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Rapid Design Method and System Development for Aircraft Wing Structure

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Abstract

This work is mainly done by too many manual operations in the aircraft structure design process resulting in heavy workload, low efficiency and quality, non-standardized processes and procedures. A top-down associated design method employing the template parametric technology is proposed here in order to improve the quality of design and efficiency of aircraft wing structure at the preliminary design stage. The appropriate parametric tool is chosen and the rapid design system of knowledge-driven aircraft wing structure is developed. First, a skeleton model of aircraft wing structure is rapidly built up through the template encapsulated design knowledge. Associated design is then introduced to realize the association between the typical structural part and skeleton model. Finally, the related elements are referenced from skeleton model, and a typical structural part reflecting an automatic response for design changes of the upstream skeleton model is quickly constructed within the template. The rapid design system proposed and developed in this paper is able to formalize the design standardization of aircraft wing structure and thus the rapid generation of different aircraft wing structure programs and achieve the structural design knowledge reuse as well.

Key words: top-down; rapid design; template; aircraft wing structure; associated design

1. Introduction

Market competition becomes more and more intense for mechanical products and requirements for the product become more and more strict. Companies need to employ all kinds of comprehensive and advanced design techniques, ideas and rapid design methods, and strive to improve the design quality and efficiency, shorten product development cycle and reduce costs in order to meet market demand. Because of the small volume for aircraft, the product structure changes following the aircraft types alter quickly, and therefore the aircraft structure rapid design is especially important.

Aircraft structural design is usually a complex systemic engineering, covering the whole process of preliminary design, detailed design, prototype, and batch production [1]. Also structural design involves a wide complex association of many design constraints which are often required to be constantly modified, coordinated and analyzed during the design process. Currently, digital design methods are often used in the process of aircraft structural design to expedite the goal of design and achieve a full 3D digital modeling as well [2]. Design technologies such as online design, concurrent and collaborative design have been extensively utilized. However, there are still many problems in the process of aircraft structural design which could be mainly reflected in the following aspects:

(1) Aircraft structural design involves a lot of engineering knowledge. Actually the core competitiveness of aircraft industry, to a large extent, depends on the accumulation and reuse of design knowledge. In the current design environment, due to many manual interactions as well as the lack of effective knowledge accumulation and management,

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the work efficiency is usually very limited, and design quality cannot be guaranteed. Knowledge sharing and reuse of the structural design process is difficult.

(2) In the process of aircraft structural design, change is inevitable and the upstream design change leads to that of the downstream design [3]. However, in the traditional design, there is no effective association between the different parts of a product and the designers are also not able to recognize the change. The disconnection between the upstream and downstream is often transferred by notification which bring about many problems: ① The models affected by the upstream model are easily neglected. ② Change made in the upstream models often cannot be passed to the downstream models on time. ③ Manual change operations are always tedious and it is prone to the data inconsistencies of the downstream models.

To realize the design knowledge reuse, automatic modification and update of parts in the process of aircraft wing structural design as well, a top-down associated design method using template is proposed and investigated here. This rapid design system available for aircraft wing structure design is developed with the automatic generation of skeleton model, and rapid modeling of a typical structural part could also be achieved.

2. Top-down design

Two modeling approaches are usually employed during the process of a product design, which is bottom-up and top-down design [4]. For the bottom-up design approach, parts are first generated, and then the components are assembled. The modeling approach is simple and easy to be understood and thus accepted. Due to the lack of assembly information before the overall design, however, it is difficult to support the concurrent and collaborative design of the product.

Top-down design is an approach by creating top-level skeleton and passing down step by step. Designed product is regarded as a hierarchy when conducting the top-down modeling [5]. Part is the bottom structure and the product that can be decomposed into several sub-components is the top level, which is shown in Fig.1.

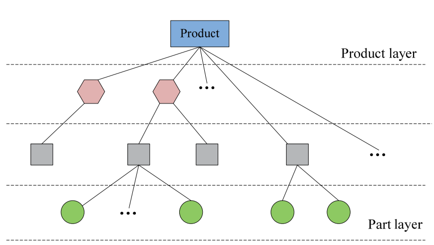


Fig. 1. The structure tree of product assembly

Top-down design begins at the final product root and ends when the design has been successfully executed on every part. This modeling method considers the association and position between parts early in the design. The design of the components and individual parts are then achieved after the completion of the top skeleton design of the product. Usually the detailed design advances simultaneously without over consideration at the conceptual design phase. Therefore, it becomes possible for concurrent design implementation in different departments. It is considered as an advanced design method and there have been several studies focusing on the top-down product design. For example, Mun [6] pointed out that the design process can be decomposed into functional design, conceptual design and detail design, while a top-down product design system should support multiple abstract models for all the three design phases mentioned above. Kim [7] described an assembly association model and developed an ontology based on the model which captured the semantics of assembly or joining concepts and associations. Aleixos [8] analyzed the top-down product design modules by the commercial CAD systems and proposed a hierarchical control framework based on the CAD systems.

The process of top-down design coincides with people's habits of mind, meanwhile designers can better exert the potential to reduce unnecessary repetitive work and improve the efficiency of product design.

3. Rapid design methods and development tool

The process of product design is generally iterative, and the design modifications are inevitable. In addition, the product structure has a large number of identical or similar components and parts. They are almost the same with only little difference in some parameters or structure. Therefore, the parametric design technology begins to be of great concern for researchers. Parametric design is to drive product associative parameter changes through the control on the product features and dimensions, to achieve automatic design model. Its essence is the geometric constraints and parameter-driven model variants [9].

3.1 Template parametric technology

Engineers in design accumulated a large number of processes, methods and experiences, while the process requires a lot of work to be sorted. Most design methods and experiences with more fragmented and disorderly store in the hands of experts, which cannot be deemed as the business intelligence assets. These have greatly limited the structure design efficiency. To reduce the dependence of design results on software, knowledge and experience, more advanced method is to utilize "template design of engineering problems" through encapsulation.

In aircraft wing structure, structural dimension and the number of parts have almost the same function, layout, and generation process of parts, although they bear some difference [10]. Therefore, the components of aircraft wings have a strong template feature.

Templates encapsulate the specific process of design, modeling and analysis. By changing the input parameters, different geometry and analysis models can be obtained. Its main function is to achieve the standardization and parameterization of the design process, while the design methods, rules and experience are integrated in the same model. Designers do not need to rebuild models for each component during the product structure design.

3.2 Associated design

Associated design belongs to parametric design technology, unlike the general parametric technology. The product associated design technology mainly deals with the drive association of geometric elements or parameters between the different product parts.

Associated design is a technology which uses parametric drive to create the dependency association between parts and then realize the automatic update and synchronization with the help of product data management system [11]. It provides tools with rapid update between the upstream and downstream parts and is able to guarantee the data consistency by maintaining the dependency associations. Associated design can be abstracted as a function below shown in (1):

$$y = f(x) \tag{1}$$

Where is the upstream design input and is the downstream design output, f is the association function between the upstream and downstream design.

3.2.1 Top-down associated design based on skeleton model

The associations between the product components and parts are usually lacked in the traditional top-down product design which causes low design efficiency and data inconsistency, however, the top-down associated design based on skeleton model is a very effective approach.

Skeleton model is a component framework and it defines the space requirements and other geometric physical properties of product [12]. In detail, the skeleton model includes all the following parameters or technical information into consideration:① Important design datum of product such as datum point, line, plane and surface. ② Some main control parameters of product. ③ Important associated information of product design. Skeleton model is able to provide support for concurrent and collaborative design of the final products. Through various constraints defined in skeleton model, the design tasks can be decomposed to different organizations or individuals, thus achieving the rapid product design in the premise of strict compliance with the design and constraints.

Consistent with the constitution structure of a product, skeleton model has a multi-level structural characteristic. Hence, in addition to the main top skeleton, there are also several sub-skeletons which are shown in Fig.2.

Multi-level skeleton model is like a tree structure, where the root node represents the top-level main skeleton model, minor node represents the sub-skeleton model, whereas the leaf node represents the bottom skeleton model. Different levels of skeleton model relate to the different levels of design information.

In the corresponding assembly level, skeleton model is the first part of product assembly. The other components or parts reference datum elements for modeling through "External References". It drives other models after the design completion which is shown in Fig.3. Design information is

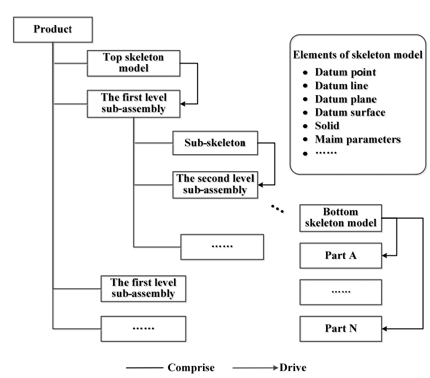


Fig. 2. Multi-level skeleton model

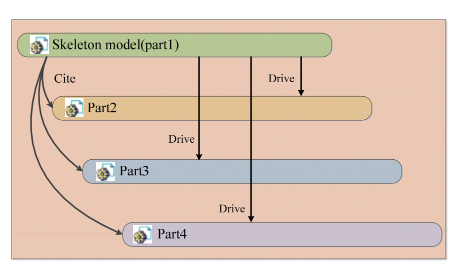


Fig. 3. Design driven by skeleton model

only transferred from skeleton model to other components or parts in one direction while the information cannot be passed to skeleton model.

Top-down associated design based on skeleton model is able to maintain and manage high-level design changes. If the design content of the top skeleton model is modified, all the associated subsystems will respond to the changes which can guarantee the control of the design changes and ensure collaborative design of product. In addition, all the design associations only point to one direction which could avoid circular update.

3.2.2 Implementation method of design

When conducting product modeling with the method of top-down associated design based on skeleton model, we should have a detailed understanding of the product. Overall planning is usually first step to take. The next one is to establish skeleton model and carry on elements publication and part modeling. The specific implementation method and product modeling process is shown in Fig.4.

Step1 The first step is to carry out the overall planning of the product and define the design content and product assembly structure tree. After analyzing the function and the composition of various components, the next level structure tree is then built for the individual parts.

Step2 It is to establish the product control structure and all levels of the assembly structure skeleton model. Skeleton model is constructed by interrelated characteristics in assembly tree that is abstracted from the product design rules. All these characteristics can be passed down in assembly structure tree and also be passed between different levels.

Step3 Based on the "publication" mechanism of CATIA, datum point, line, plane and main parameters in skeleton model can be selectively published. Each part has characteristics inherited from the upstream components and it is driven by the upstream components.

Step4 Geometric elements or parameters in the upstream skeleton model are referenced by the way of "External References" or "External Parameters" in order to build the detailed model.

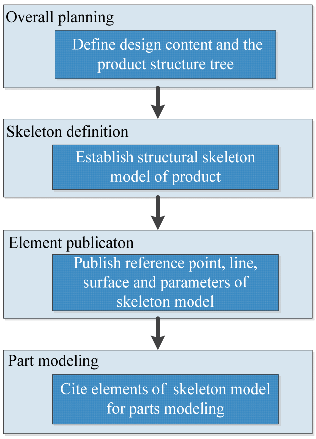


Fig. 4. Top-down associated modeling process

3.3 Development platform and tool

CATIA is the most common CAD modeling software and measure in the structural design of aviation enterprises. Almost all aircraft structural design parameters are based on CATIA environment [13]. There are four different parameterization levels which can be customized effectively in CATIA V5. The most important parametric tools include CAA (Component Application Architecture), VBScripts, CATIA knowledgeware and native CATIA parameterization which are shown in Fig.5.

CAA has the highest customizability and CAA, C++ and API provides better interface, but the comparably complicated program language are the main reasons why CAA is often dismissed in favor of Visual Basic (VBScripts) [14,15]. Although the function of VBScript is less powerful than that of CAA, it has a low development difficulty and is easily understood, and more importantly it could fully meet the functional requirements of aircraft structural rapid modeling. Therefore, Visual Basic and VBScript are chosen as the development tools to carry out program design.

4. Aircraft wing structure definition

The aircraft shape and its components are always very complicated. However it is not hard to find out that a wide variety of aircraft components can be divided into two categories after the analysis: wing structure and non-wing structure. The aircraft wing structure includes fixed wing leading edge, wing box, fixed wing trailing edge, horizontal tail wing box, elevator, vertical tail wing box, rudder, ailerons, flaps, spoilers and other components as illustrated in Fig.6. The plane coordinate system is defined. X-axis points toward the tail from aircraft head, Y-axis points toward the left or right

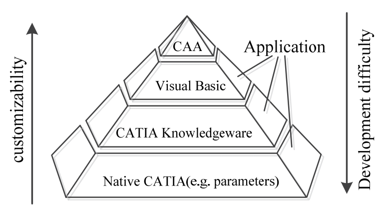


Fig. 5. CATIA parametric degree

side of fuselage from the aircraft symmetry axis, and Z-axis points upward from the bottom. The rapid design system of skeleton model and typical structural part developed in this paper follows this coordination system.

Such aircraft structures have several similar characteristics:① The structural shape is controlled by a number of cross-sections; ② All of the control section shapes are selected by standard data and the shape defined by these data is called "airfoil"; ③ The section data can be rotated based on the airfoil, but rotation is limited within the section plane; ④ All of the control sections parallel to aircraft symmetry axis (X-axis).

The structures satisfying the above characteristics can be defined as "aircraft wing structure". According to the common features of wing structure, a unified parametric modeling method applicable for all structures can be obtained after analysis and data abstraction. Wing box is the most important and complex component in aircraft wing structure, therefore, wing box is selected as the object in the paper for rapid design study.

5. Rapid modeling of skeleton model

Skeleton model without the specific part dimensions and details is characterized by the functional requirements and design intent of aircraft wing structure. It defines the overall framework of the entire aircraft wing components and assembly association between various parts. Not only skeleton model is the result of aircraft wing structural design, but also it is the starting point for the detailed design of structural components. The parts, piping and systems are to some extent directly or indirectly depend on the skeleton model in the process of aircraft wing structural design.

Based on the template parametric technology previously described, a knowledge-driven rapid design system of the aircraft wing structure will be developed. The system utilizes the shape and size parameters of aircraft wing structure as the input, automatic layout and rapid generation of skeleton model are obtained as the output. It also has the ability to perform rapid modification of skeleton model according to the optimization results at the preliminary stage. Fig.7 is the developed template of skeleton model for horizontal wing structures such as fixed wing leading edge, wing box, horizontal tail wing box, elevator, ailerons, flaps, etc.

In the template, the upstream inputs are some planes and aircraft wing surfaces, which include reference (or chord) plane, projection surface, the upper and lower wing surfaces, the root and tip rib station planes. The structure layout definition and main parts size parameters as downstream results are outputted.

After the competition of the upstream information selection and parts parameters set, users can run the template by clicking "OK" button. CATIA software can be driven to execute in accordance with the parameters defined by the template and skeleton model of aircraft wing structure can be generated rapidly. Two kinds of skeleton models of aircraft wing structure generated by the template as examples are shown in Fig.8. The upper airfoil surface is hidden for clear demonstration. The red represents the lower wing stringers and their corresponding station planes. The work in this paper can also be used as a link for rapid optimization. After the competition of the aircraft wing structural layout optimization, users are able to modify parameters in the template interface or transfer data from the upstream design according to the optimized results in order to achieve rapid reconstruction of the aircraft wing structure skeleton model and output the new models and parameters.

During the skeleton model generation process of aircraft wing structure, it generally takes more than four hours by hand, and eight hours at least for the complex wing box structure. However, based on the developed automatic system, the process takes less than 10 minutes, including the time of parameters input and modeling driven by

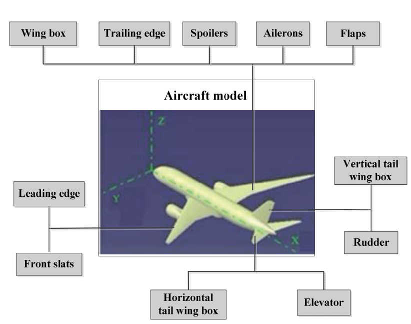


Fig. 6. Aircraft wing structure components

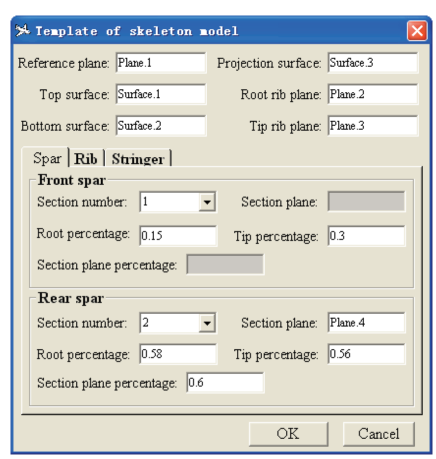


Fig. 7. Template of skeleton model

CATIA, which greatly improve the design efficiency and shorten the design cycle, and ensure the design quality and standardization.

6. Rapid modeling of typical structural part

Typical structural part is a single solid model with a huge amount of characteristics and high reuse and similar structural part obtained by induction in aircraft wing structure. In the design process of an aircraft wing typical structural part, the conventional design method has not yet formed a system, and it is still discrete and isolated which is mainly reflected in the following aspects:① Manual interaction design is usually achieved by designers in the modeling process, therefore, the design quality often depends on the designers' skill level and experience. ② Association is not built between structural parts and skeleton model. ③ The lack of digital design methods for the knowledge accumulation results in that the existing design knowledge cannot be effectively summarized and reused.

For the purpose of improving the modeling speed, this paper aims to construct a rapid design system suitable for the aircraft structural design specialty including the generation of skeleton model and typical structural part, which is shown in Fig.9.

In the process of creating a typical structural part, the previous described template parametric technology and associated design technology are employed. Knowledge summarized by designers in the modeling process is encapsulated into a template and thus the association is established between typical structural part and skeleton model, achieving the rapid modeling of typical structural part and automatic response for the changing upstream skeleton model at the same time.

6.1 Feature analysis of rib

Rib is the most representative structural part in the aircraft wing components. Three types of ribs are often used in the aircraft wing structure including the machined rib, sheet metal rib and composite rib, of which machined rib has more features and is the most complicated structural part. Therefore, machined rib is selected as the design object for the typical structural part rapid modeling.

Backus-Naur Form (BNF) is a formal method used to describe the given language rules with the characteristics of precise definition, concise form and rich expression capability. BNF form in this paper is employed to describe common knowledge types for a typical aircraft wing structural part. The machined rib characteristics and basic parameters of Backus-Naur Form can be summarized as follows:

<rib features> ::=({<section types>}, <rib flanges>,

<rib web>, <stiffeners>, [lightening holes], [maintenance hole], [stringer gaps], [subsidence])

<section types>::=(<C-section >, <I-section>)

<C-section>::=(<flange towards the wing root>, <flange towards the wing tip>)

<rib flanges> ::=({<upper flange>, <lower flange>}, <flange width>, <flange thickness>)

<rib web>::=(<web thickness>)

<stiffeners>::=(<long stiffener>, <transverse stiffener>,

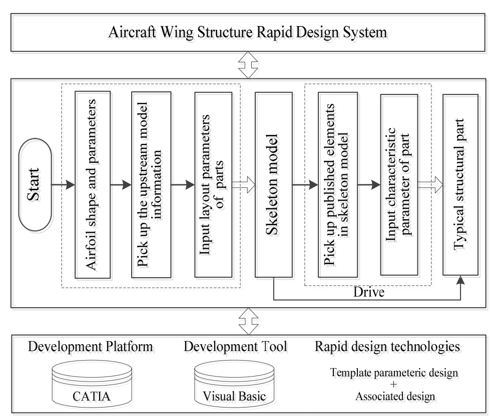
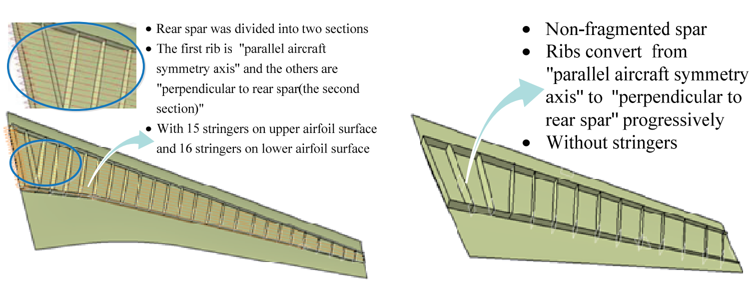


Fig. 9. Frame of the aircraft wing structure rapid design system



(a) Wing box (b) Horizontal tail box

Fig. 8 Skeleton models of aircraft wing structure

<longitudinal stiffener>)

<long stiffener>::=(<stiffener width>, <stiffener thickness>, <offset distance away from rib flange>)

<transverse stiffener>::=(<stiffener width>, <stiffener thickness>, <distance between stiffeners>)

<longitudinal stiffener>::=(<stiffener width>, <stiffener thickness>, <distance between stiffeners>)

<lightening holes>::=({<circle hole>}, <hole numbers>, <hole diameter>, <hole position>)

<maintenance hole>::=(<circle hole>, <polygon hole>)

<circle hole>::=(<hole diameter>, <hole position>, <convex platform height>, <convex platform width>)

<polygon hole>::=(<hole side length>, <hole position>, <convex platform height>, <convex platform width>)

<stringer gaps>::=(<gap width>, <gap height >)

<subsidence>::=({<top flange subsidence>, <bottom flange subsidence>}, <inner starting station>, <inner ending station>, <outer starting station>, <outer ending station>, <subsidence depth>)

6.2 Elements publication management

Publication is an operation for better controlling the created external reference characteristics and is also the process of naming elements with the specific tags. If an element needs to be referenced by other parts, the element should be published within the "publication" mechanism of CATIA so that it could be visible to all parts of the work domain.

In general, elements used to be published include wireframe elements such as points, lines, and surfaces. They could also be rectangular, cylindrical or parameters constructed solid geometry. In the collaborative design process, published elements are easier to be identified and referenced by all designers and are also easier to achieve the replacement between parts. The elements with the same name can link automatically. Although it is also able to realize the association between parts by referencing ordinary or unpublished elements, the linkage is easy to be disconnected and is difficult to achieve automatic update of the part. Therefore, unpublished elements are usually forbidden to be used and only published feature elements can be referenced in the aircraft wing structure design.

For skeleton model of aircraft wing box structure shown in Fig.8 (a), all part station planes should be published for the downstream structural parts modeling. However, only a small part of elements are used for the creation of a single typical structural part. There are some elements for the creation of a machined rib such as rib 8, which include the upper and lower surfaces, rib station plane, the front and rear spar station planes, the stringers station planes used to generate stringer gaps as shown in Fig.10.

6.3 Description of the rib modeling

According to the overall structure and features of the rib, the parametric modeling process is divided into four main steps which are described as follows:

Step1 It is to publish design benchmarks and important control parameters that are related to the rib in skeleton model of aircraft wing structure, which include the upper and lower wing surfaces, ribs station plane, starting plane, ending plane, and the relevant stringer station planes.

Step2 The elements for modeling should be copied by the way of "As result with links" to the wing rib model.

Step3 Based on modular design, a clean main load-bearing structural model that is "shape framework" (see Fig.11) is achieved. The model reflects the size distribution of bearing components, but does not include any features. Only the most important parameters are considered.

Step4 On the shape framework, it can be further refined by adding the modular features. Additional features can be "addition (e.g. stiffeners)", "subtraction (e.g. lightening holes)", and they also can be "addition and subtraction (e.g. convex platform)". Through the flexible application for these features, a detailed CAD model can be obtained.

After the above steps, the final rib model will be constructed. It has association with the upstream skeleton model. If the skeleton model contents are changed, for example the wing surface or rib station plane, the rib model is capable of rapidly responding to the design changes and automatic update.

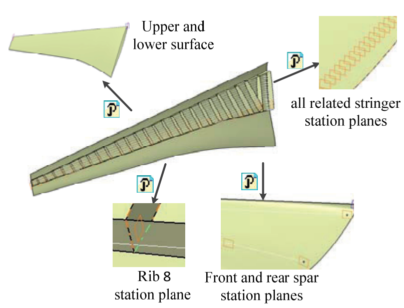


Fig. 10. Elements publication of wing box

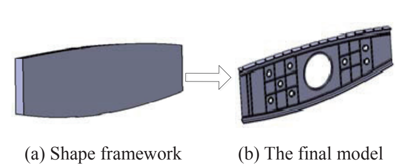


Fig. 11. The rib model

6.4 Template development and automated generation of rib

A knowledge-driven rapid modeling system of aircraft wing structure is developed by the template parametric technology. The system is appropriate for the rapid generation of detailed complex rib models without chamfers and fillets. The template developed by Visual Basic is shown in Fig.12. To achieve the reuse of design knowledge and common abstraction on the geometric dimensions, the mapping interfaces of the upstream information and design parameters are required for the information transmission and interaction with CATIA, thus to complete the geometric reconstruction in design environment. The interfaces of "Upstream information" and "Basic parameters" are included in the template.

The "Upstream information" interface is designed for gaining design datum of the upstream wing structural skeleton model. It is usually a communication channel for reconstructing the rib in actual design environment and represents a directed bound feature set for the external features. Only published elements are allowed to be picked up or selected in skeleton model. "Basic parameters" interface is a channel for achieving parameters mapping. The template geometric layer can capture the parameter values specified by designing through the "Basic parameters" interface. The interface design is fulfilled by extracting the main geometric parameters in the internal constraints of aircraft wing structure. By clicking the "OK" button after inputting all of the information, typical structural part is then produced by the template which is illustrated in Fig.13. The process takes at least 20 hours completely handmade by structural engineers and needs longer time for new engineers who are unfamiliar the modeling process because of its more characteristics. If the rapid design methods and developed tools are employed, this process will be greatly reduced, generally no more than 15 minutes.

The rib created by the top-down associated design skeleton model is a separate part. The position of the rib is determined by selecting design datum planes, the upper and lower wing surface in skeleton model of the wing structure. The output model is assembled in the absolute coordination system under the parent component without re-assembly. Similar to the rib, other typical structural parts can also be obtained in this way which is shown in Fig.14.

Since the rib references the upstream skeleton model information by the way of "As result with links", if the skeleton model contents are changed after the accomplishment of rib structure produced by the template, the rib can automatically respond to the changes through the association with skeleton model. Its color may become red, indicating that it needs to be updated. Based on the mature mechanism of CATIA, the rib can be updated automatically, maintaining the upper and lower flange close fit with the inner surface at the same time.

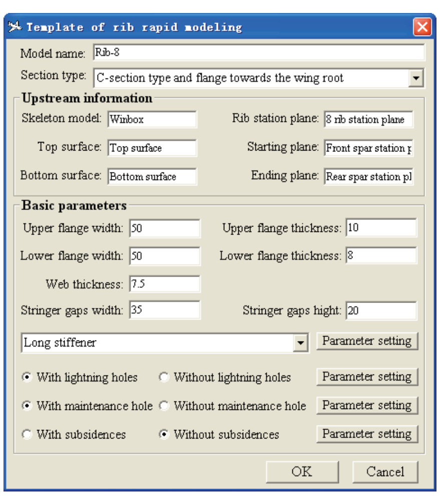


Fig. 12. Template of rib rapid modeling

7. Conclusion

A top-down associated design method based on skeleton model is proposed and proved in this study. The related geometric elements are copied to the typical structural parts from skeleton model of aircraft wing structure. Design changes can be effectively controlled through

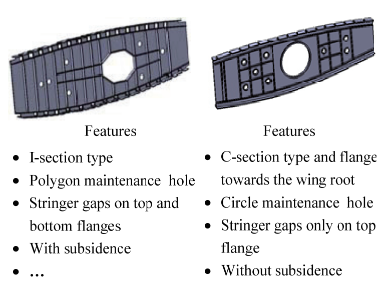


Fig. 13. Two models produced by template

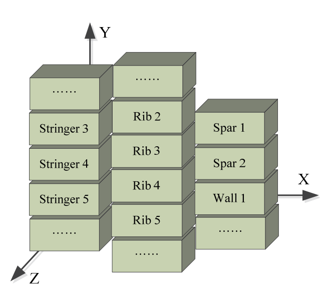


Fig. 14. Automatic assembled typical structural parts

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the association between typical structural parts and skeleton model. The design method ensures the effective transmission and consistency of data and information of upstream and downstream models and consequently avoid a large number of model modification workloads simultaneously. The method also strictly guarantees the assembly position of typical structural parts, which greatly improves design quality and efficiency of aircraft wing structure.

Template parametric technology is also employed in the process of the top-down associated design. Rules and ample experiences generalized in the process of manual interaction design are encapsulated in a standard form of knowledge. A rapid design system of aircraft wing structure is developed, and automatic generation of skeleton model and typical structural part of aircraft wing structure are achieved. Aircraft structural engineers need to understand the design itself rather than focus on duplicated and complicated modeling process, allowing engineers to apply more energy to engage in creative work. Therefore, with the re-design ability of template, rapid design system developed in this article lowered the threshold for the use of software, reduced the repetitive works, and can greatly improve the speed, efficiency and modeling standardization degree.

The research in this paper has universal versatility, not only could it be applicable to aircraft wing structure, but also to the rapid and variant design of other complex products.

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