Static analysis of high-rise concrete buildings with holistic 3D models

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Abstract

Holistic 3D calculation models have become an indispensable part of the structural analysis of complex and/or unconventional structures. The determined load distribution within the structure and the particular stressing of the members are hereby strongly depending on the modelling approaches. This contribution shows the effects of different modelling approaches by a systematic investigation of a representative high-rise reinforced concrete building with flat slabs and a core for the structural stability. In principal, the difference between the conventional method using extracted 2D submodels and a linear-elastic holistic 3D model is shown. Following, the effect of the regarded connection stiffness between the structural elements, the significance of a construction stage analysis (CSA) and the influences of creep and shrinkage of the concrete on the load distribution are presented in detail. It was found that all parameters as well as their interplay have clear influences on the determined stressing and should be addressed accordingly.

Keywords: structural analysis; holistic 3D model; construction stage analysis; creep; shrinkage

1 Introduction

3D calculation models become more and more standard practice in structural design of building constructions (like one is shown in Figure 1). The reasons are the increasing digitalisation of the planning process in general and the particular optimization potential in the dimensioning of individual structural elements since the interaction between the horizontal and vertical bracing systems can be simulated more realistically. Moreover, holistic modelling approaches considering construction stages, soil-structure interactions, time-dependent effects of concrete and redistribution of stresses due to cracking can lead to a quality jump in the prediction and the assessment of the actual structural behaviour of buildings. The possible potential of a more accurate description of the load distribution with holistic 3D models has been outlined in [1], [2], [3], [4], [5], [6].

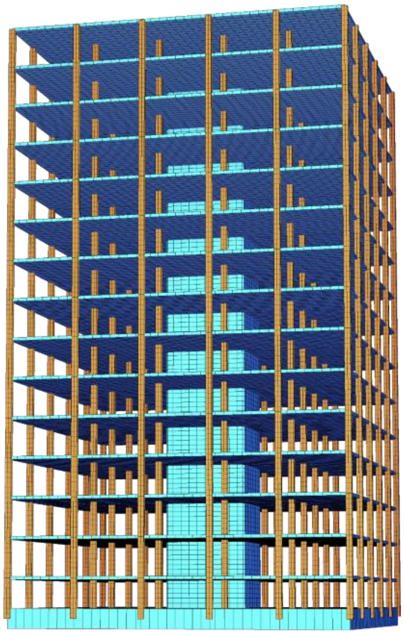

Figure 1. holistic 3D calculation model of the representative high-rise building

In addition, through the application of holistic 3D calculation models, useful information from structural analysis can also be integrated into the "Building Information Modelling" (BIM) with a high degree of automation.

However, the practical application of 3D calculation models shows a strong sensitivity on differential displacements in the structure. An oversimplified modelling implies therefore the risk of an incorrect determination of the load distribution. Moreover, time-dependent effects of creep and shrinkage which occur particularly in reinforced concrete structures lead to differential deformations between columns and core walls and thus to additional load redistributions, see e.g. Fintel et al. [7] and Kurc & Lulec [3]. Further challenges of the application of 3D calculation models were illustrated for example by Rombach [8], Bischoff [2] and Fastabend et al. [1]. The effects of different types of modelling or of different levels of modelling complexity are usually partially as well as separately investigated. Systematic and more general investigations for the derivation of general recommendations for the practical application of holistic 3D calculation models are missing. Thus, today's application of 3D models requires a high expertise for modelling and result interpretation.

Hence, a current research project of the Institute of Structural Concrete of the Graz University of Technology and FCP Fritsch, Chiari & Partner ZT GmbH is focused on a detailed systematic investigation of the different modelling approaches on a representative high-rise reinforced concrete building (in Figure 1; geometry see [4]). This includes effects like the construction process considering the deformation compensation through the construction stages, the modelling of the connection stiffness between the structural elements, the soil-structure interaction, the reduction of stiffness due to cracking of the slabs and the time-dependent behaviour of concrete (creep and shrinkage). An aim of the project is to develop validated recommendations for the practical application of holistic 3D building models.

This contribution shows selected results with focus on the differences between the structural analysis using extracted 2D submodels or holistic 3D model with and without construction stage analysis (CSA). Furthermore, the significance of the modelling approach of the connection stiffness between the structural elements and the influences of creep and shrinkage of the concrete are discussed in detail. In addition, the significant effect of the internal restraining of these time-dependent deformations by the provided reinforcement on the load distribution in the building is illustrated.

2 Modelling

2.1 Representative high-rise building

The representative high-rise building consists of a simplified floor plan (see Figure 2 considering the symmetry) that does not change over the building height. As a result, the load paths are still relatively visible and the influences of the examined effects can be explained in a reasonable way. The building has 15 floors, with a height between floors of 3,5 m and thereby a total height of 52,5 m. The flat slabs have a thickness of 28 cm. For structural stability, a 7,0 x 7,0 m core with a wall thickness of 30 cm is centred in the building. Around it, there are two rows of columns in a 6,0 x 6,0 m grid with dimensions of 50 x 50 cm. Further background on the chosen geometry of this representative high-rise building can be found in [4].

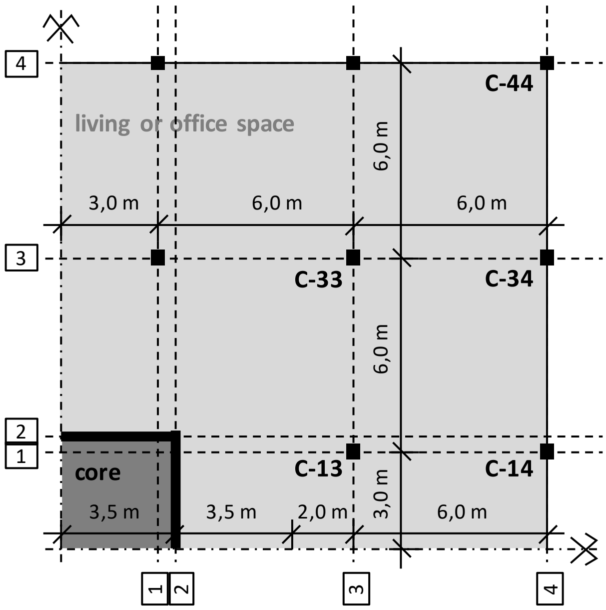

Figure 2. floor plan of the representative building

The generation of the holistic 3D calculation model was realised with the finite element software

"SOFiSTiK". The script-based input of the model via the associated text editor "Teddy" was completely parameterised to ensure the highest flexibility in the execution of parameter studies. As common in practice, the core walls, the slabs and the foundation plate are modelled with 2D shell elements and the columns as 1D beam elements (uncracked and without reinforcement as reference case). Additionally, the centroidal axes/planes of the structural elements are used as the static system axes/planes of the 3D model.

This model can also consider the effects of soil-structure interaction, as shown in [4], or the effects of stiffness reduction due to cracking of the slabs by using an engineering approach. However, these effects are not discussed in this contribution and therefore the following results are based on uncracked slabs and a perfect uniform settlement. The perfect uniform settlement is simulated with a rigid bedding of the foundation slab in vertical direction.

2.2 Connection stiffness

In reinforced concrete constructions, especially in cast-in-place constructions, rigid connections providing adequate connecting reinforcement are usually constructed between vertical and horizontal structural elements. Nevertheless, cracking in the areas close to the connection causes rotations so that the rotational stiffness of the connection itself is reduced. Therefore, the connection is usually modelled as hinged in practical applications. For the evaluation of the effect of different connection stiffnesses, a comparison between the two extreme scenarios rigid connection and hinged connection is carried out. But the rigid connection can be seen as a reference model because in the holistic 3D model it is attempted to determine the rotations realistically with regard to cracking in the structural elements (also near the nodes).

2.3 Construction stage analysis (CSA)

Generally, construction stage analyses are rarely applied for the static calculation of buildings. But as shown in preliminary studies [3], [4], [5], [9] the influence of the construction stages is quite significant for the static calculation with a holistic 3D model and several approaches are possible. As shown in [10], lumped construction stages can reduce the calculation time of the model, but a post-fitting of the deformation profile of the column over the building height is necessary, which cannot be implemented trivially in the holistic 3D model. A detailed modelling of the construction process including the supports and formwork is shown in [11]. However, the implementation of such a detailed modelling seems to exceed the performance capacities and is not suitable for practical application. The chosen engineering approach is similar to that used by Kurc & Lulec [3] and is illustrated in Figure 3. Here the complex construction process is modelled with simplified discrete construction stages on the basis of a timely group control of structural elements.

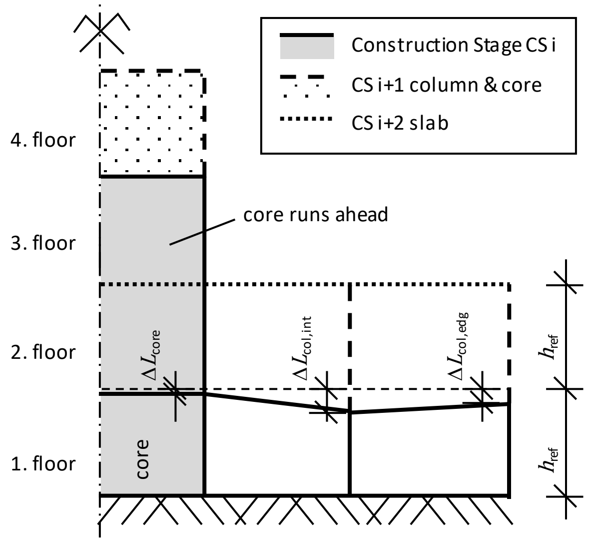

Figure 3. schematic illustration of the construction stages

In the first construction stage, only the foundation plate is activated. Then, the core runs two storeys ahead. Subsequently, there are two construction stages: i) vertical structural elements (columns & core); and afterwards ii) horizontal structural elements (slab). These two stages are repeated alternately until the building structure is completed. In the modelling of the construction stages, the deformation compensation during the construction process is also considered. This means that new installed structural elements are always activated in the reference position and afterwards they have to bear their dead weight. As a consequence, the vertical structural elements are always extended by a difference in length ΔL to compensate the pre-deformation of the subjacent structure (see Figure 3).

2.4 Creep and shrinkage

The implementation of the time-dependent deformation behaviour of concrete (creep and shrinkage) is based on the models of Eurocode 2 [12] with a verified modification of creep according to Schlicke [13], [14], [15]. Generally, the creep deformations are determined separately for each finite element and depend on the respective load history and concrete age. The creep and shrinkage deformations are modelled in the finite element model as strain impacts, whereby only the differential strain between the start and end of the time step is added to the system per time step. The length of the time step during the construction is fixed to one day and increases to seven days after completing the final storey. Time-dependent development of the Young's modulus and hygrothermal effects are not considered.

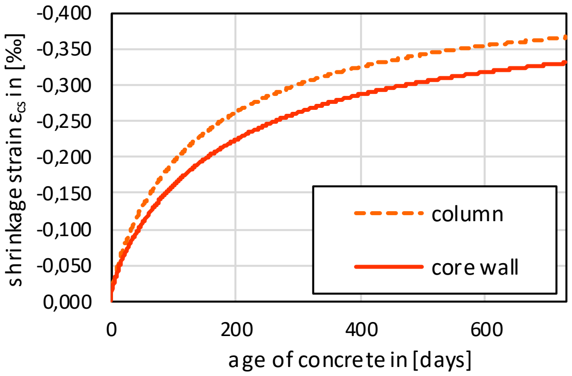

Figure 4. shrinkage strain of columns and core walls as a function of their age

The implemented shrinkage strains include both the drying shrinkage and the autogenous shrinkage, which is less significant for normal-strength concrete. As input parameters for the determination of the shrinkage of all structural elements, a relative humidity of 50 %, a cement type of class N and uniform concrete quality of C30/37 is defined. Furthermore, the respective effective thickness h_0 is calculated depending on the dimensions of each individual structural element. Figure 4 shows the time-dependent development of the shrinkage strains of columns and core walls. Differential shrinkage deformations and differential creep deformations between column and core lead to a load redistribution in the highly statically indeterminate high-rise building.

2.5 Provided reinforcement

In practical structural analysis, concrete elements are usually modelled as uncracked and without reinforcement. Nonlinearities, cracking and provided reinforcement are only considered in the design of the cross-sections. Nevertheless, the provided reinforcement restrains the deformations due to creep and shrinkage and an internal stress condition occurs. The creep and shrinkage strains determined according to the Eurocode are valid only for pure concrete elements. Different degrees of reinforcement in core walls and columns lead to differential deformations and consequently to a load redistribution in the holistic 3D model.

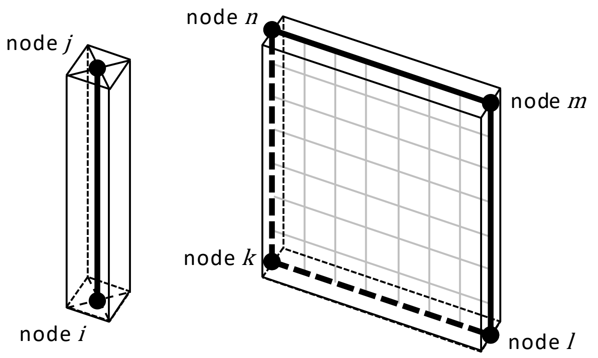

Figure 5. modelling of the provided reinforcement via node-identical truss elements in the beam elements (left) and membrane elements in the shell elements (right)

The present reinforcement in the structural elements was hereby modelled with additional elements sharing the same nodes as the structural elements, as illustrated in Figure 5. Thereby truss elements (steel reinforcement) are attached to the previously generated beam elements (concrete) and membrane elements (steel reinforcement) are attached to the previously generated shell elements (concrete). As these new reinforcement elements always have identical nodes as the concrete elements (nodes i - n) a rigid bond between concrete and reinforcement is assumed. The truss elements can only transfer normal forces N and the membrane elements only transfer normal forces n_x and n_y and no shear forces n_{xy}

according to the orthogonal reinforcement mesh. For the modelling, the provided reinforcement area is converted into an area equal thickness (t_x or t_y) for the membrane elements respectively into an area equal diameter d for the truss elements.

For the present results, only the vertical reinforcement in the core walls and columns was simulated. There are three different cases: i) reference case - without reinforcement ii) constant reinforcement - minimum reinforcement in the core (0,2 %) and in all columns 6,0 % reinforcement over the entire height (= maximum calculated reinforcement ratio based on 2D analysis) iii) graded reinforcement - minimum reinforcement in the core (0,2 %) and optimized reinforcement ratio based on 2D analysis in each individual column.

3 Results

3.1 General

To illustrate the different load distribution in the building by different modelling approaches, the maximum column forces (occurring directly above the foundation plate) due to the dead weight loading of the static structure are compared with each other hereinafter. The designation and position of the respective column is displayed in the floor plan in Figure 2. Due to symmetry, it is sufficient to give only the results of five columns.

3.2 Extracted 2D submodels vs 3D model with and without construction stages

Figure 6 presents the comparison of maximum column forces according to the different modelling approaches. The first slot in the chart shows the results of the analysis with extracted 2D submodels, the second slot the ones from the 3D model without construction stages (= final system) and the third slot the ones from the 3D model with construction stages. Moreover, each slot includes the result of three cases of modelling the connection stiffness i) all hinged ii) hinged connection between columns and slabs and rigid connection between core walls and slabs iii) all rigid.

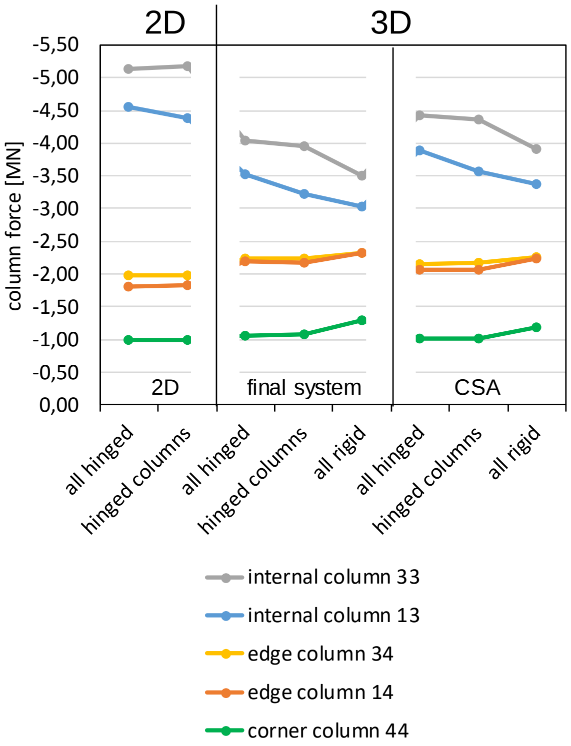

Figure 6. comparison maximum column forces – 2D submodels vs 3D model with and without CSA and varied connection stiffness

Independent of the modelling approach, the internal column C33 is the highest loaded column and the corner column C44 has to bear the lowest normal forces at the ground floor. In comparison to the extracted 2D submodels, the 3D models give a homogenization of the column forces. Thereby, the greater homogenization is obtained in the final system (without construction stages). The calculation on the final system with all hinged connections results in a reduction of the maximum column force C33 by 21 % and in the construction stage analysis the reduction is only 13 % compared to the 2D submodels.

Regarding the influence of the connection stiffness, Figure 6 reveals that there is only a slight difference between “all hinged” and “hinged columns”. Only the force in the internal column C13 changes significantly. Comparing the column force C33 from the "all hinged" 3D model with the corresponding force from "all rigid" 3D model, a reduction of 12 % and 13 % is obtained.

3.3 Time-dependent analysis

3.3.1 Creep and shrinkage

The following calculation with creep and shrinkage is based on the linear elastic load history considering the construction stages and rigid connections of all structural elements. The effect of provided reinforcement was neglected at this point (reference case). In general, this analysis shows a time-dependent load redistribution from the highly loaded internal columns to the corner columns and to the core walls. The normal force in the edge column remains almost identical.

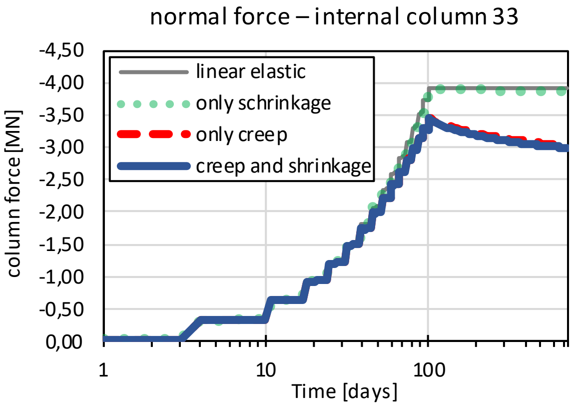

Figure 7. development of the maximum normal force of the column C33 with only shrinkage, with only creep or with creep and shrinkage

Figure 7 illustrates the effects of simulating only shrinkage, only creep and creep and shrinkage together for the high loaded column C33 over a period of two years. The stepped load increase in the first hundred days is caused by the construction stages. It is obvious that the individual load increments of column C33 decrease per storey which can be explained by the increasing frame effect with ongoing construction. Moreover, it can be seen that there is only a minor reduction in force due to shrinkage alone (green dotted line). But creep alone (red dashed line) causes a force reduction of 23 % and creep and shrinkage together (blue continuous line) about 24 % compared to the linear elastic result (grey continuous line). Compared with the results of the extracted 2D subsystems, the column force C33 is reduced by over 40 %; although this is only a theoretical case without regarding the effects of cracking of the slabs and internal restraining by the provided reinforcement.

3.3.2 Provided reinforcement

Based on the linear elastic calculations with consideration of the provided reinforcement, a maximum variation in the column force C33 of only 6 % was determined. As can be seen in Figure 8, the time-dependent calculations with creep and shrinkage and the three different provided reinforcement cases results in significantly larger variation of the column force.

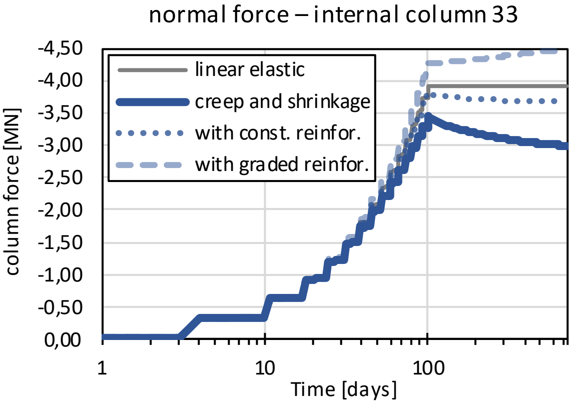

Figure 8. development of the maximum normal force of the column C33 creep and shrinkage and provided reinforcement

In the case of constant reinforcement applied to all vertical structural elements (core walls 0,2 % and columns 6 % - blue dotted line), the load reduction decreases to 6 % in comparison with the linear elastic calculation without reinforcement (grey continuous line). In contrast to this, a graded reinforcement in all columns (blue dashed line) even causes a load increase of 15 % in the column C33. The reason for this is that in this approach all corner columns as well as the edge columns generally contain significantly less reinforcement (from the 4th floor upwards only minimum reinforcement). This results in greater deformation due to creep and shrinkage and consequently to a transfer of forces from the edge columns and corner columns to the internal columns. But the column force C33 with graded reinforcement is still around 12 % lower than the column force from the extracted 2D submodels (5,14 MN) indicating still a result on the safe side when using 2D submodels.

4 Discussion

4.1 Connection stiffness

The present results reveal a certain influence on the modelled connection stiffness. As expected, the hinged connection of all structural elements results in the lowest load rearrangement in the system. A rigid connection of core walls and slabs only has an influence on columns located close to the core wall. Further, there are almost no influences of a rigid connection if the geometry of the core walls to each other leads to geometrical bending restraint of the slabs in the core (like for column C33). In contrast, a rigid connection between columns and slabs has significant influences. However, it should be noted that the "global" frame effect of the 3D model has a greater influence than the additional "local" effect of the connection stiffness.

4.2 Construction stage analysis (CSA)

CSA has a major influence on the results of 3D models as the frame effect is built up gradually with the storeys. This leads to a smaller homogenisation of the column forces than the calculation using the final system. As a further consequence of CSA, also the deformation differences between core walls and columns due to the dead weight of the static construction become smaller. The point of the maximum vertical deformation shifts from the top of the building (final system) to about the half of the building height (CSA). Overall, it seems that a suitable modelling of the construction process is essential for the practical application of 3D models.

4.3 Time-dependent analysis

Creep and shrinkage lead to an increase of the deformations in the building whereby only the differential deformations between columns and core walls cause load redistributions. In this study, core walls and columns have almost similar shrinkage strains in a time step (compare Figure 4) due to a comparably similar effective thickness ($h_{0,\mathrm{core}} = 300\ \mathrm{mm}$ & $h_{0,\mathrm{column}} = 250\ \mathrm{mm}$) and an earlier construction of the core wall in the same storey. Creep can lead to significant load redistribution since structural elements with high concrete stresses show significantly more creep deformation and consequently transfer their load to elements with less deformations. If the provided reinforcement is also considered in the time-dependent analysis, the deformations due to creep and shrinkage are significantly restrained in case of high reinforcement ratios. For smaller differences between reinforcement ratios, like in constructions with shear walls and only a few columns, the effect of the provided reinforcement seems smaller. It is noted that without a consideration of the provided reinforcement, the redistribution potential from column to core is usually overestimated.

5 Conclusion and outlook

A static calculation using 3D models is influenced by many different factors. In general, the results of 3D calculation models are sensitive to differential deformations in the building and generate significantly different load distributions than the conventional 2D calculation method.

In this contribution, the effects of different modelling approaches were investigated by a systematic analysis of a representative high-rise reinforced concrete building including the effect of different connection stiffnesses, CSA and time-dependent concrete deformations with and without provided reinforcement. The following conclusions can be drawn:

- Rigid modelling of the connection stiffness leads to a higher homogenisation of the column forces; the effect of the connection stiffness between slabs and cores is affected not only by the deformability due to cracks but also by the geometrical bending restraint in the wall corners.
- CSA has a significant influence due to the gradually built up frame effect in the building and a suitable modelling of the construction process seems essential.
- The influence of shrinkage on the load distribution is very small for similar effective thickness and similar reinforcement ratios.
- Creep can cause a significant load redistribution in case of different concrete stresses in the structural elements, whereby the provided reinforcement has to be considered in this context.

Overall, holistic 3D models show potential for optimisation in comparison to the extracted 2D submodels, but require a consistent consideration of the relevant factors, like construction process, creep & shrinkage, provided reinforcement, soil-structure-interaction and cracking.

In the future, further investigations will be performed regarding cracking of the slabs, creep deformation of the slabs and restraint forces between two cores caused by shrinkage.

6 Acknowledgement

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