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Analysis and validation of the digital chain relating to architectural design process

Achievement of a folded structure composed of wood panels

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Abstract. The research presented in this paper revolves around the experimental development of the morpho-structural potential of folded architectural structures made of wood. The aims are to develop an innovative system for timber used in sustainable construction and to increase the inventory of wood architectural tectonics. First, this article provides a characterization of the digital chain associated to the development of non-standard folded structures consisting of wood panels. The purpose is to study the architectural design process from parametric modeling (through CNC machining) and assembly operations to production by way of a full-scale experimental pavilion. Secondly, a number of analytical experiments have been performed towards the completion of the pavilion, in order to validate the design process.

Keywords: Architecture, folded structure, robotic fabrication, computational design, parametric modeling, wood panels.

1 Introduction

The term “fold” as used in the field of architecture shows a shift in the designs and vocabularies of contemporary forms. For example, Peter Eisenman has used, for the Rebstockpark project, the fold as a concept of changing forms continuously through time [1] or even Rem Koolhaas for his work on the "trajectory" where folds generate more singularities [2]. The fold is partly based on the theoretical foundations of the philosopher Gilles Deleuze, in which the traditional form and its material relation as a spatial mold, has given way to “a continuous variation of matter as a continuous development of form” [3]. The designed architectural object, takes place in an evolutionary continuum where the parameter variation replaces the constant laws. The “event object” with vast potentials and modulation possibilities is replacing the traditional “fixed monument object”. The fold as a process means an adaptive formalization mechanism. Henceforth, the fold is becoming a conceptual tool to address the realm of contexts and perspectives in architecture.

The practices of digital technology as developed today in the field of architectural design and manufacture have instrumented the idea of a continuous development of

the shape. This practice has spread the idea of fold to the production process. The chronological chain, from design to manufacturing, is no longer linear but becomes a series of simultaneous developments and possible variations. As the philosophical concept can operate as an architectural one, the fold becomes a productive concept that can be explored. The emergence of new materials or new components and their relating technicalities makes possible this continuum of shape (de)formation and virtualization on a basis of potential variations of the production tools. It aims, although to a limited extent, is to focus on the fold with respect to its morpho-geometrical dimension and its ability to respond to a fluctuation of contexts and uses. The fold brings a fresh look on the integration of the structural dimension as a modulation factor and allows adaptive modeling within the design-manufacturing continuum. Finally, we report on an experiment leading to the production of a folded structural envelope made of laminated wood panels.

2 The fold

2.1 The fold : a Morpho-structural system

In nature the fold can adapt to local stresses and external forces which will lead to a deformation of the material. The fold can suffer a deformation as in the case of geological folds characterized by orogenesis. It may also be a shaping genetically adapted like palm leaves which fold is formed during the growth cycle to provide it with wind resistance. Generally, the fold provides rigidity while minimizing the material used. For example, we find that this logic of resistance in the field of stamped metal sheet technology is used in the automotive, aerospace and general engineering industrial sectors. In architecture the fold provides many morphological but also structural possibilities. It brings rigidity and inertia as required for the structural stability of the architectural works adopting it. Moreover, by principle, the fold highlights an efficient relationship between the projected area and the material quantity required for the construction. The saving made on the material gives a real environmental dimension to the fold. In addition to the conceptual dimension mentioned in the introduction, the fold provides a genuine tectonics in architecture. This leads to a visual evidence superposing both the clarity of a plastic form, and veracity of a construction design [4] benchmarked against the material and structural dimension of the designed shape. The characteristics of the fold define a language; a source of architectural and structural motion [5].

2.2 The folded material

From a physical point of view, every material can theoretically be folded. But from the viscous to the rigid substance, the folding can result in stress efforts specific to each matter. We can classify a fold by continuity or discontinuity of material.

The continuous material. The fold is commonly associated with the deformation of a thin material surface with a small bend radius regarding the thickness of the material (metal foil, paper, fabrics ...) but it can also be obtained by means of molding technologies. A bending action, which consist to roll back the material according to a determined angle, introduces internal stresses of traction / compression and causes a reduction of material thickness. Mathematically, it is estimated that the tangents at a point of the surface are continuous in all directions. In that case, we can define a minimum acceptable bend radius before the material breaks. Materials with plastic dimension have a maximum degree of deformation. This plastic deformation gives limits to bending radius. However, the disadvantage of this technique lies in its inability to produce big structures.

The discontinuous material. A fold can be accepted as a union of different surfaces. Mathematically it can be defined by the discontinuity of tangents to a point of a surface and in a given direction. The one-time change of direction in physics means an interruption of matter and thus the notion of assembly. A classification of assembly types must be appropriate to the material in use, to ensure continuity of internal its forces. This third method interests us regarding its use on industrial wood panels.

Fig. 1. Continuous tangent (minimum radius of curvature) - Discontinuous tangent (assembly)

3 Fold and Folding models

Our research turns to the use of flat industrial panels for the developing folded wood structures. Currently, an insufficient mastership of the physical wood behavior laws to make panels deformable has not yet allowed an easy use of the material. Hence, we orientate our work towards a technology of assembled folds.

3.1 Study corpus

Applied initially to walls or roofs, folded structures quickly evolve towards arch, portal frame or folded shell. The first two projects present folding structures with continuous material. The UNESCO concrete building in Paris by P.L. Nervi reconnects the dialogue between form and structure [6]. The architectural realization "Corogami Folding Hut" by David Penner reveals folds generated by mechanical bending action in order to obtain a sufficient rigidity [7]. In the environment of wood material several experimental achievements have demonstrated the high potentials of wood assemblies to create particularly inventive architectural design. The pavilion

designed by Hybrid Space Lab office in Berlin, consists of triangular plywood sheets sewn together with cable ties [8]. The Thannhausen Music Hall in Germany designed by architect Regina Schineis, shows a regular folding ensuring a portal frame system fixed to a concrete slab [9]. The temporary pavilion in Osaka realized by Ryuichi Ashizawa Architects [10] and the Chapel of St Loup in Pompaples [11] attest wooden folded structures virtues by their structural and architectural qualities. Oriented mono-directionally folds increase the stiffness of thin surfaces. Structurally, these constructions work as a series of portal frames. The Japanese pavilion is equipped with a primary skeleton creating ridge and valley edges and covered of panels in a wind bracing way. Quite the contrary, the chapel wood panels ensure both the architectural envelope and the structural system. Laminated timber panels associated with a "digital production line" approach have opened up new perspectives for the building industry in creating prefabricated wooden structures. Timber panels like cross-laminated timber (CLT), or laminated veneer lumber (LVL) introduce specific features like their availability on large sizes or their high strength even for thin panels. While traditional timber-frame structures use timber panels only for cladding and cross-bracing of beams, new typologies such as Timber Folded Plates use plate-assemblies as load-bearing structures (i.e. Interlocking Folded Plate Structure) [12].

Fig. 2. Interlocking Folded Plate Structure (left) and The Temporary Pavilion (right)

3.2 The fold model

The fold is the unit element of the folding. It consists of two entities called "faces". As part of our work on folded architectural structures made of wood panels, we consider only planar faces. The combination of two faces at a common edge and to the appropriate non-zero angular value, creates geometrically a fold. It is characterized by the notion of amplitude (height of the fold defining its inertia) and the concept of frequency (base of the fold). Folding is the combination of several folds.

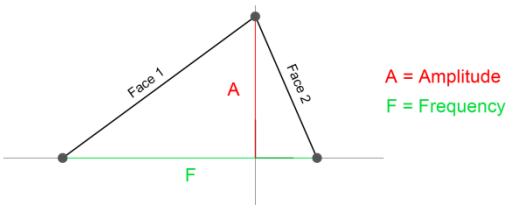

Fig. 3. Model of fold

3.3 The folding model

Architectural typologies concern continuous covering envelopes (vaults) or revolving forms which interest lies in their inherent stability (dome). The shape of the envelope, as defined by architectural criteria, represents the basis of fold modeling. The use of flat panels leads to the creation of break lines during the generation of the folded envelope. These break lines discretize the support skin in planar surfaces matching with the curvilinear morphology of the initial envelope. The fold is then oriented in relation to the normal of the envelope surfaces; it is controlled by parameters of frequency and amplitude of the fold. The folding method defines the disposition rules of peaks and valleys edges according to the normal of the face. Pilot criteria based on the material, structural behavior and manufacturing techniques are associated to these parameters. The choice of material interacts with the rigidity (Young's modulus), thickness of the panels (changing the assembly by nature, reacting to the weight), and the dimensioning of raw panels (modifying the pattern layout and size of the panels). The structural validity is generated by an analysis software that impacts stiffness, folding inertia (controlling amplitude and frequency), and stability (modifying the break lines, assembly stiffness). The manufacturing imposes geometric constraints derived from a Numerical-Control tool parameter settings, such as angular cuts and maximum panel size (weight and size management). Finally, it makes sense to set up a management system monitoring the kinematic impact to verify the feasibility and accuracy of the assembly parameters. The architectural validation will be established by the designer.

4 Digital fold

The current state of the digital chain as proposed in our work consists of a parametric design phase of morpho-structural envelopes associated to a robotics manufacturing phase. The digital design environment is composed by the modeler Rhinoceros coupled to Grasshopper (editor of graphic algorithm for parametric geometric data management) and the finite elements analysis software Cast3M for structural verification. The digital production environment is organized according to the Computer Numerical Control (CNC) machine used.

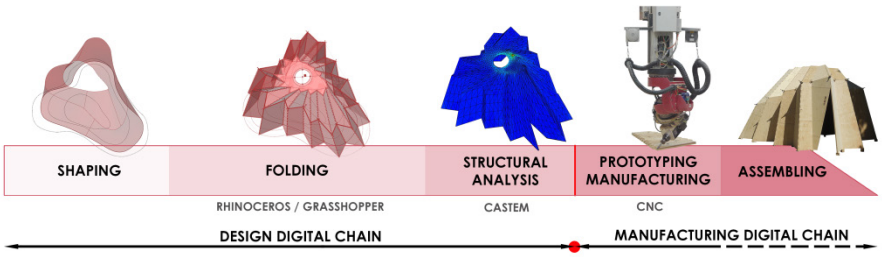

Fig. 4. Progress of digital chain

4.1 Parametric design

The digital continuum is ensured by the creation of clusters so as to generate different command codes. This digital model does not define an optimal solution but is sufficient. Those parameters allow the architectural folded shapes to match as much as possible the satisfactory structural features without deviating from the morphology of the initial envelope.

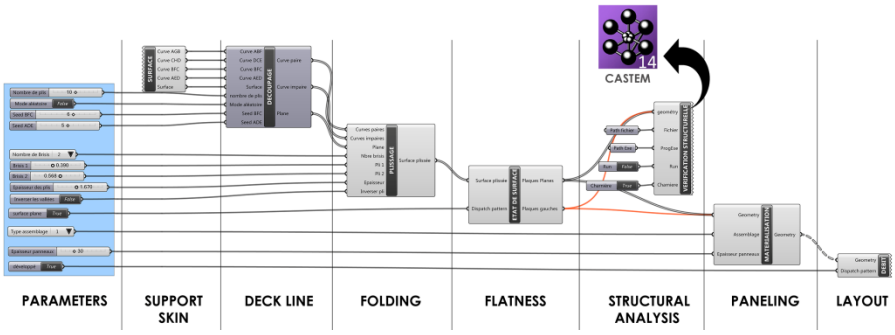

Fig. 5. Digital device of design

Shape Parameters . The "envelope support" is defined by a Nurbs typed curvilinear surface.. These envelopes are characterized by two directions. The first enables a discretization of the initial envelope into a number of configurable break lines, and the second corresponds to the folding orientation. The folding algorithm determines a regular or an irregular grid. It can manage the fold's amplitude by using the normal vector of the faces alternated positively or negatively. The frequency and amplitude parameters are managed through a table of values. The creation of the fold generates two panels of 4 non-coplanar edges; a VBnet script allows the determination of surface flatness with a variable degree of precision. The structure thus adapts to the deformation capacity of the material which requires pre-stressed panels for mounting.

Assembly parameters. When applied to wood structures, each panel has to be assembled. The assembly is defined by the number of degrees of freedom (lineal pivot), as well as by a specific joint method (dovetail joints). The choice of the number of degrees of freedom for stability verification is imposed on us. The modeling of timber structures requires to take joint slips in consideration (refer to paragraph 5.2). The technological part of the assembly leads to a specific production level and assembly kinetics. Currently, kinetics of assembly in the digital continuum is not taken into account. Setting the thickness of the surface model reveals a geometric complication which leads to, in most cases, a duplication of nodes. This problem can be tackled by a local construction feature (obviously by connectors…). Nevertheless, this kind of intervention remains manual thus calling for further reflection on the design.

Structural analysis parameters. The introduction of a structural evaluator using the method of shell type finite elements (Cast3M) enables the validation of stability of the structure and its dimensioning. The meshing (discretized geometry), the materials and the limited kinematic (supports) and static (loads) conditions are commanded by specific clusters (Grasshopper). The structural fold gives inertia to the envelope, brings stiffness to big surfaces with a minimum of material, and stabilizes the structure through three-dimensional combinations. These three mechanic principles of the fold are considered to be the evaluation criteria for structural envelopes. Although the structural analysis has not yet led to automatic modifications effected on the envelope morphology thus data has to be treated manually as a means to interact with the different parameters set out in the morphological modeler.

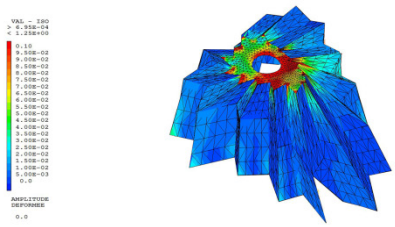

Fig. 6. Deformation structural analysis

4.2 Digital manufacturing

The machining methodology depends directly on the characteristics of the tools used (admissible size of raw wood panels, characteristics of cutting tools, methodology of clamping system, …) and of the material (nature of the material, …). These characteristics make it possible to define the pattern layout of different elements comprising the folded structures. This layout takes into consideration the management of woodgrain and off-cuts to achieve structural optimization. The model integrates an algorithm that numbers the pieces and examines the different elements from all angles by a grid pattern defined on a two-dimensional plan. At this stage, the numeric command necessitates the writing of command lines to enable the generation of tool paths in order to cut pieces according to the pattern layout made beforehand.

5 Experimental fold

The purpose of this experiment is to validate the accuracy of the parameters implemented in the design phase as well as the correctness of the implementation. The experiment takes place against the backdrop of an exhibition known as the “Wood Challenges” [13], where the inventive capacities of wood to deal with architectural, technical, economic and environmental issues of today and tomorrow are demonstrated. This " welcome pavilion” (L=8m; l=5m; h=4m) has been created to test the digital chain of computer design to digital manufacturing.

The envelope support was folded according to the morphological criteria as required by the designer and coupled to the parameters of the material (laminated wood panels 10500mm x1800mm x 40mm) and those of the CNC machine tool (5 axes CNC Güdel machine, figure 4a) put at our disposal as well as the parameters set out from the structural analysis. A dovetail connection system was chosen to process the folding edges and a tongue-and-groove system was adopted to join the panels along the break lines. In order to distribute the structural forces more evenly, a compression ring was added. This type of piece requires manual intervention in the computer model. The digital manufacturing requires several data transfer formats. A STEP standard was used in order to achieve the data transfer from Grasshoper to Lignocam; a BTL standard, provided by Lignocam, is particularly interesting since it takes into account the specifics of wood process; for example, a half lap on a piece extremity cannot be machined in the same way as a longitudinal process. Finally the trajectories generated by Lignocam are transferred to Woodlex gantry thanks to L1E and ABB Robo-studio. The different data exchange formats (STEP, BTL, ISO and RAPID) evidence a risk of breakdown in the continuity of the digital chain.

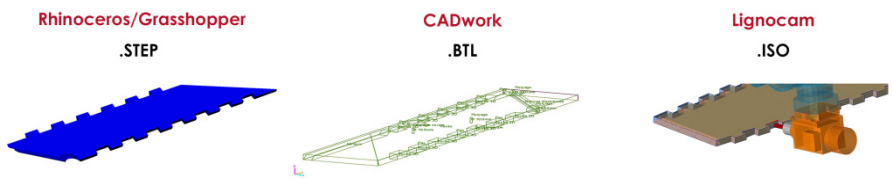

Fig. 7. Data transfer formats

The production process included the cutting and machining of 57 wood pieces. The problematic of raw panel constrains a specific clamping method needing a double positioning of wood pieces. So clamping system has been divided into two steps. First, a nesting procedure is necessary before placing drillings over the raw timber panel in order to locate the pre-machined items at their correct position. After doing so, each pre-milled panel is finished and a mounting test is performed at the workshop in order to check the installation kinematics and joint gaps.

Fig. 8. Digital device of manufacturing and Assembled structure.

5.1 Characteristics of assemblies

Technological choice of connections. A twisted dovetail joint might be sufficient for assembling the structure [14]. However, the assembling kinematics selected, linked to the difficulty of handling such heavy panels, required the use of two different joints; the dovetail defined in the project does not allow a complete panel blockage, so a tongue and groove system was used to lock each panel.

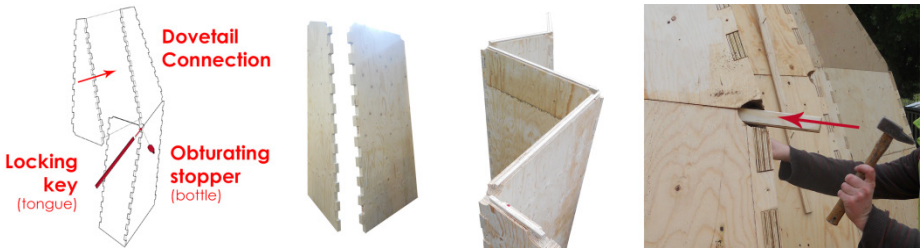

Fig. 9. Woodworking joints

Structural characterization of connections. Each assembly is defined by a junction family (dovetail, tongue and groove, ...). A parametric and geometrical definition of assemblies in Grasshopper software allows the manufacturing of these assemblies. The assembly is modeled by its connection type (linear pivot) in a finite elements shell type software (CAST3M). Each assembly is represented by a coupling of different degrees of freedom (3 translations and 3 rotations) and is defined by the stiffness corresponding to the joint slip (1 joint slip per degree of freedom). This coupling is implemented in the finite element analysis software by a stiffness behavior associated to its technological landmark.

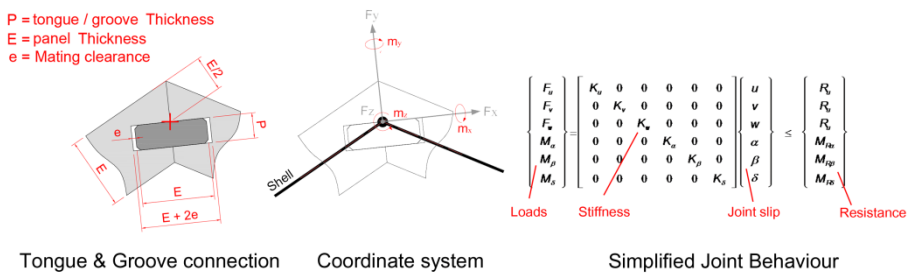

Fig. 10. Structural characterization of tongue and groove assemblies

5.2 Morphological and structural validation

The morphological analysis is done in two steps. Firstly, the morphological analysis helps validating the lassergrammetry work performed on the piece after milling it, giving us information about the dimensional error in percentage between the

numerically modeled piece, and the processing panel piece (5%). This error is due to a lack of precision in the robot's movements and also the positioning of the tool holder. Secondly, the analysis is to validate the assembling methodology with the complete use of lasergrammetry for structure assembly, so as to analyze the morpho-structural impact of dimensional deviations on each assembled element (average precision 1/1000). These errors are the result of an incomplete imaging linked to the scanner, manual cleaning of specks and spots, scanner precision and hygrometrical behavior of the material used. By examining the tolerances in traditional wood construction, we find this to be an exceptionally low value. This precision fulfills the necessary and sufficient conditions for the machining precision process to be validated and the assembly protocol confirmed.

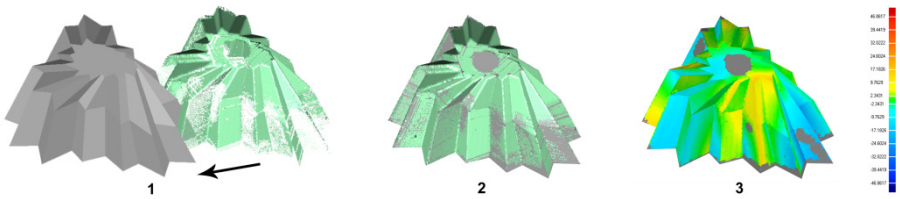

Fig. 11. Morphological analysis by scanning

The experiment is to replicates the effects of a specific vertical load and the effect of wind on the structure by lateral traction. To identify the structure's experimental stiffness (Ks), the displacement ratio of structural nodes was measured by using mechanical sensors and lasergrammetry devices.

The structural validation is performed through backward reasoning. In order to adjust the joint slip variable in the numerical model the conditions of the experiment were simulated in the finite shell elements calculation software (CASTEM). Parameters concern elastic properties of the material (Young's modulus for dry wood) and the stiffness of assemblies. These, define a relaxation of the degrees of freedom, as well as the internal joint slip of the assemblies (relative movements between two assembled pieces). To confirm the correctness of the parameters, we compared the overall digital behavior of the structure with the results of the experiment. The elastic behavior obtained during the loading phase corresponds to a structural accommodation cycle. Analysis and experimentation thus rest on the stiffness obtained during unloading, which becomes purely elastic. At the same time, this experimental loading was simulated on finite elements calculation software to define a digital elastic stiffness of the structure (Ks) depending on joint slip according to an assembly stiffness (Ka) with an enterprise value of zero to (+) infinity. Against the data obtained from the calculation software, the digital model of a perfect assembly is ten times superior to the experimental value found. It is therefore necessary to take assembly shifting into account. It can be stated that the assemblies correspond to a lineal pivot coupled to stiffness [15]. Experimental structural stiffness obtained by unloading is plotted on the curve (Ks as function of Ka) to define the assembly stiffness of the folded structure. The value of the stiffness obtained is relatively low.

This is due to high humidity present in the wood panels. Important work on assemblies still needs to be done. By playing with different assembly typologies and technologies (connectors, gluing, etc.), the stability of structures can be increased.

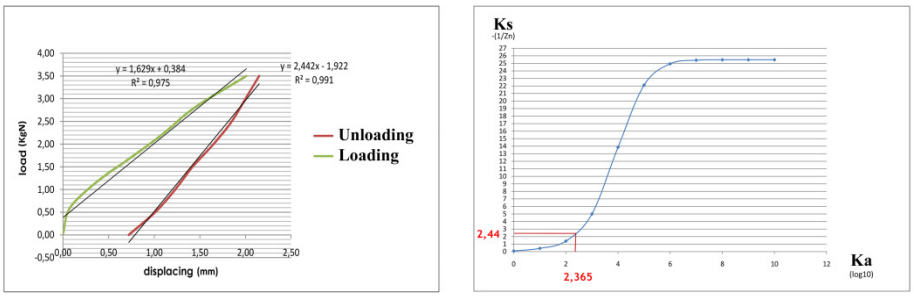

Fig. 12. Experimental stiffness (left) - Ks as function of Ka (right)

6 Conclusion

The fold is part of the new architectural design languages. The digital dimension participates actively in this morphological quest and is today a basic of architectural research. In our work, we tried to outline a first numeric controlled design tool whereby the folded structures under study are considered to be architectural "objectiles" [16]. Technical variables (structural analysis, manufacturing, erecting and materiological) integrate the architectural design genesis. In the context of the fold as a formalization process, these variables lead to a geometrical fold (re)configuration in order to find an acceptable form.

Nevertheless, the numeric continuum is incomplete. Several actions require a manual intervention, notably in the return of results of the structural analysis, data management of the tooling and the installation phase. The experiment, as conducted, allows us to validate our digital design tool and digital manufacture of folded structures made of solid wood panels. This pushes us to further pursue our work in the automatization of geometric correctors and optimization of the digital chain.

One possible perspective of our work consists of developing the assembly by robots. Its usefulness lies in the development of alternative construction techniques ensuring transposition of industrial manufacturing technologies by combining prefabrication and production advantages [17]. Our morphological study on the theme of fold, and its derivative towards folding, is presented as a possible solution to an architectural production assisted by digital technology, as Lynn [18] or even Cache has conceived. The interest of the dynamic flow of morphological genesis with literally complex structures does not lie in the shape obtained, but in the technological process itself. This digital approach, leading to new practices, requires special training in order not to lose the scope of skills acquired previously.

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