PRACTICAL DESIGN AND EVALUATION OF CFRTP BODY STRUCTURES FOR MICRO EV

K. Goto[1*], K. Uzawa[1], J. Takahashi[1], K. Kageyama[1], H. Murayama[1], T. Matsuo[1], M. Yamane[1], I. Ohsawa[1]

[1]*Department of Systems Innovation, School of Engineering, The University of Tokyo, Tokyo, Japan*
**kgoto@giso.t.u-tokyo.ac.jp*

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Abstract

In order to evaluate the potential of carbon fiber reinforced thermoplastics as automotive structural material, comparing practical CFRTP body structure design to other design solutions made of other materials is indispensable. This paper presents practical Micro EV design examples and test/analysis correlation result, CFRTP material models, which is necessary to design Micro EV structure.

1 Introduction

A weight reduction of automobile is essential to reduce the amount of energy used in transportation section. Carbon fiber reinforced thermoplastics (CFRTP) is now being developed as a next-generation material for lightweight mass-production car body. The Japanese METI-NEDO (Ministry of Economy, Trade and Industry - New Energy and Industrial Technology Development Organization) project "Development of Sustainable Hyper Composite Materials Technology" (2008fy-2012fy) aims to develop low cost and high performance CFRTP for automotive application. The material developed in this project is mainly carbon fiber/polypropylene prepreg which has high strength, energy absorption capability, formability and recyclability. This project reached the end of material development phase and has proceeded to the application phase [1].

On the other hand, automobile itself is changing its form in order to be more efficient. Many car manufacturers and start-ups are developing electric vehicles called Micro EV. These Micro EVs are categorized into new Japanese automobile category which will be set within this fiscal year classed between Japanese minicar and Kei-car. Following Table 1 shows an outline of these categories [2].

	Minicar	New category (Micro EV)	Kei-car
Seating capacity	1	2	4
Crash safety standard	None	Less-restricted than Kei-car	Same as full-sized car
Drive on highway	Not-permitted	Not-permitted	Permitted
Maximum length	2.5 m	Smaller than Kei-car	3.40 m
Maximum width	1.3 m		1.48 m
Maximum height	2.0 m		2.00 m

Table 1. Micro EV outline, in comparison with minicar and Kei-car [2].

The CFRTP's features: high mechanical property, large energy absorption, manufacture by high-cycle molding and recyclability are fit also for Micro EV application. Especially, energy absorption is important for Micro EV because the crash zone of Micro EV is smaller than average cars. Therefore, as the next step of CFRTP development, we evaluate the CFRTP's advantage as structural material of Micro EV in comparison with other materials and set guidelines to develop the material.

2 Approach

First, we perform 3-point bending impact test to know impact characteristic of CFRTP sample which is developed in above-mentioned METI-NEDO project. We build an FEM model of the test in order to derive a material model of CFRTP for FEM analysis through test-analysis correlation. Next, we design the shape of Micro EV structure made of CFRTP in consideration of CFRTP's characteristics. Along with it, the shape of structures made of GFRP and aluminum are also designed. Then the thickness of the parts of each structure is set so as to have a certain level of rigidity and crash safety. This is confirmed by static and crash FEM analysis using the material model of CFRTP. And, CFRTP's advantage as structural material of Micro EV is evaluated by comparing total weight and estimated production cost of each structure.

3 Impact test and FEM analysis

In order to test the impact characteristic of CFRTP itself, three-point bending impact tests were performed. The tests are based on JIS K 7084; testing method for impact properties of CFRP by instrumented three-point bending impact test. According to the standard, the span of supporting points is set as 60 mm and the impact speed is set as 3.8 m/s. Width and thickness of specimen are set as 15 mm and approximately 4 mm [3]. Tested materials are quasi-isotropic laminate of unidirectional carbon fiber reinforced PP prepreg (QISO) with around 40% Vf and laminate of carbon fiber mat reinforced PP prepreg (CMT) with around 20% Vf. The stacking sequence of quasi-isotropic laminate was $[(0/45/90/-45)_s]_4$. Both of these are the material developed in the METI-NEDO project.
Then we built a quarter FEM model of the test and set the symmetry conditions. The FEM model is shown in Figure 1. FEM analysis was performed with LS-DYNA.

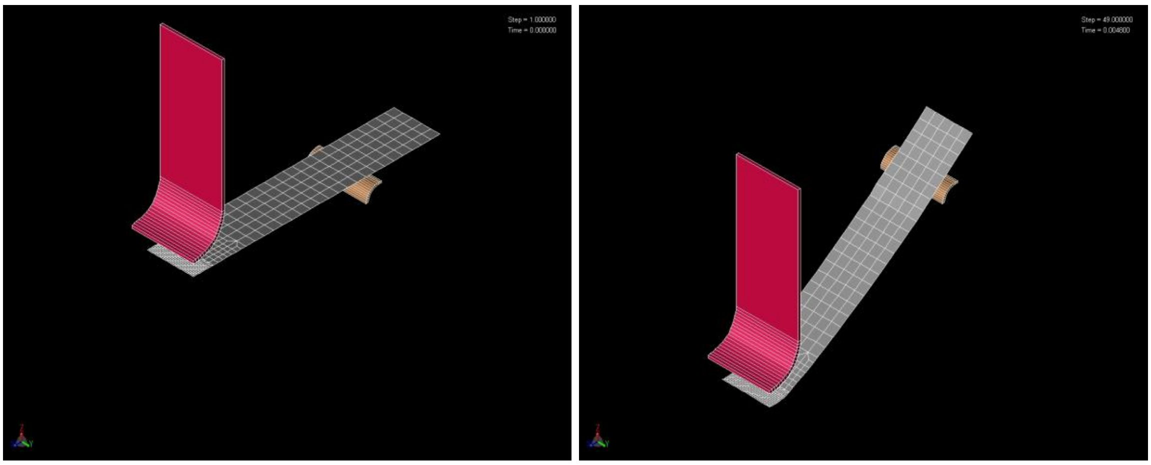

Figure 1. Quarter model of impact test, before and after the impact.

For the QISO material, material model 54, "ENHANCED COMPOSITE DAMAGE" was selected, and for CMT material, material model 3, "PLASTIC KINEMATIC" was selected. The input values of each model were shown in Table 2.

	MAT_ENHANCED_COMPOSITE_DAMAGE							
QISO	MID	ρ	Ea	Eb	(Ec)	PRba	(PRca)	(PRcb)
	-	1.40e-09	40000	5000	-	0.22	-	-
	Gab	Gbc	Gca	(Kf)	Aopt	-	-	-
	1400	1400	1400	-	2	-	-	-
	Tfail	Alph	Soft	Fbrt	Ycfac	Dfailt	Dfailc	Efs
	-	-	-	-	-	0.02	-1	-
	Xc	Xt	Yc	Yt	Sc	Crit	Beta	-
	360	1600	108	54	70	54	-	-
CMT	MAT_PLASTIC_KINEMATIC							
	MID	ρ	E	PR	Sigy	Etan	Beta	-
	-	1.08e-09	11000	0.3	210	-	-	-
	Src	Srp	Fs	Vp	-	-	-	-
	-	-	0.008	-	-	-	-	-

Table 2. LS-DYNA Input values of QISO and CMT.

Results of impact test and correlated FEM analysis are shown in Figure 2 and Figure 3. The test and FEM result were processed through a low-pass filter with cutoff frequency of 4 kHz.

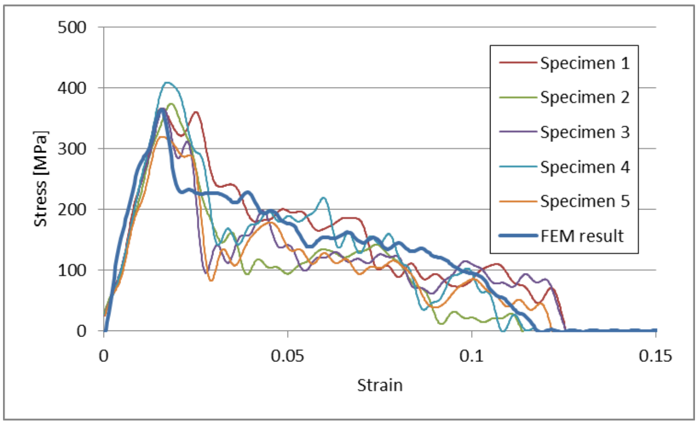

Figure 2. Stress-strain curve of impact test and FEM analysis (QISO).

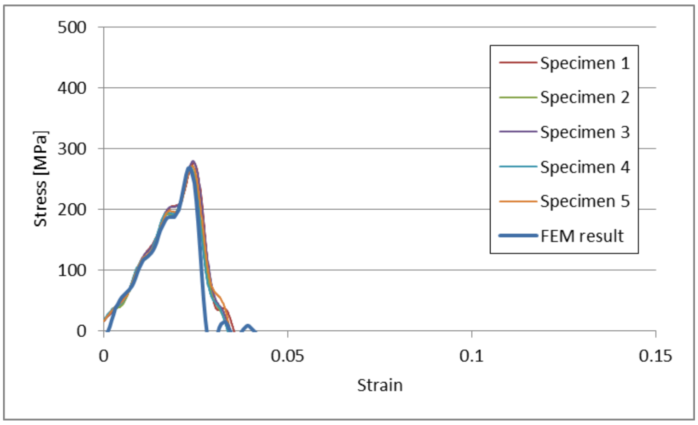

Figure 3. Stress-strain curve of impact test and FEM analysis (CMT).

According to the test results, QISO material shows ductile behavior and CMT material shows brittle behavior. The ductile fracture process of QISO material gives this material an energy absorption capacity almost same level of steel, most prevailing structural material for automobile [1]. From this fact, it is said that QISO material is suitable for car body structure and the structure made of QISO material will be similar to steel monocoque.

4 Design of body structures for Micro EV

4.1 Specifications of Micro EV

First, we set the specifications of the target Micro EV as following Table 3.

Annual production	More than 5000
Vehicle price	Less than 1,000,000 yen
Seating capacity	2
Cabin length	1400 mm
Cabin width	900 mm
Luggage area capacity	More than 80 L
Driving range	60 km
Battery type	Lithium-ion

Battery compartment capacity	More than 40 L
Vehicle length	2500 mm
Vehicle width	1300 mm
Vehicle height	1200 mm
Tire	90/90-12
Front suspension type	Double wishbone
Rear suspension type	MacPherson strut
Motor	Front, in-wheel
Battery position	Front, outside cabin

Table 3. Specifications of target Micro EV.

Here are the how and why we set the specification as above.

In order to reduce energy consumption, the majority of automobiles should be efficient. So, the target Micro EV should be affordable and mass product. Thus we set minimum annual production to five thousand and maximum vehicle price to one million yen.

According to a research performed by the Ministry of Land, Infrastructure, Transport and Tourism, the seating capacity of Micro EV is expected to be two [4]. The shoulder (bi-deltoid) breadth of 95th percentile Japanese male/female is 495/443 mm, the chest depth is 240/241 mm, the buttock-knee length is 616/578 mm, and the lower limb length is 1089/1003 mm according to Anthropometric Dimension Database 1991-92 by Digital Human Research Center, AIST [5]. From this data, we derive the minimum width and length of passenger cabin, 900 mm and 1400 mm, when two passengers are seated as shown in Figure 4.

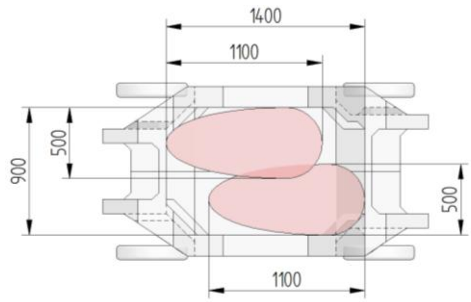

Figure 4. Assumed seating configuration of Micro EV.

Also, enough space for the two passengers' luggage is needed. We assume that the normal luggage size for two is two small suitcases (40 L) or one large suitcase (80 L). So, the luggage area capacity should be more than 80 L.

According to another document provided by the Ministry of Land, Infrastructure, Transport and Tourism, the anticipated scenes in which Micro EV is utilized are urban transportation and tour around sightseeing area [6]. So we estimated that a range of 60 km is enough for the target Micro EV. In order to achieve a driving range of 60 km, 40 kg of lithium-ion battery is likely to be equipped [7], and the volume of the battery will be 15 L [8]. Also controller unit etc. is necessary for EV. Thus we set the minimum battery compartment capacity to 40 L.

The above-mentioned research performed by the Ministry of Land, Infrastructure, Transport and Tourism also says that the vehicle dimension of Micro EV is expected to be small enough so as not to lose the advantage of micro mobility [4]. Additionally, in order to reduce energy consumption, Micro EV should be light-weight and have low running resistance. Thus we set length, width and height of the target Micro EV to 2500 mm, 1300 mm and 1200mm, the minimum dimensions to get enough capacity for passengers, luggage and battery described above.
Other specifications are determined by reference to example of existing Micro EV, mainly COMS manufactured by Toyota Auto Body Co., Ltd. since 2000, almost the only minicar available in the Japanese market. The tire size and front suspension type are same as COMS, 90/90-12 and double wishbone. We choose MacPherson strut as rear suspension type because it is simpler and better suited for securing width of luggage area than double wishbone. And we assume that the target Micro EV is driven by front-mounted in-wheel motors unlike COMS driven by rear-mounted in-wheel motors. This is for the space-saving and efficient energy recovery from regeneration brake system done by the motors which also function as generator. Also, we choose front-mounted battery so as not to waste the driving power. This is also because, for safety reason, it is better to mount the battery outside the passenger cabin, unlike COMS whose battery is mounted beneath passenger.

4.2 Shape design of body structure of Micro EV
The next step is to reflect these specifications into the shape of the body structure. In this study, the body structure of target Micro EV is defined to consist of front and rear impact structures, suspension installation point, front and rear bulkheads and side sills. In order to meet the specifications and function as a Micro EV body structure, we set the overall dimensions of body structure and constraints on the shape of suspension installation point, front and rear pillar base, passenger cabin, battery and luggage area, and wheel arches. The dimensions of body structure and its shape constraints are shown in Figure 5. The shape of passenger cabin, battery and luggage area and wheel arches shown in this figure are the minimum limits, so they can be expanded.

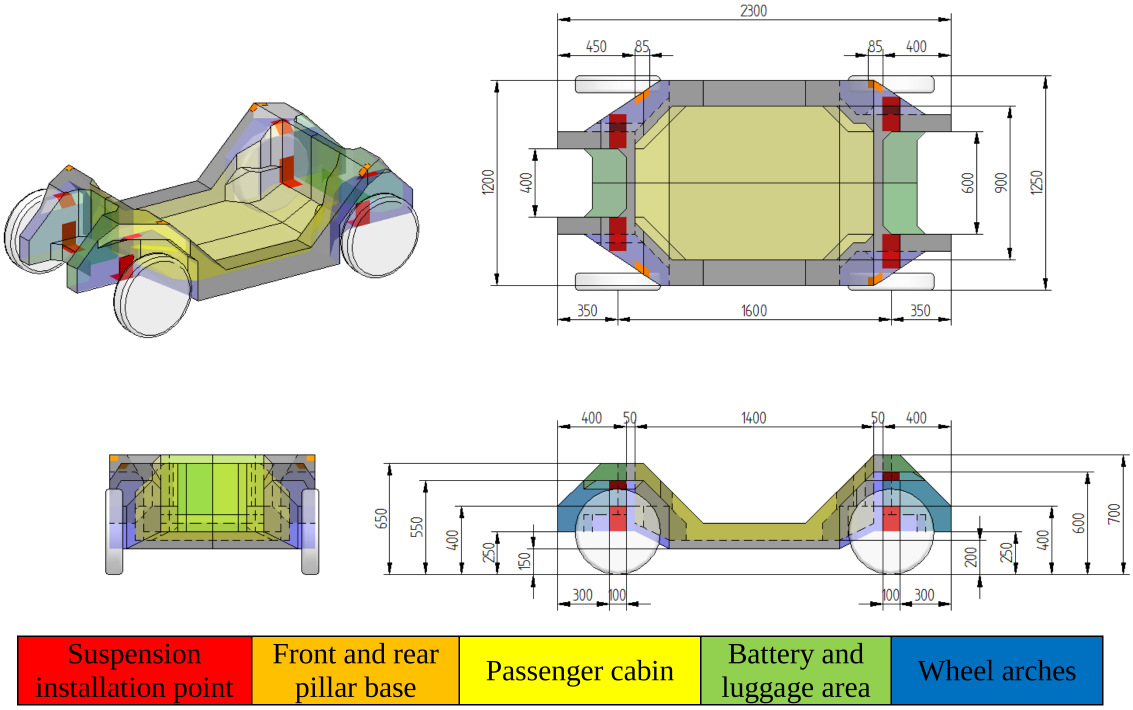

Figure 5. Dimensions of body structure and its shape constraints.

Then we design the specific shape reflecting features of the applied material. The aim of this study is to evaluate the CFRTP's advantage as structural material of Micro EV in comparison with other materials; therefore we have to design the body structure made of also other materials than CFRTP. Automotive structural material is divided into two major material groups: metal and composite material. In this study, aluminum and glass fiber reinforced plastics (GFRP) was selected as a representative material from each group. We chose aluminum because COMS, about the only available Micro EV in Japan, has aluminum chassis. And we chose GFRP, not CFRP, because CFRP is too expensive to be structural material of affordable mass-production automobile, more than five thousand annual production and less than one million yen vehicle price, without manufacturing process with very high-productivity like that of CFRTP [9]. In this paper, because of space limitations, we don't explain details of design process of specific shape of body structure and show only design policy and limitations of body structure made of each material.
The design policy and limitation of CFRTP body structure are listed below.
-Parts are manufactured by high-cycle press molding and welded.
-Parts has open cross-section and has to be made by single press action.
-Long side of the parts should be smaller than 1000 mm.
-Minimum welding margin is 25 mm.
-Force loading point should have closed cross-section consists of few parts.
-Side sills are connected with a member to deal with side crash force.
Three-quarter view and cross-section view of CFRTP body structure is shown in Figure 6.and Figure 7.

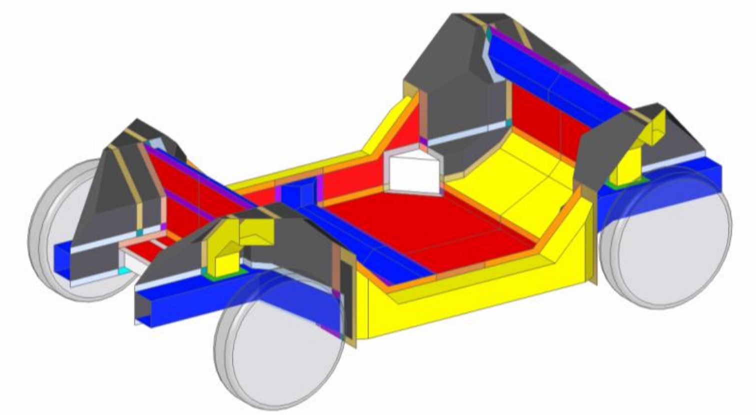

Figure 6. Three-quarter view of CFRTP body structure (color-coded according to parts and joint area).

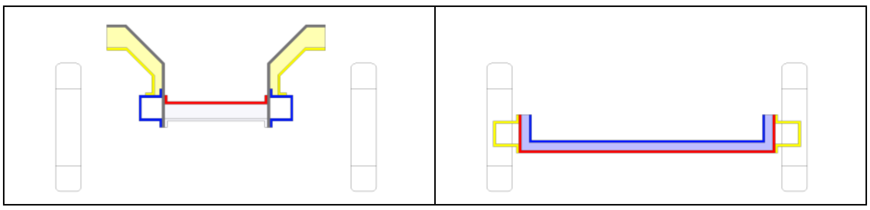

Figure 7. Cross-section view of CFRTP body structure at front axle (L) and midpoint of wheel base (R).

The design policy and limitation of GFRP body structure are listed below.
-One piece monocoque structure produced through Resin Transfer Molding.
-Side sills, floor and bulkheads are thickened with foam core.
-To minimize cost, monocoque should be made with one pair of mold.
-Sub-frames are attached to front and rear end of monocoque.
-Sub-frames are made of aluminum pipes.

-Shock absorber installation points are located on the monocoque to maintain body rigidity.
Three-quarter view and cross-section view of GFRP body structure is shown in Figure 8 and Figure 9.

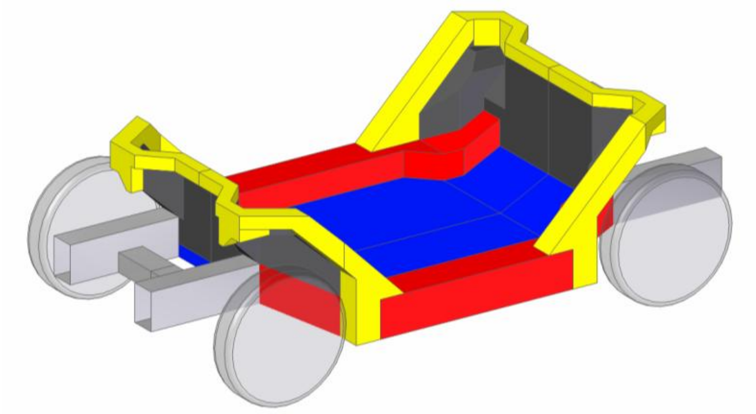

Figure 8. Three-quarter view of GFRP body structure (foam core is colored in red, blue and yellow).

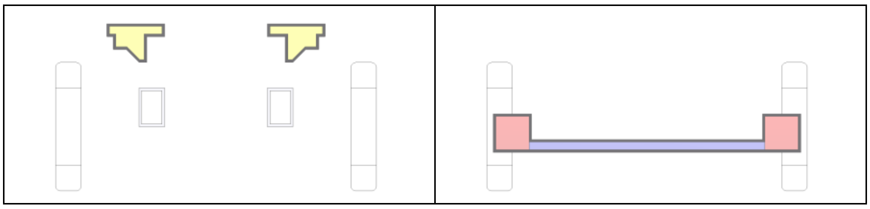

Figure 9. Cross-section view of GFRP body structure at front axle (L) and midpoint of wheel base (R).

The design policy and limitation of aluminum body structure are listed below.
-Space frame structure made of aluminum extrusion.
-Parts must have constant cross-sectional profile.
-Rivets and adhesive are used to join the parts.
Three-quarter view and cross-section view of aluminum body structure is shown in Figure 10 and Figure 11.

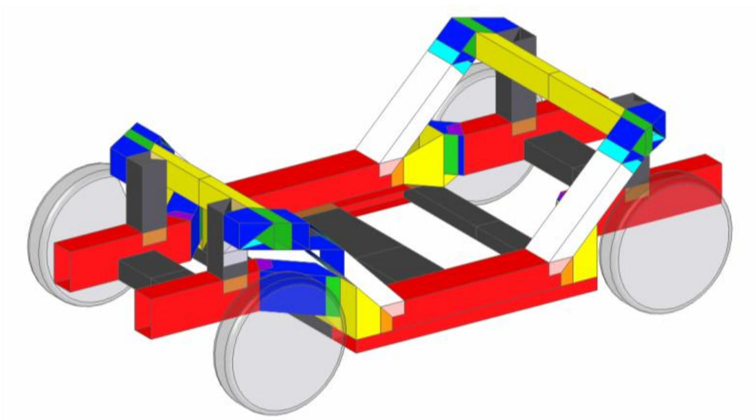

Figure 10. Three-quarter view of Aluminum body structure (color-coded according to parts and joint area)

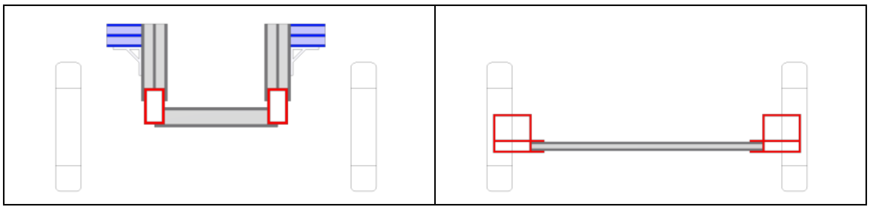

Figure 11. Cross-section view of aluminum body structure at front axle (L) and midpoint of wheel base (R).

5 Conclusion

-The CFRTP development should aim at Micro EV application because the CFRTP's features, especially large energy absorption, are fit for Micro EV application.
-Test/analysis correlation of 3-point bending impact test was performed to derive CFRTP material models.
-The specifications of target Micro EV and the main dimensions of body structure reflecting them are determined.
-Micro EV body structures made of CFRTP, GFRP, aluminum which is utilizing features of each material was proposed.
-To evaluate CFRTP's advantage in total weight and production cost, detailed design with FEM analysis using material data derived from test/analysis correlation is needed.

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