STUDYING DESIGN ABDUCTION IN THE CONTEXT OF NOVELTY

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Abstract

Design abduction has been studied over the last several decades in order to increase our understanding in design reasoning. Yet, there is still considerable confusion and ambiguity regarding this topic. Some scholars contend that all regressive inferences in design — and design is mostly done by such backwards or regressive reasoning — are in fact abductions. Others focus on formal syllogistic forms in their attempt to clarify abduction. In contrast, we argue here that a defining characteristic of abduction is the production of, or the potential to produce, novel outcomes. Novelty is shown to be relative and depend mostly on what is known to the “reasoner” at the time of making the inference. Novelty is also shown to not necessarily be part of the direct outcome of an abductive inference; but rather, an attribute of an abductive design strategy that is intended to produce a new idea.

Keywords: Design theory, Design cognition, Human behaviour in design, Abduction, Innovation

1 INTRODUCTION

The American pragmatist philosopher Peirce (1839-1914) suggested that there is a main form of inference, abduction, besides deduction and induction, and that abduction is the only type of inference capable of producing new ideas. His work related to processes of scientific discovery, where abduction was a stage of forming hypotheses to explain surprising facts. The following is the basic verbal formulation of Peirce's abduction (Peirce CP 5.189, 1903):

The surprising fact, C, is observed;
But if A were true, C would be a matter of course, (1)
Hence, there is reason to suspect that A is true.

Here A is proposed as an explanatory hypothesis, implying that it needs to be further tested and verified by deduction and induction to complete the scientific inquiry process. Based on Peirce's seminal ideas, scholars have proposed modified, widened or alternative definitions of abduction and devised taxonomies of abductive inferences. For example, Schurz (2008) presents a thorough classification of abduction patterns, all of which are "special patterns of inference to the best explanation (IBE)". He lists four main types of abduction based on three dimensions: the type of hypothesis (conclusion) abduced, the type of evidence to be explained, and the cognitive mechanism driving the abduction. Schurz refers to "the official Peirce abduction schema" as "factual abduction" of the following syllogistic structure, where both the given fact and the abduced cause are instances of a more general law or rule:

Known Law: IF *Cx* THEN *Ex*
Known Evidence: Ea has occurred
--- (2)
Abduced Conjecture: Ca could be the reason

Influenced by treatments of abduction in philosophy of science, design researchers have attempted to shed light on design by using the concept of abduction. The first treatment is by March (1976), who suggests that abduction, which he calls "productive reasoning", is the key mode of reasoning in design. He also points to the confusion and misunderstanding created by not distinguishing between scientific and design hypotheses, and between logical propositions and design proposals. Whereas the goal of science is to establish general laws, he says, design is concerned with realizing a particular outcome. The pattern of abduction proposed by March is: from certain characteristics that are sought, and on the basis of previous knowledge and models of possibilities, a design proposal is put forward. March's abduction is one of three steps in his cyclic design process, which is similar to Peirce's methodological process in science.

Among the many other later treatments of design abduction, Roozenburg's (1993) definition of explanatory and innovative abduction is noteworthy. He argues that the scientific view deals with "explanatory abductions", which follow the tradition of Peirce and March and are good for diagnosis or troubleshooting, but that the core of design reasoning follows another type of abduction, for which he proposes the terms "innovative abduction" and "innoduction" (Roozenburg and Eekels, 1995). In fact, says Roozenburg, Peirce distinguished between the explanatory abduction as in (2) and innovative abduction, in which the law is not known and needs to be inferred together with the presumed reason for the evidence; and it was March who did not make that distinction.

A more recent paper (Dorst 2011) proposes yet another view on design abduction. It claims that there are two types of abduction relevant to design: *abduction-1* which follows a similar pattern to (2), and *abduction-2* which is comparable to Roozenburg's *innoduction*. Furthermore, Dorst suggests chaining these two inferences into a single reasoning step, which is the core of 'design thinking'. Chen et al. (2015a, 2015b) also present a two-step reasoning process, from function to principle and from principle to system. They explain that both are "implicit abductions" or innoductions, because they lack sufficient premises for generating only one result. Along with Roozenburg's introduction of the concept of innovative abduction and Dorst's and Chen et al.'s adoption of it, other design scholars still maintain Peirce's view and apply his "process of scientific inquiry," consisting of cycles of abduction, deduction, and induction, to the area of design (e.g., Pauwels and Bod, 2014). A comprehensive literature survey on design abduction can be found in Koskela et al. (forthcoming).

Reviewing the related literature suggests that research into abduction in design is still in a relatively undeveloped stage. There seems to be gaps in coverage, lack of depth and diverging outcomes. By focusing on the differences between science and design as well as on empirical knowledge of different phenomena characterizing design, new conceptions of abduction in design can be derived. Interestingly, some design scholars seem to have veered away from the more technical treatments of abduction based on logic theory, and towards a "softer" approach in which abductive reasoning is associated with notions of intuition (Cross 2006, p. 33) and creativity and subconscious activities (Dew, 2007). Another interesting approach can be found in Ullah et al. (2012), who analyze the cognitive process in design using C-K Theory, and claim that it is more complex than classical abduction, being a motivation driven process.

A fundamental issue to be addressed in this paper is whether a novel outcome, or at least the potential for it, is a precondition for defining some design reasoning as abductive. Peirce presented abduction as the only inference that produces new ideas. But in the context of science, defining what is new seems easier than in design. In design, we seek specific solutions to specific problems, so even a habitual solution that is slightly different from similar artifacts may be claimed to present some extent of novelty. Furthermore, it may be argued that if a solution to a problem already exists, then there is no design process at all; but if a solution does not exist, then (some) novelty will inherently characterize the solution when it is created. So, on the one hand it seems that if something is being designed, then some novelty is involved. On the other hand, we do not usually associate novelty with routine designs: redesigning an automobile to be made of a little more plastics and aluminum in order to reduce its weight does not seem innovative nowadays, but inventing Hyperloop transportation does. Clearly, there are various degrees of novelty associated with different design solutions. We try in this paper to show that the extent of novelty depends on aspects such as the knowledge that the "abducer" has at the time of making the inference, and the context or purpose of the inference, which may not always be the immediate generation of a design solution.

2 SELECTIVE AND CREATIVE ABDUCTIONS

If we look at the Peircean verbal formulation, expression (1), it is possible to offer two interpretations to the 'if A then C' rule in the second line:

Interpretation I: The surprising fact C can be explained by many rules; 'if A then C' is one of them, but there are also 'if B then C', 'if D then C', etc. The abducer's task is to select among these rules the best one and turn its premise into the "working hypothesis". This interpretation is somewhat supported by Peirce's attaching the notion of "uberty", fertility, to the outcome of abduction, hinting that there is some process of selection based on evaluation criteria.

Interpretation II: There is no known rule that can explain the surprising fact C. The abducer's task is to put forward an 'if A then C' rule that is completely new.

Clearly, abduction as in interpretation I is easier to carry out. We may call it "selective abduction". Abduction according to interpretation II is much more difficult, because an unknown premise needs to be discovered. We may call it "creative abduction". These terms are after Magnani (2001).

In design, the "classical" way to write Peirce's abduction as a syllogism is to interpret the surprising fact as the desired result, the purpose of the designed artifact:

$$\begin{array}{ll} q & \text{(q is a given fact, a desired result)} \\ p \rightarrow q & \text{(a given rule, IF p THEN q)} \\ \hline p & \text{(p is the conclusion, the cause)} \end{array} \qquad (3)$$

This is the form implied by March (1976) and also called *abduction-1* by Dorst (2011) for the cases when the rule is given. Our understanding is that only one rule comes into play in this case, and that

because the rule is given, there is no innovation involved. In fact, as discussed in the next section, this may not be abduction at all.
In contrast, Roozenburg (1993) claimed that Peirce's abduction should be written as:

$$
\begin{array}{ll}
q & \text{(} q \text{ is a given fact, a desired result)} \\
\hline
p \rightarrow q & \text{(a rule to be inferred first, IF } p \text{ THEN } q \text{)} \\
p & \text{(} p \text{ is the conclusion, the cause that immediately follows)}
\end{array}
\tag{4}
$$

This Roozenburg calls *innovative abduction* or *innoduction*, and Dorst calls *abduction-2*. They claim that this is the real 'kernel of design', where the rule is unknown and needs to be inferred first. The real question to be addressed now is, where does the rule come from? We do not know whether the abducer knows several rules that are applicable and makes a selection (as in interpretation I above), or he/she "invents" a new, previously-unknown rule (as in interpretation II). While the latter case is certainly innovative, the former may also represent some degree of novelty, as in applying one of several known solutions in a new situation.
An intermediate conclusion is that using the syllogistic form of abduction may be misleading, not being able to fully capture the circumstances under which this inference takes place. One missing aspect seems to be knowing exactly what the abducer knows. In science, we take it for granted that the knowledge is universal: an observation is surprising if the whole scientific community does not have an explanation for it. But is this also the case in design? In design, we are interested in solving a particular problem, not resolving a universal issue. The starting point, the function or the desired result, is "surprising" or anomalous in the sense that we do not know yet what artifact will provide it. The rule we use in our reasoning may be a working principle associated with the desired function, or a description of some structure associated with the working principle (an in-depth discussion of this topic is presented in Kroll and Koskela (2016)).
What is known at the time of making the inference is closely related to the issue of novelty. Novelty and innovation have of course been studied in depth over the last several decades, but we shall take a rather simplifying look at them here. Brown and Chandrasekaran (1985) divided design activities to three classes: Class 1 leads to major inventions or completely new products, and requires extremely innovative behavior because neither the knowledge sources nor the problem-solving strategies are known in advance. Class 2 is closer to routine design but still involves substantial innovation. It may arise during routine design when a new requirement is introduced that takes the design away from routine, requiring the use of new components and techniques. It differs from Class 1 in that the knowledge sources can be identified in advance, but the problem-solving strategies cannot. Class 3 is selecting among previously known sets of well-understood design alternatives, with the knowledge sources already identified. If all design alternatives fail, the designer may switch to Class 2 activity.
Gero (1990) similarly classifies design into routine, innovative, and creative. Routine design proceeds within a well-defined state space of potential designs, where the variables and their applicable ranges, as well as the knowledge to compute their values, are all directly instantiable from existing design prototypes. Innovative design takes place when the state space of potential designs is well-defined, but the designs produced are outside the normal space. This is produced by manipulating the applicable ranges of values for variables. The result is a design with familiar structure but novel appearance because the values of the defining variables are unfamiliar. Creative design uses new variables producing new types, thus extending or moving the state space of potential designs. Sometimes a new and disjoint state space is produced.

3 THE RELATIVITY OF NOVELTY

Let us try to imagine several design situations, as described below, and examine whether they represent abductions or not.

Scenario 1: While designing a geared speed reducer, and after specifying the gears and shafts, the time comes to decide on the type of bearings to be used. The designer may think as follows:

"I need to design the shaft support, and I know from my experience with similar tasks that ball bearings provide shaft support. Therefore, I specify ball bearings."

Here the designer thinks of only one rule that may be applied, either because his/her experience is quite poor and limited, or because he/she does not think deeply and just recalls the first rule that comes to his/her mind. It is quite easy to write the above statement as the syllogism in expression (3), to which some researchers refer to as abduction. However, the designer here clearly does not select the rule among a plurality of rules, nor does he/she invent a new rule. We claim that this type of reasoning, albeit fitting the syllogistic pattern in (3), should not be considered an abduction; but rather, an ordinary regressive reasoning step.
In fact, the above hypothetical scenario, which we claim is non-abductive for lack of innovation, is very close to being deductive. Consider the following designer's reasoning:

"I need to design the shaft support, and I know that in my company, we always use ball bearings for that purpose when designing similar products. Therefore, I specify ball bearings."

The syllogistic form

q	shaft support (the desired result)	
$q \rightarrow p$	if shaft support then ball bearings (the rule)	(5)
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p	ball bearings (the conclusion)	

is actually a reversal of the abductive pattern in (3) that now describes a deduction; a well-known property in logic theory. This last thinking by the designer is of course even less innovative than the previous one, because the designer blindly follows some standard company rule. Interestingly, a forward-reasoning step (deduction) is used here in a means-ends type chain of backwards reasoning. Cross (2004) already mentioned that novice designers tend to work more deductively, by following existing rules and standards, as opposed to the generative reasoning by the more experienced designers.

Scenario 2: The same situation as before, but the reasoning is somewhat different:

"I need to design the shaft support, and I know from my experience with similar tasks that ball bearings provide shaft support, and also straight roller bearings and taper roller bearings and a few other types of bearings, and I also know that the loads are relatively small and that low cost is desirable. Therefore, I specify ball bearings."

Here the designer thinks of many rules that may be applied (because he/she has a lot of experience, or because he/she thinks systematically), and also considers the context (small loads, low cost), and this makes him/her select one rule and immediately the solution emerges. Although it is possible to write this reasoning process as the syllogism in expression (4) and claim that this is selective abduction, it is not really an application of a known solution in a new situation; but rather, in a familiar situation. Thus, this should not be regarded as abduction at all.

Scenario 3: A similar problem, of designing shaft support, but this time the application area is quite unique:

"I need to design the bearings for the guide pulleys that operate the gates of the new (opened June 2016) channel of the Panama Canal. As an expert bearing designer, I know the loads are extremely large, the environment is harsh, the required life is 35 years, and that maintenance-free operation for five years must be guaranteed. Such a specification has never been met by roller bearings; however, I believe that it would be possible to design specially-coated spherical roller bearings for this purpose."

Here the designer has considerable knowledge in designing bearings, and is capable of designing a special bearing that uses known principles but its dimensions and coating are unique. This solution is innovative to a certain extent, perhaps matching Brown and Chandrasekaran (1985)'s Class 2 activity or Gero's innovative design category, and therefore may be claimed to represent abduction.

Scenario 4: A totally different situation is the following imaginary recreation of inventing the *first ever* straight roller bearing:

"I need to design a rolling-element bearing for heavy radial loads, and I know from my experience with ball-bearing design that one way to do it is to increase the contact area between the rolling elements and the races (the rings). Therefore, I replace the balls with rollers."

The situation here is of "living in a world" of ball bearings, and inventing a new structural principle for bearings. Arriving at this first ever roller bearing can certainly be considered a Class 1 activity or creative design, and hence, an abduction.

We may describe an even more innovative situation, that of inventing the first ever rolling-element bearing. This may of course refer to the intuitive insight gained by someone thousands of years ago, that sets of logs could be laid on the ground to make it easier to move a large stone block. Or it can refer to the invention of the first modern ball-bearing around 220 years ago, that was probably less intuitive and more grounded in physical principles and in previous work by scholars such as Leonardo da Vinci and Galileo. All these inventions can certainly be claimed to have resulted from abductive reasoning. But what if someone invents a rolling-element bearing today, without having any prior knowledge of such existing devices?

Imagine a 10-year old child playing with his Lego bricks, and by some intuitive reasoning he uses the supplied wheels around an assembly of bricks to facilitate low-resistance rotation (and not as conventional wheels). Of course, we are all familiar with bearings, so there is very little value to society in this "invention". Nevertheless, should the child's reasoning not be considered creative and innovative, and hence, abductive, in light of the fact that he had no knowledge of bearings at the time of making one? It does not seem to matter that the child did not think in terms of replacing sliding motion with the preferable rolling motion, and instead used his intuition to come up with a solution. The innovation is still there.

As an intermediate conclusion, we can say that while novelty is a necessary characteristic of abduction, establishing whether something is novel is quite difficult in design. Novelty in this case is not universal or absolute; but rather, relative to what the reasoner knows at the moment of making the inference. In other words, the same verbal or syllogistic description may be called abduction in one case, and just ordinary regressive reasoning in another, depending on the context and circumstances.

4 ABDUCTIVE STRATEGIES IN DESIGN

Having argued that a certain degree of novelty is required of an inference of a design solution to be labeled 'abduction', the question now is whether it is possible to identify other forms of reasoning that are abductive, yet do not easily manifest themselves as novel solutions. Koskela et al. (forthcoming) claim that abduction has many faces: it is a *property* of an inference and not just a *type* of inference, it may be manipulative, strategic, etc. Manipulative abduction (Magnani, 2004) refers to carrying out some action in a way that removes ambiguity and sheds new light on the suggested hypotheses, and eventually leads to a solution. Strategic abduction (Paavola, 2004) is the broader view that takes into account the constraints and hints that help find hypotheses, wherein the abductive inference itself is aimed at finding an overall pattern into which all evidence and clues fit.

Let us look at another hypothetical scenario from the domain of bearing design. The designer again needs to specify the supports for a shaft, and his/her thoughts are as follows:

"I need to design the shaft support, but for a different product from what we had done before; this time the size is bigger and so are the loads. I know from my experience that ball bearings provide shaft support, and are cheaper and simpler than other types and this is what we have always been using. But I suspect that due to the heavier loads, we'll need straight roller bearings this time. However, let's try to first design with ball bearings so that we can rule them out."

Here the abductive reasoning is used to lay out a strategy: the designer attempts a solution in which he/she intuitively does not believe, just to get it out of the way. If the attempt succeeded, then a good solution will be obtained. If it failed, then the designer has established a well-founded justification to go with more expensive alternatives. Although there is no obvious novel outcome in this reasoning, this is a deliberately chosen step of elimination that contributes to eventually generating a solution, so we consider it to be abductive strategic reasoning leading to manipulative abduction.

Two cases of abduction taking place—first an intuitive abductive inference and second an abductive strategy—are described in the following real case study. A few years ago one of us (EK) was present at a formal design review of a small satellite designed by students. The design included a propellant tank as in Figure 1 with the following approximate dimensions: r_o = 50 mm, r_i = 45 mm, l = 100 mm. It was to be made of titanium and serve as high pressure fuel tank in a nanosatellite. The parts—cylinder and two hemispheres—were to be fabricated by machining and welded together. The mass of this relatively thin-walled empty tank was about 1.3 kg; a considerable constituent of the 1–10 kg mass of this class of satellites.

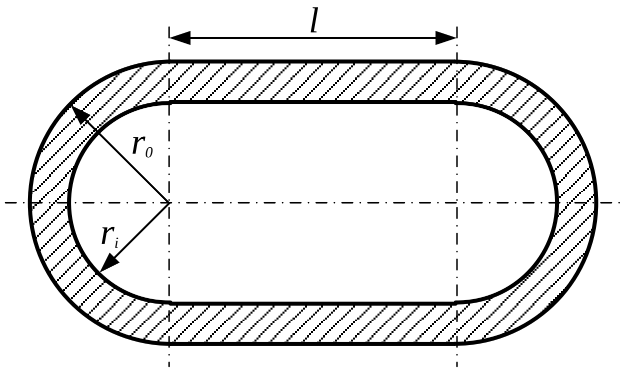

Figure 1. A domed-cylinder pressure vessel

At the time it occurred to EK that introducing radial reinforcing rods in such a vessel should reduce the required wall thickness, and thus the overall weight. Of course, such geometry is more difficult to fabricate, but perhaps it would be worth the effort (considering the high cost of putting a single gram in orbit). This was clearly an abductive reasoning step: weight reduction was desirable, an intuitive hypothesis was created: reduce total weight by making the walls thinner and make up for it with internal reinforcements. If succeeded, this was certainly an innovative solution.

A couple of years later, EK assigned the task of investigating the benefits of internal radial reinforcements in spherical pressure vessels to a student. The idea was that 3D printing of metallic parts had become quite feasible, so the barrier of complex geometry was no longer valid. The decision was to start with spherical vessels as a simple case, and the sketch in Figure 2 was given to the student.

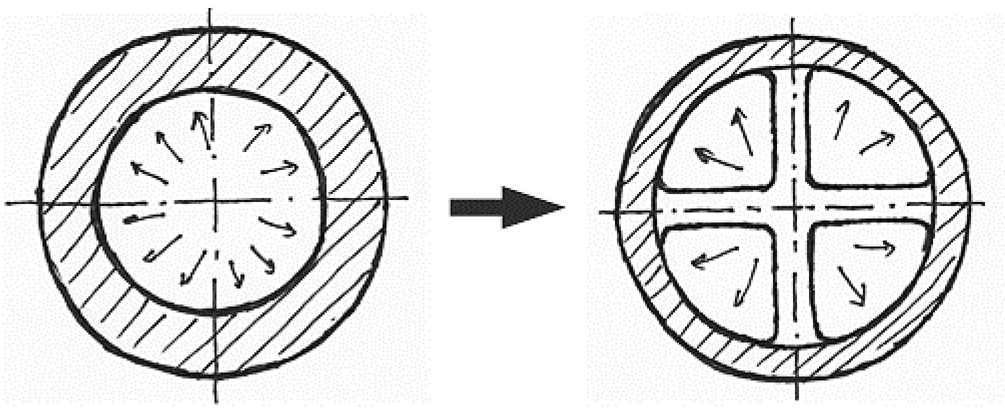

Figure 2. A sketch depicting the first abduced idea: reduce weight of pressure vessels by making the walls thinner and adding internal reinforcements

The student carried out many finite-element stress analyses as in Figure 3, but the results were disappointing: the effect of stress concentration at the point of connecting the internal rods to the outer shell could not be eliminated, no matter how large were the fillets used. The conclusion was that a sphere is a perfect geometry for carrying an internal pressure, and any attempt to modify it would fail. Interestingly, this meant that the previous intuition-based abduction actually failed, although at the time of coming up with the idea of radial reinforcements, there was a strong sense of certainty that it would work. Peirce (CP 5.181, 1903) also mentions the subjectively felt certainty connected to the outcome of abductive processes.

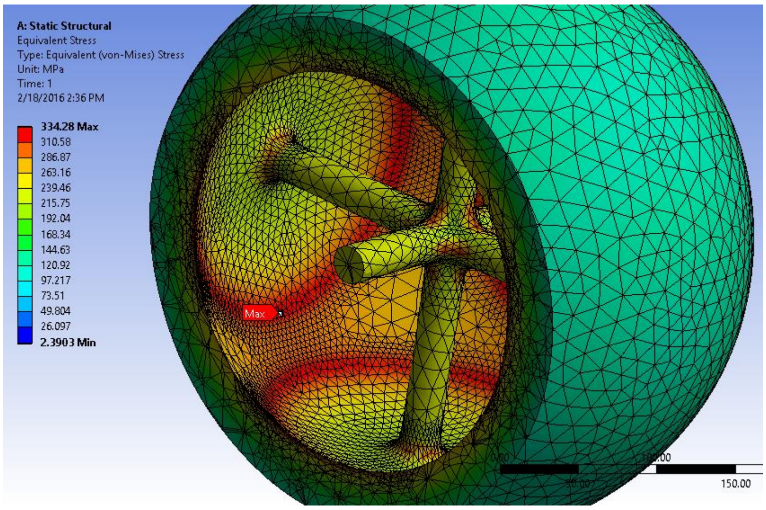

Figure 3. Stress analysis of an internally-reinforced spherical pressure vessel. Red areas denote high von-Mises stresses

At that point the interest turned into cylindrical pressure vessels, which were not as "perfect" as spheres. However, because spheres turned out to be so "ideal", it was felt that aiming at turning cylinders into more sphere-like shapes might be beneficial. This resulted in the "peanut"-shaped vessel of Figure 4, that after some trial-and-error produced a ~26% weight reduction over a simple domed cylinder of the same capacity.

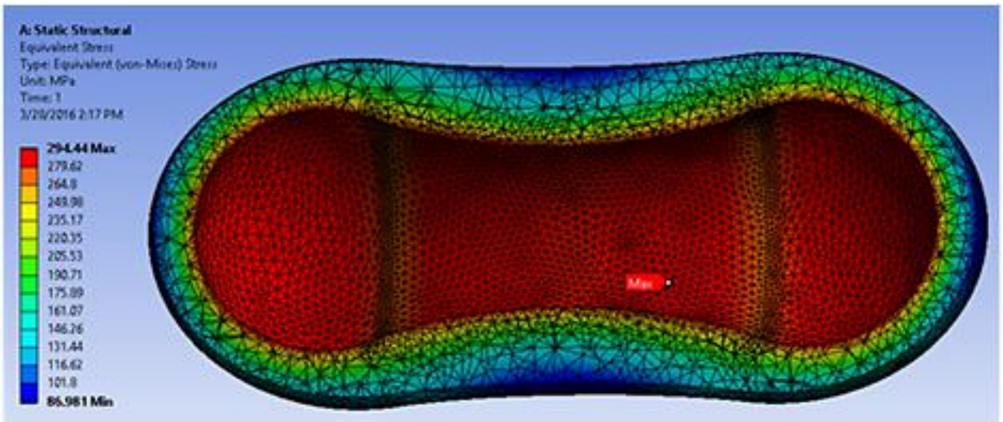

Figure 4. Stress analysis of a "peanut"-shaped vessel consisting of two connected spherical cavities

In this case there was initially no particular design problem to be solved. The problem of reducing the weight of pressure vessels was (perhaps abductively) created from knowing the importance of weight reduction in space applications. The first reasoning activity was based on intuition regarding a possible solution (radial reinforcements), and although it eventually failed, the initial proposal of the solution principle was innovative and thus, abductive. A few years later, the solution idea was checked and turned out to be unsuccessful. However, it was from the gained understanding of what is good and what is bad for pressure vessels that a new improvement direction emerged: make pressure vessels with variable wall thickness and a shape of a peanut, and this proved to be a good, innovative solution. In other words, the strategic abduction was in deciding to shift the solution direction from internal reinforcements to shape morphing, and it came about when realizing that even when the optimal shape (a sphere) could not be used, perhaps due to space limitations that dictated a cylindrical shape, elements of the optimal shape (spherical cavities) might still work.

5 DISCUSSION AND CONCLUSION

Many design-related inferences and phenomena seem to resemble abduction. There is also a large body of knowledge on abduction in science with some of it possibly pertinent also to design. However, there are still many conflicting issues and ambiguities regarding design abduction: Is all design abduction? Are there design activities that are not abductive? Is abduction associated only with proposing design solutions or with other activities too? In an effort to move towards defining design abduction and study design phenomena in relation to abduction, we focused here on the issue of novelty and examined its relevance to abduction.

Novelty in design has been shown to be relative and depend on what the reasoner knows at the time of making the inference. In this sense, the situation in design is very different than in science, where novelty tends to be more absolute. We demonstrated the relativity of novelty and the significance of the surrounding circumstances through several hypothetical scenarios of designers' thought processes in different settings. The scenarios seem quite realistic and related to the well-understood domain of rolling-element bearings in mechanical design. They represented varying degrees of innovation that depended on how familiar the situation was, how well-defined the problem was, and what knowledge was applied in arriving at the solution. We concluded that it was the degree of novelty that determined whether an inference was abductive, regardless of the possibility to write it in the "classical" syllogistic form of abduction.

Next we suggested that design abductions take place also in cases that are not as simple as a single inference that produces a design solution. We demonstrated strategic abductions that involve inferring hypotheses that may not produce an immediate solution but may move the designer closer to it. One such strategic abduction was to choose a specific bearing alternative in order to eliminate it, a decision that was assisted by various clues that led to a certain intuition regarding the situation. Another demonstration was through a real case study of designing lighter pressure vessels. The design started with an intuition regarding a possible solution direction, which eventually failed. Nevertheless, this was an abductive step due to its potential novelty. A later strategic abduction was able to use the previously generated insights in order to change the solution direction, and resulted in a novel outcome.

Research efforts in design abduction should continue for the sake of deepening our understanding in design and the opportunity to learn from scholarly studies by philosophers of science. One of the possible directions to carry out such research is analysis of empirical cases wherein a good accounting of the thought process exists. Alternatively, semi-empirical case studies can be created by designers who may be able to describe realistic, albeit hypothetical, scenarios based on their experience.

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