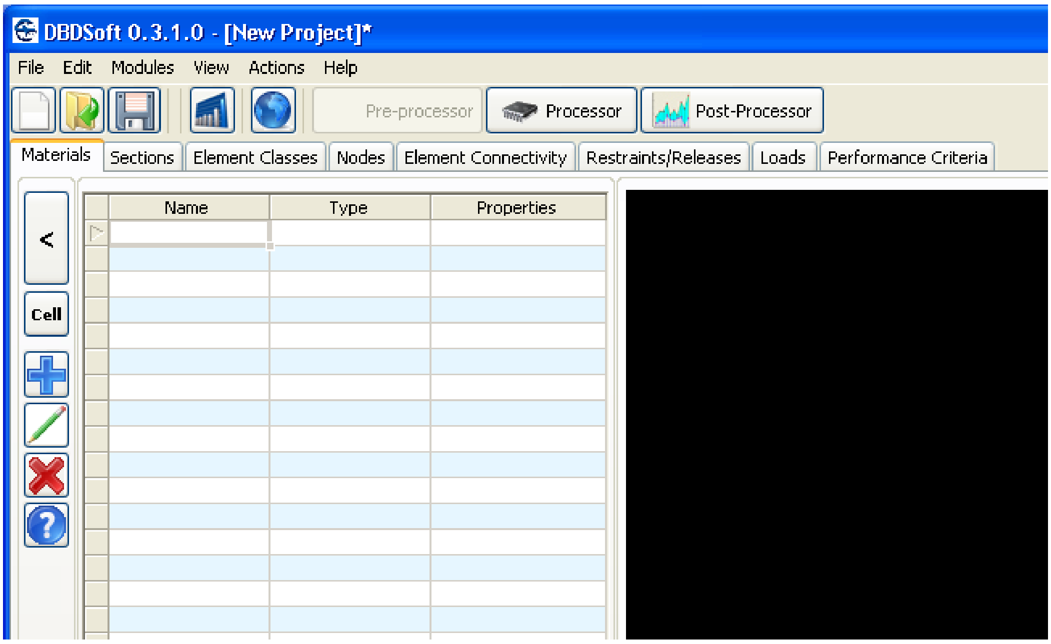


Figure 4.1. Screenshot of DBDSoft illustrating the input tabs in the pre-processor stage.

The material properties that should be specified for RC structures are simply reinforcement yield strength, F_y, ultimate strength, F_u, and elastic modulus, E_s, and the concrete compressive strength (f'_c). Note that in line with Direct DBD recommendations (Priestley et al. 2007) the values to be specified should correspond to expected material properties rather than characteristic 5th percentile values.

The specification of section dimensions, nodal locations and element connectivity follows a standard modelling approach, with the use of non-structural nodes to indicate the orientation of the minor axis of the sections within the global coordinate system as is done in other programs such as Seismostruct (Seismosoft 2012). Note that the section dimensions are not used to obtain member stiffness values (for reasons explained in Section 3) and are instead used to identify section yield curvature values and ductility demands.

Two types of restraints or releases can be specified: (i) restraints of single nodes, as shown in Figure 4.2, which should be located at the base of the building and (ii) flexural releases of element ends to indicate pin locations or pinned connections.

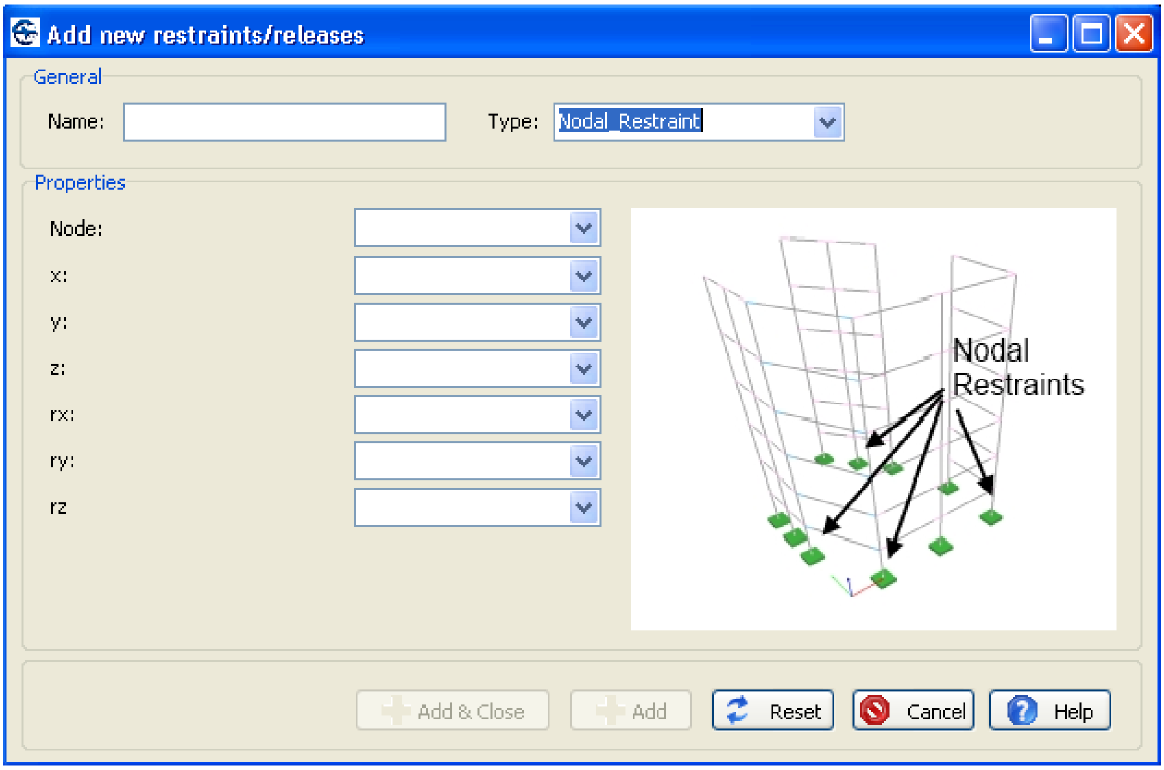


Figure 4.2. Screenshot of the Nodal Restraint input fields within DBDSoft.

4.2. Loading and Design Criteria

As DBDsoft is a tool for undertaking Direct DBD, the design spectrum that should be input corresponds to the displacement response spectrum. A separate design spectrum should be input for each principle X and Y direction, as well as for each different intensity level that should be considered in the design (although note that if spectra at different intensities have the same shape, a single displacement spectrum could be input and then scaled by different load combination factors).

Figure 4.3 illustrates the input field for definition of the displacement response spectrum. In order to specify the design displacement spectrum all that is required is the corner spectral displacement, $\Delta_{D,5\%}$ and the corner period, T_D. The program then assumes linearly increasing spectral displacement demands from zero (at a period of T = 0s) to at a period of $T = T_D$), with a plateau in spectral displacement demands beyond the corner period. In order to avoid overestimation of the spectral displacement demands in short periods, the program also requests that the user specifies a peak ground acceleration, which is then internally multiplied by 2.5 in order to estimate the spectral acceleration plateau, which is then used to limit the design base shear in line with the recommendations of Sullivan et al. (2010).

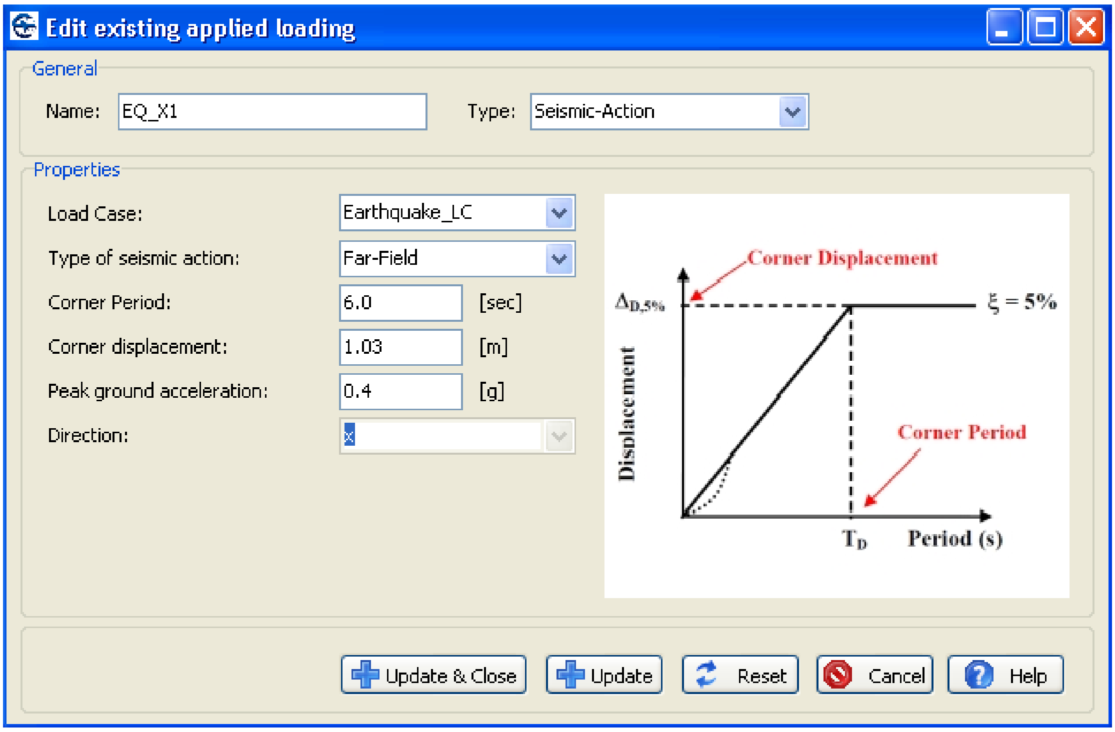


Figure 4.3. Screenshot of the seismic loading input fields within DBDSoft.

In addition to specifying seismic loading, the user should also define seismic masses. In the current version of DBDsoft, the seismic masses should be input as concentrated masses. Future versions of the software may incorporate additional options for the specification of seismic masses.

The objective of Direct DBD is to identify the strength required of plastic hinge locations that will ensure that design criteria are satisfied. Design criteria that can be considered in Direct DBD are peak storey drifts, section curvature demands and residual deformations (see Sullivan et al. 2012a). In the current version of DBDsoft, the user can only specify storey drift limits that should therefore consider demands on both structural and non-structural limits. Future versions of the software will look to permit the specification of section curvature limits that could be obtained either from refined moment-curvature analyses of sections or using empirical expressions.

4.3. Classification of the lateral stability system

Having input the structural geometry, restraints, loading and performance criteria, the designer moves to the processor phase in which the lateral load resisting system is classified by the software and the strength proportions are input. The software classifies the lateral stability system by progressing from one vertical element to another and considering the interconnectivity between vertical elements. In this way, separate sub-systems, such as cantilever walls or frames, can be indentified. This phase is helpful for checking the structural model and also because it permits the assignment of different strength proportions to the separate sub-systems in subsequent phases of the program.
Figure 4.4 presents an example classification of a RC frame building. Note that three distinct frames are identified (distinguished by different colours/shading) and the program identifies which of these sub-systems is contributing to the different global (X and Y) response directions. In addition, the program indicates the intended location of plastic hinges. This is an automatic feature of DBDsoft, that

assumes that plastic hinges should form at the base of all walls and columns (provided that releases are not specified at the bases) and at the ends of all beams. If releases are specified at the ends of a beam then the program accounts for this by neglecting the contribution of the beam to the lateral load resisting system.

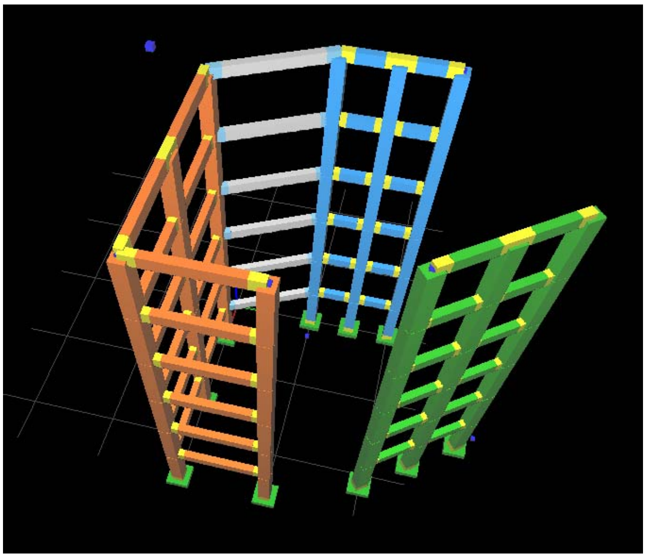


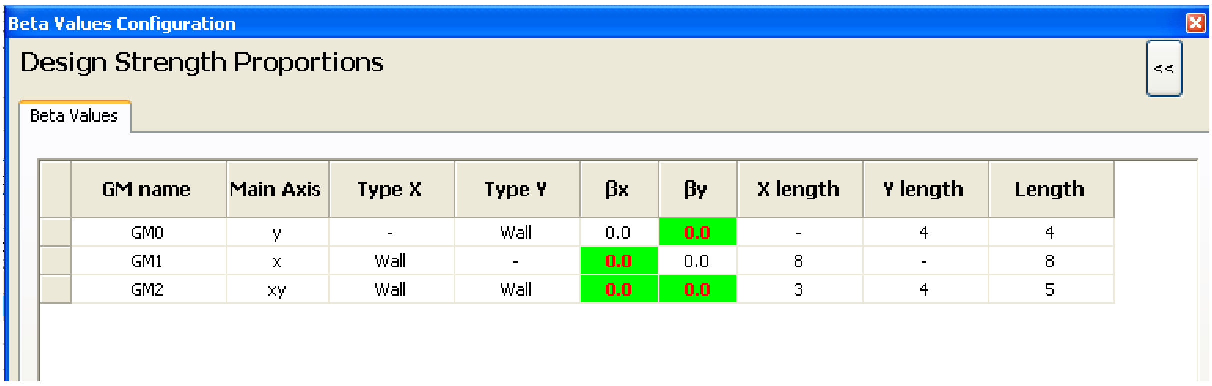
Figure 4.4. Screenshot of a 3D RC frame building that has been internally classified within DBDsoft.

4.4. Use of strength proportions to control the design

Arguably the most innovative aspect of DBDsoft is the specification of strength proportions within the processor phase. As was discussed in Section 2, the use of strength proportions in Direct DBD is useful for a number of reasons but arguably it is most valuable because it provides the engineer with control of the design. The specification of strength proportions is done in two phases within DBDsoft: (i) specification of local strength proportions, and (ii) specification of global strength proportions.

Local strength proportions refer to the ratio of the bending moment of a single plastic hinge to the sum of the bending moments of all plastic hinges in the local sub-system (eg. a frame within a frame-wall structure) for a given excitation direction. Local strength proportions are denoted by the β_{xx} or β_{yy} symbols for the X and Y directions respectively. Local strength proportions can be set by the designer to optimise, for example, the required beam strengths within a frame structure by specifying that all beams at the same level within a frame will be provided the same strength (and therefore same beta value). As multi-storey frame buildings could possess a large number of plastic hinges that would require a rather time-consuming specification of individual (local) beta values, DBDsoft permits the rapid assignment of local strength proportions by using an “auto-betas” button, that automatically assigns strength proportions to the structural systems in a sub-system by considering relative section sizes and desirable vertical distributions of lateral resistance (e.g. a shear resistance that is greater at the base of a frame than at the top).

Global strength proportions refer to the ratio of the overturning resistance of a sub-system to the sum of the overturning resistances of all the sub-systems in the global system for a given excitation direction. Global strength proportions are denoted by the β_x or β_y symbols for the X and Y directions respectively. Global strength proportions can be set by the designer to reduce torsion, for example, or to ensure that walls possess similar reinforcement ratios, even if they are of different length (see Section 2 and Priestley et al. 2007 for further clarification). The program internally multiplies the local strength proportions by the global strength proportions to obtain final design strength proportions for every plastic hinge location in the building.



GM name	Main Axis	Type X	Type Y	βx	βy	X length	Y length	Length
GM0	y	-	Wall	0.0	0.0	-	4	4
GM1	x	Wall	-	0.0	0.0	8	-	8
GM2	xy	Wall	Wall	0.0	0.0	3	4	5

Figure 4.5. Screenshot of global beta (strength proportions) input fields for a building possessing three separate walls (GM0, GM1, and GM2).

4.5. Equilibrium Analyses

With the structural inputs and strength proportions defined, the user can run the design. The program internally identifies the design displacement profile considering the user-defined design criteria, and then converts the MDOF system into an equivalent SDOF system. Ductility demands for each plastic hinge are computed and these are factored using a work-done procedure to obtain the system ductility and equivalent viscous damping, in line with the recommendations in DBD12 (Sullivan et al. 2012a). With the system damping and design displacement known, the program proceeds to identify the required effective period from the scaled displacement response spectrum. This is then used together with the effective mass to compute the required effective stiffness, which is multiplied by the design displacement to obtain the design base shear for the substitute structure.

In order to identify design strengths of sections using a traditional Direct DBD procedure, the design base shear is distributed up the height of the structure as a set of equivalent lateral forces. The structure can then be analysed for this set of lateral forces to find the required plastic hinge strengths. However, in the current version of DBDsoft this elaborate process is simplified somewhat owing to the fact that the beta values (set to be in equilibrium with the external lateral loads) already indicate a valid distribution of the internal forces within the structure. As such, the design strength of plastic hinge locations is simply found as the beta value multiplied by the global design overturning moment (given by the product of the design base shear with the equivalent SDOF system effective height). For wall structures the program also reports the shears up the height of the wall that are obtained using the traditional Direct DBD distribution of equivalent lateral forces.

4.6. Verification Exercises

A series of verification exercises have been undertaken for the software. In particular, regular 3D frame and wall models, of 6 and 8 storeys respectively, have been designed using the program and the results have been compared with results obtained by hand calculations. This procedure successfully demonstrated that the program undertakes the design correctly. However, further verification exercises are planned on a wider selection of case study structures and it is expected that minor bugs will be found and then corrected.

5. LIMITATIONS OF CURRENT VERSION AND FUTURE RESEARCH NEEDS

The current version of DBDsoft is capable of obtaining design strengths of plastic hinge regions in regular low- and mid-rise RC wall and RC frame buildings. The program does not yet implement the procedure for dual frame-wall systems or coupled wall systems. Nor can the program currently deal with U-shaped, T-shaped or other irregular shaped RC sections or wall configurations. Buildings with significant irregularities in-plan or in-elevation should not be designed using the current version of the software. In addition, the software assumes rigid foundation response and therefore, it should not be used for systems with weak or flexible foundations or for systems in which significant soil-structure-interaction may be expected.

Higher mode effects and capacity design requirements are not evaluated within the software. Future research will consider implementing eigen-value analyses that could be undertaken at the end of an initial Direct DBD solution to account for higher mode effects on both forces (for capacity design) and deformations (for Direct DBD as part of an iterative procedure within the software). In addition, future versions of the software will look to ask the user to define likely material overstrength values so that, together with allowances for higher modes, capacity design forces can be identified.

All the above limitations of the software are only expected to be short-term, with an on-going research project aiming to increase the applicability of the software and extend it to other structural configurations and material types.

6. CONCLUSIONS

A three year Italian research project has recently seen the realisation of a computer program, named DBDSoft, that permits the Direct DBD of regular reinforced concrete frame and wall buildings. Development of the program required several conceptual programming challenges to be addressed. In particular, unlike traditional structural analysis software, the stiffness of elements is not known at the start of the procedure and therefore the program could not utilise traditional matrix based structural analysis. Furthermore, it was recognised that for a given structural configuration there will be more than one acceptable seismic design solution and therefore, designers should be free to direct the seismic design towards the solution they desire.

To overcome such challenges the DBD program incorporates a novel feature in which designers assign strength proportions to plastic hinge locations in the design “processor” phase of the program. This strength assignment procedure provides the engineer with fast, effective control over the final design solution and permits equilibrium analyses to be undertaken instead of stiffness-based analyses. The process of assigning strength proportions could also be a useful development for programs currently wishing to adapt pushover-analyses for seismic design.

In addition to the specification of strength proportions, the program only requires standard structural inputs to be defined, after which point the software internally identifies the design displacement profile, considering the user-defined performance criteria. The software then converts the MDOF structure into an equivalent SDOF system to obtain the design base shear using the standard Direct DBD procedure, and then executes equilibrium analyses in order to arrive at required design strengths of plastic hinge locations.

The current limitations of the software have been described and include the fact that the program can only currently consider regular frame or wall structures possessing rectangular sections. On-going research is looking to more thoroughly validate the program and increase the applicability of the software, extending it to other structural configurations and material types.

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